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IHACRES-3S – A 3-store formulation for modelling groundwater-surface water interactions

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Abstract: A streamflow regime can be broadly categorised as perennial, intermittent, or ephemeral, with ephemeral streams having relatively short-duration flow after rainfall and no baseflow, and intermittent streams having a more sustained flow during the wet season, but no baseflow during extended dry periods. Most existing rainfall-runoff models have been developed for humid catchments, in which streamflow is perennial. Thus the assumptions on which they are premised are often inappropriate for capturing the dynamic interactions between stream and groundwater in the more variably-connected systems in semi-arid and arid catchments.

This paper presents IHACRES-3S, a new formulation of the IHACRES rainfall-runoff model, which has been developed for modelling streamflow in variably-connected groundwater-surface water catchments or catchments at risk of a change in flow regime due to groundwater extractions or climate change, such as the Messara catchment in Crete. The linear routing module has been reformulated as a 3-store model, with the new store behaving as a seasonal perched water table. Variations in the recharge between the two subsurface stores and the introduction of a streamflow evaporation term are shown to improve model performance, with the latest formulation able to capture the timing of the switch from a perennial stream to an ephemeral stream, as well as the low flow behaviour between wet seasons (Figure 1). Including a streamflow evaporation term is also shown to contribute to improved performance in modeled baseflows in the Messara catchment. Model complexity has increased due to the addition of new parameters and assumptions and more sensitivity testing is required to determine the final formulation, and level of complexity, as well as its wider applicability.

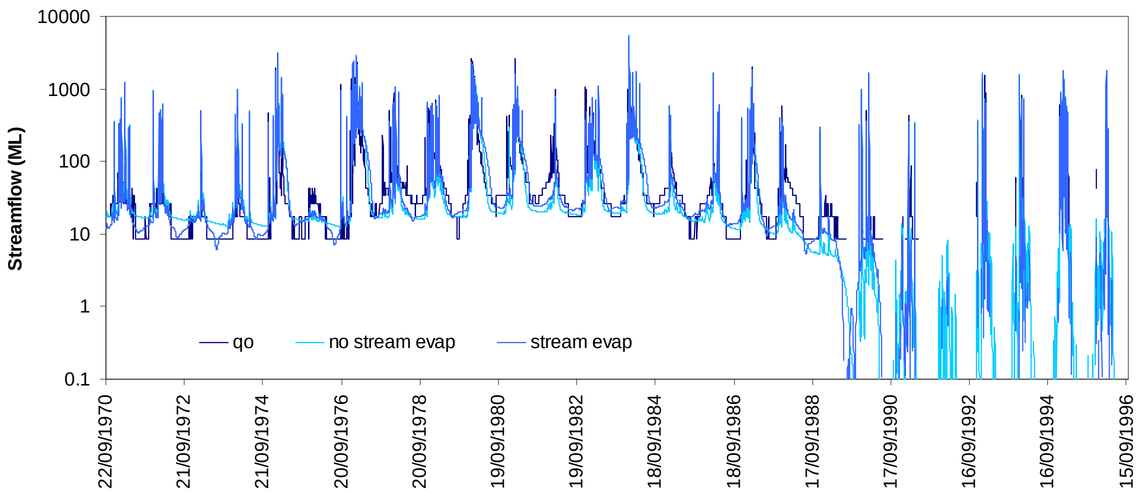

Figure 1. Observed flow (qo) and modeled flows for 'no stream evap' and 'stream evap' versions.

