# Improvement of Physical Basis of Conceptual model, LASCAM, with Explicit Inclusion of Within Catchment Heterogeneity of Landscape Attributes

**C. Zammit[a], M. Sivapalan[a], N.R. Viney[b] and M. Bari[c]**

[a] Centre for Water Research, The University of Western Australia, 35 Stirling Highway Crawley WA 6009, Australia (sivapala@cwr.uwa.edu.au)

[b] CSIRO Land and Water, Private Bag No. 5, Wembley WA 6913, Australia

[c] Water and Rivers Commission, 3 Plain Street, East Perth WA 6004, Australia

**Abstract:** The main drawback of conceptual hydrological models is the number of parameters that need to be estimated by calibration. Application of such models to predict ungauged catchments is not feasible without substantial improvements to the modelling framework. In this paper, we present the results of improvements to the LASCAM model (a large-scale conceptual catchment model of streamflow, salinity, sediments and nutrients), which are realised by a step-by-step approach based on the explicit inclusion of subcatchment variability of landscape attributes, especially topography and soil depths. The description of the soil hydrology of the surface soil layer follows a VIC-type approach based on measurable soil depths. Due to the importance of the unsaturated zone delay, the description of the