Keywords: *Groundwater-surface water interactions, rainfall-runoff modeling, streamflow depletion*

1. INTRODUCTION

As demands on increasingly scarce water resources have increased in response to population and economic growth drivers, the need to improve our understanding of the interactions between surface and groundwater systems and to represent these interactions in hydrologic models has grown. Most rainfall-runoff models have been developed for use in humid, temperate catchments and often perform poorly when applied to more arid systems. The various reasons for this are canvassed in Wheater *et al.* (2008), and include relatively low-scale human settlement, the challenges posed by lack of reliable input data and the inappropriateness of model assumptions in semi-arid and arid systems. Rainfall tends to be episodic, localised and often very intense, and rain-gauge density is typically low, resulting in rainfall records which do not adequately reflect the rainfall distribution pattern. The relatively sparse vegetation cover means more rapid hydrologic responses, a more significant overland flow component and episodic groundwater recharge. And the hydrologic connection between streams and groundwater tends to be more variable, and this dynamic is not captured in many rainfall-runoff models. The degree of coupling between groundwater and surface water systems defines a stream's flow regime and has implications for the model structure needed to predict streamflow response.

A flow regime can be broadly categorised as perennial, intermittent, or ephemeral. Ephemeral streams are defined as having short-lived flow after rainfall and no baseflow, while intermittent streams have baseflow during the wet season. Different conceptual models are needed to capture the behaviour of these different flow regimes, which reflect the differences in stream-groundwater hydrologic connectivity. In perennial systems, there is a permanent connection between the stream and groundwater, and good results can be obtained from rainfall-runoff models that do not explicitly represent the groundwater store. As the hydrologic connectivity becomes more transient and a catchment's runoff response more non-linear, such as for intermittent streams, the need for more explicit representation of the groundwater increases. However, where there is no hydrologic connection between stream and groundwater aquifer, such as in ephemeral systems, explicit representation of a groundwater store should not be required. Ye *et al.* (1997) show that a single store-single decay coefficient model was sufficient for modelling the ephemeral Canning River in Western Australia.

This paper presents a new version of the IHACRES rainfall-runoff model, IHACRES-3S, developed for modelling streamflow in variably-connected groundwater-surface water catchments or catchments at risk of a change in flow regime due to groundwater extractions or climate change. It builds on model developments started in the Coxs Creek catchment, New South Wales, Australia (Herron and Croke, *in press*), but continued in the Messara catchment in Crete. The processes governing the interactions between aquifers and streams can be extremely complex and the extent to which this detail is represented in a model will depend on its purpose. Rassam and Werner (2008) summarise many of the processes – stream depletion, overland and throughflow, streamflow attenuation, operation of instream storages, offstream storages, bank storage, over-bank flooding – which can influence groundwater-surface water interactions, but not all of these are necessarily important at the catchment scale. Our aim in expanding the capability of a simple lumped conceptual rainfall-runoff model to predict streamflow behaviour in variably connected groundwater-surface water systems is to capture the timing of the switching on and off of streamflow in response to fluctuating groundwater levels, with as few additional parameters and data requirements as possible.

2. THE MESSARA CATCHMENT

The Messara catchment in southern Crete covers an area of 398 km^2. The climate is sub-humid Mediterranean, with 40% of the 600 mm mean annual rainfall occurring in December-January and negligible rain between June and August. About 25% of the annual rainfall recharges the groundwater aquifers, primarily during the wetter winter months, and another 10% runs off to the sea. Groundwater stores peak during March-April and then gradually deplete over the summer-autumn period, until recharge occurs again in winter.

The catchment has been the focus of previous hydrologic modelling studies (Croke *et al*., 2000; Vardavas *et al*., 1997) because increased groundwater pumping following the conversion of dryland agricultural production (predominantly olives (175 km^2) and vines (40 km^2)) to drip irrigation fed production since 1984 has seen groundwater tables fall by up to 20 m. The once perennial Messara River is now ephemeral, with the surface and groundwater systems hydrologically disconnected. In addition to irrigation extractions, modelling by Croke *et al.* (2000) indicates a significant natural loss (~55 ML/day) through evaporation and sub-surface outflow to the sea.

The Messara catchment has a good coverage of daily rainfall (15 sites) and pan evaporation data (5 sites) to inform the model. Monthly readings of groundwater levels have been made at 25 bore locations. Vardavas *et al.* (1997) provide mean monthly pan coefficients for converting pan evaporation to potential evaporation.

3. MODEL LINEAGE

The basic IHACRES model is a conceptual rainfall-runoff model consisting of two modules: a non-linear loss module which converts rainfall to effective rainfall (rainfall that contributes to streamflow); and a linear routing module, which uses a recursive relation at each time-step to model streamflow as a linear combination of antecedent streamflow and effective rainfall (Jakeman *et al.*, 1990). Various formulations of each module have been developed over time. Here we couple the CMD version of the non-linear loss module (Croke and Jakeman, 2004)) to a 3-store (3S) routing module to produce a predictive model capable of simulating the streamflow behaviour of variably connected groundwater-stream systems.

IHACRES-3S builds upon the GW module of Ivkovic *et al.* (2009) and the preliminary modifications of Herron and Croke (*in press*) from modelling the Coxs Creek catchment in New South Wales, Australia. Ivkovic *et al.* (2009) introduced a groundwater store into the linear routing model, recharged by a constant proportion of the effective rainfall and depleted by discharges to the stream, irrigation extractions and/or other natural losses. Herron and Croke (*in press*) made some relatively minor changes to the model, adding a stream to aquifer infiltration term to switch off quickflow, and an effective rainfall threshold to vary the partitioning of effective rainfall between quick and slow flow pathways.

Due to the unquantified influence of inconsistencies in measured rainfall on model performance in the Coxs catchment, however, Herron and Croke (*in press*) concluded that evaluating further model developments in this catchment would be difficult. Instead IHACRES-3S has evolved through trialing and testing successive adaptations of the Herron and Croke (*in press*) version in the Messara Catchment. Initially, a simpler, two stores version was tried, using a non-linear response function for slow flow discharge, rather than the standard linear response. While calibrations of this version during a 'wet' period yielded some improvements in model performance, a parameter set could not be found that would satisfactorily reproduce streamflow volumes and patterns in other parts of the record, particularly a run of dry years in the early 1970s and following the increase in groundwater extractions for irrigation after 1984.

3.1. IHACRES-3S

Figure 2 illustrates the conceptual IHACRES-3S model. No changes have been made to the CMD module or quickflow pathway, but in this formulation the slow flow pathway comprises two layered stores. The upper store, G_1, receives rainfall inputs and discharges to the stream, Q_{s1}, and recharges the lower store. G_1 has a lower limit of zero, representing a fully 'drained' condition. Conceptually, the upper store can be viewed as a perched water table, which develops in response to rain and tends to be relatively short-lived, perhaps, seasonal. Thus the time constant, τ_s, for discharge from the 'soil' store will be somewhere between that for quickflow, τ_q, and the groundwater discharge time constant, τ_g. G_2 is recharged from G_1 when G_1>0 and discharges to the stream, Q_{s2}, when G_2>0. The sum of Q_{s1} and Q_{s2} is Q_s. We assume that all extraction, E, and natural groundwater losses, L, are from G_2. The approach avoids the need to specify a maximum capacity for either storage, but the introduction of a recharge term, R, between the stores adds a new parameter or, at the very least, an additional assumption about catchment characteristics.

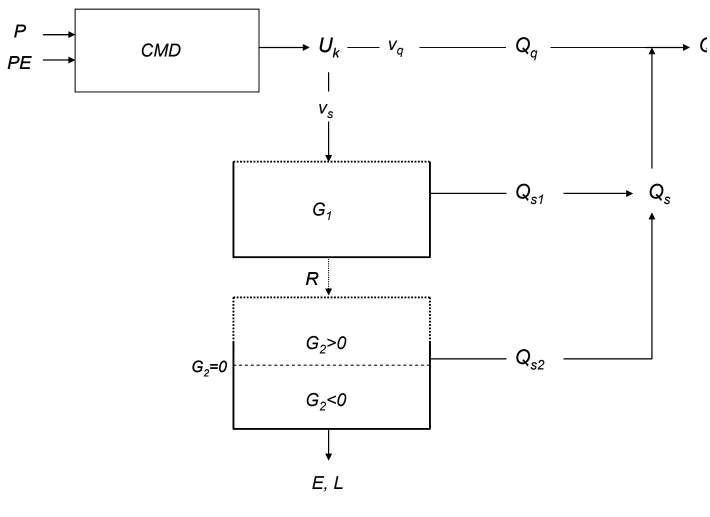

Figure 2. Conceptual model of IHACRES-3S

A couple of approaches for setting R were tested. In the first, a constant rate was assumed for G_1>0, roughly estimated as the product of catchment area and a ballpark estimate of the saturated hydraulic conductivity of limestone. For G_1=0, R=0. In the second approach, R is a function of the volumes of water in G_1 and G_2 and is calculated in two steps. Here we assume that as G_2 increases above zero, the unsaturated zone between the two stores decreases and with it the capacity for recharge. Taking the simpler case of $G_2 \leq 0$, R=0 when G_1=0, but increases linearly with increasing G_1 until some threshold volume, g_1, above which R assumes a constant maximum rate, R_{max}. The recharge threshold, g_1, is a new parameter, which can be set following inspection of the observed and modelled data. If, however, G_2>0 (i.e. above the elevation of the stream bed), then R is decreased exponentially with increasing G_2, using an arbitrarily defined exponent of $G_{2(\text{i-1})}/G_{2(\text{day1-1})}$, where $G_{2(\text{day1-1})}$ represents the storage volume at the start of the modelled run. Conceptually, this reflects the convergence of the two stores towards a single aquifer under wet conditions.

Problems in reproducing the shape of the hydrograph between wet seasons were evident, which led to another adjustment to enhance the seasonal variation in catchment response: the addition of a saturated zone evaporation loss to the calculation of streamflow. This adjustment does not impact on the groundwater store.

3.2. Calibration

A manual calibration process was undertaken with the aim of generating a hydrograph in which the shape of the recessions and the timing of 'switches' were consistent with the observed pattern. During the early part of the record in which streamflow is still perennial, the timing refers to the switch to and from baseflow conditions, which occurs with the draining of G_1, and the re-establishment of a water table in G_1 at the start of the wet season. As groundwater levels fall, the model must also capture the timing of the switch to an ephemeral system and the seasonal flow pattern that dominates thereafter.

Table 1 lists the model parameters for IHACRES-3S. Values have been assigned for some parameters, based on knowledge of model sensitivity (e.g. d), form of input data (e.g. e), information about the catchment (e.g. L), inspection of observed and modelled results (e.g. g_1) and assumptions about catchment process (e.g. R_s). An initial calibration of the original IHACRES linear routing module was undertaken on a 4-year wet period, prior to significant irrigation extractions, to set starting values for v_s, τ_q, and τ_s. With development of the 3-store model, only τ_q has remained unchanged from the original value of 1.02 days, as a sensitivity analysis showed little variation in this parameter. Thus there are six parameters which need to be calibrated for the Messara model.

Table 1. IHACRES-3S Model parameters.

Parameter	**Value**	**Description**
CMD		
d	200	Drainage threshold (Eqn 1)
e	1	Potential evaporation coefficient
f	calibrate	Stress threshold
3S		
t_2	calibrate	Effective rainfall threshold (for switching v_s)
v_s	calibrate	Fraction of effective rainfall that goes to groundwater
τ_q	1.02	Recession coefficient for quickflow (days)
τ_s	calibrate	Recession coefficient for soil store (G_1)discharge (days)
τ_g	calibrate	Recession coefficient for groundwater store (G_2) discharge (days)
R (R_{max})	calibrate	Recharge from G_1 to G_2 (ML/day)
g_1	4000	G_1 storage threshold (ML) for maximum recharge, r
L	55	Groundwater loss (ML/day) from Croke *et al.* (2000)
R_s	40	Induced recharge from stream to G_2 (ML/day)

3.3. Performance Indicators

To support the visual assessment, a number of objective functions were calculated to quantify performance across different parts of the hydrograph (Table 2). As encountered in the Coxs Creek catchment (Herron and Croke, in press) and also in the Messara catchment, using the 2-stores versions of the model, tweaking parameters to improve performance in one indicator often results in loss of performance in another. Since the aim is to capture low flow behaviour and the timing of switches between connected and disconnected stream-aquifer states, satisfactory performance in the Nash-Sutcliffe Efficiency (NSE) values for slow flow (Q_s) and the log (log$Q$) and inverse (1/Q) of total flow, are required to accept the model calibration.

4. RESULTS

Model runs using a constant recharge rate were not able to reproduce the shape of the recession limb (Figure 3(a)) Two things should be noted: the difference in the shape of the observed recession between years, which suggests a single value of R will not yield satisfactory results across all years; and the sudden drop in flow irrespective of R. The same abrupt change to baseflow can be seen in the flow duration curve in Figure 3(a). This suggests R is not constant for G_1>0.

Table 2. Performance indicators.

Indicator	Calculation	i	Biased to
Relative Bias$_Q$ (RB)	$\sum \frac{O-M}{M}$	Q Q_s	
NSE (R^2)	$1-\frac{\sum(O_i-M_i)^2}{\sum(O_i-\bar{O}_i)^2}$	Q Q_s log Q 1/Q Ranked Q	High Slow Moderate Low Regime

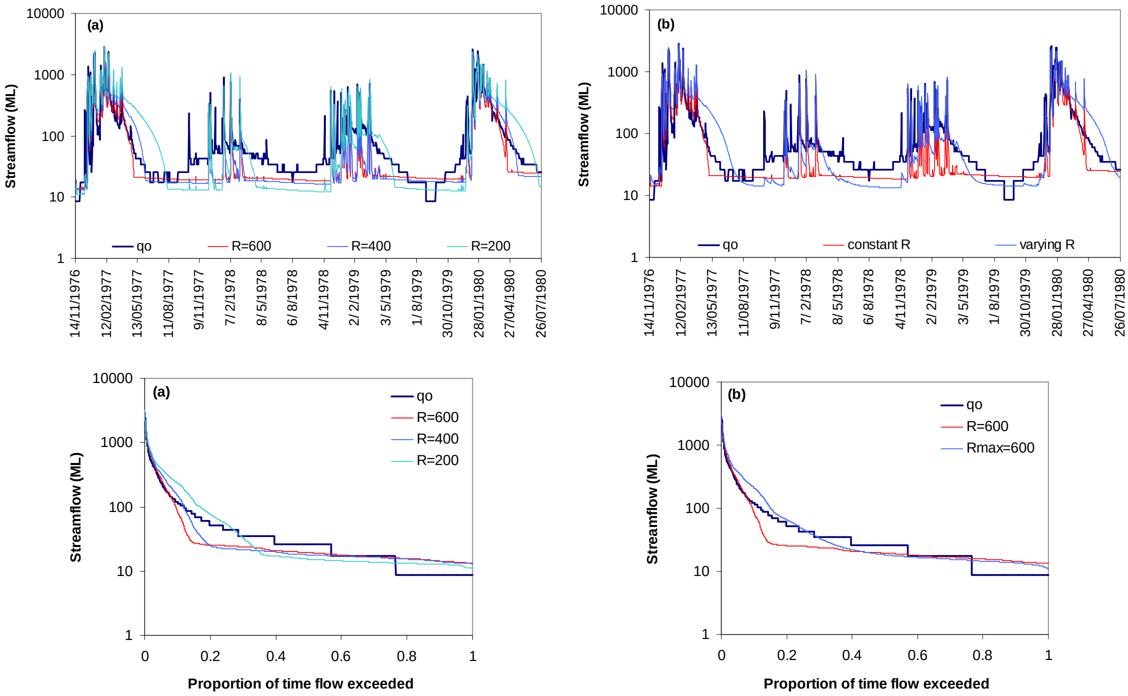

Figure 3. Hydrographs and FDCs, showing the impact (a) of different values of R (ML/day) in the constant R approach; and (b) of a variable R, on modelled streamflow, qo is observed flow.

The second approach addresses this by reducing R as G_1 decreases below a threshold value, and further reducing it if G_2>0. Figure 3(b) shows a more graduated transition to baseflow conditions at the end of each wet season, using the same parameter set, except R_{max} replaces R and the recharge threshold, g_1, has been introduced.

Calibration of the full record was also undertaken using a time-varying R. A satisfactory calibration was obtained with the parameter values in Table 3. This set was adopted on the basis of good NSE values for log$Q$ and 1/Q and satisfactory performance for Q_s. The relative biases indicate that these results have been achieved without significantly over- or under-estimating total and slow flow volumes. Figure 1 (light blue) shows the 26 years from 1970 to 1996. The

Table 3. Parameter values and model performance for IHACRES-3S with variable recharge.

Parameter	Value	Performance Indicator	Value
		RB_ Q	-0.05
f	1.0	RB_ Q_s	0.135
t_2	3.5	NSE_Q	0.71
v_s	0.7	NSE_Q_s	0.69
τ_s	110	NSE_log Q	0.81
τ_g	10000	NSE_1/Q	0.76
R (R_{max})	1000	NSE_Ranked Q	0.79

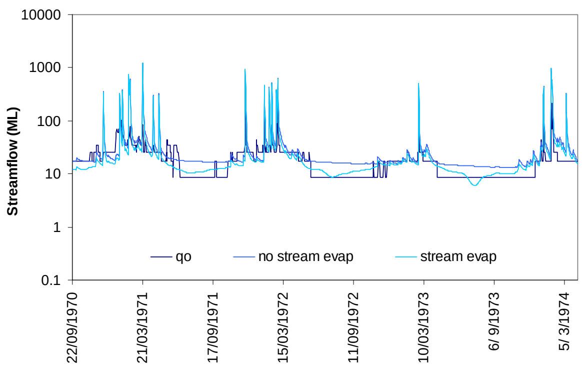

Figure 4. The impact of streamflow evaporation on the shape of the hydrograph for a sub-set of years.

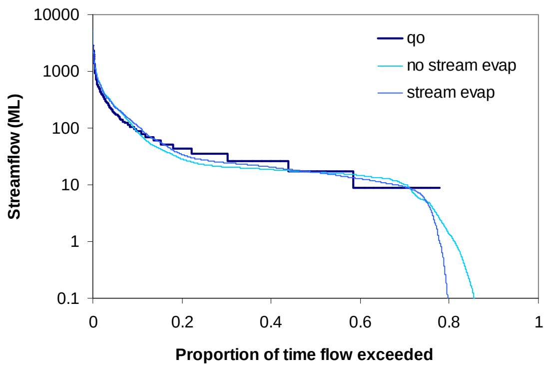

Figure 5. Observed and modeled flow duration curves for the 26 year record.

Table 4. Parameter values and model performance for IHACRES-3S with stream evaporation.

Parameter	Value	Performance Indicator	Value
f	1.0	RB_ Q	-0.08
t_2	3.5	RB_ Q_s	-0.01
v_s	0.7	NSE_Q	0.72
τ_s	150	NSE_Q_s	0.63
τ_g	7500	NSE_log Q	0.84
L	35	NSE_1/Q	0.85
R (R_{max})	1200	NSE_Ranked Q	0.78

model captures the timing of the switch from perennial to ephemeral stream behaviour well and does reasonably well transitioning to a baseflow state at the end of each wet season. A few problems still persist: there is too much baseflow in the dry years of the early 1970s (Figure 4); there is a tendency for the model to not respond early enough at the start of the wet season and the model generates too much wet season flow after 1990 when the stream becomes ephemeral.

The final modification that will be presented here was the addition of a new loss term to reflect evapotranspiration (ET) from the stream and near-by saturated areas. Figure 1 also shows these results (royal blue). The parameter set has been changed during the model calibration (Table 4), with groundwater loss reduced to 35 ML/day due to the saturated area ET loss. A sub-set of years are shown in the hydrograph in Figure 4 to more clearly illustrate the impact of stream ET on modelled flow. It can be seen how the inclusion of this loss starts to capture the hydrograph shape and magnitude of dry season lows. The effect is particularly evident in the 1990s, where the baseflow hydrograph suggests more sustained low flows relative to the modelled flow with ET loss. The flow duration curves for the two versions (Figure 5) illustrate the improvement from incorporating a seasonally-based loss mechanism on flow regime, with the FDC dropping abruptly at a similar percentile to the cessation of observed flow when stream evaporation is included. Model performance is summarised in Table 4.

Discussion

The IHACRES-3S model has been developed in the Messara catchment, Crete, with the results presented in this paper showing progressive improvements in model performance as the model was modified to address discrepancies in preceding iterations. A quick glance at the hydrographs in Figure 1 shows the model is capable of capturing the key trends over time, in particular the timing of the switch to an ephemeral stream as the groundwater aquifer is depleted below streambed level after 1990, but also the switching on-off of the perched water storage, G_1, at the start and end of each wet season. While a closer inspection reveals that the model does not reproduce all parts of the flow regime equally well, and that within any given year there are over- or under- estimates of flow, overall the results are encouraging.

The conversion from a 2-store to a 3-store model necessarily involves more assumptions about the system and more parameters within the model. Rigorous sensitivity testing is required to determine the net value from each of the modifications and the extent to which each parameter is needed. With six free parameters (as well as a number of assumptions about catchment characteristics), the issue of parameter identifiability is a real one. The use of multiple performance criteria to evaluate the model results highlights the calibration challenge, since small changes in parameter values can lead to better scores in some metrics and poorer scores in others. We have chosen to optimise against low flow performance indicators, but even so we find that an improvement in the NSE of log$Q$ or 1/Q does not necessarily mean an improvement in the NSE of Q_s.

As much as possible, we would like to be able to tie the new parameters to catchment characteristics for application of the model in other catchments. Parameters such as R, the rate of recharge between the shallow and deeper groundwater stores, the surface area of the stream and associated wet areas, and the soil moisture threshold, g_1, below which recharge to the deeper aquifer decreases can all potentially be estimated, or at the very least constrained, based on knowledge of the catchment.

Further evaluation of the model, and possible refinements, will come from applying it to other catchments where the connection between the surface water and groundwater systems is variable or where groundwater extractions could lead to a perennial stream becoming ephemeral, as has occurred in the Messara catchment. IHACRES-3S is a lumped conceptual model and cannot be used to predict within catchment responses, but the catchment-averaged groundwater store, G_2, can be compared to observed bore data to provide an additional check on the robustness of the model. In the Messara catchment, groundwater level data are available from several bores and preliminary comparisons (not reported here) indicate a sensible model result.

5. CONCLUSIONS

With the increasing scarcity of reliable surface water supplies in Australia, the demand on groundwater has increased, leading to concerns about the potential impacts on streamflow and groundwater dependent ecosystems. Models that represent the interactions between surface and groundwater systems are needed that can assist in the better management of connected and variably-connected surface and groundwater systems. The IHACRES-3S model, introduced here, has the potential to fill this gap.

The IHACRES-3S model has evolved from the coupling of the CMD non-linear loss module to a modified linear routing model (IHACRES_GW). Its 3-store formulation was found to be necessary to represent the non-linear streamflow behaviour in the Messara catchment, Crete. Additional modifications to the initial 3-stores formulation, described here, identify some of the processes that need to be represented if the timing of key responses and the flow regime are to be captured in this catchment. Due to the increasing model complexity, additional parameters and assumptions have been introduced and more sensitivity testing is required to determine the final formulation, and level of complexity, as well as its wider applicability.

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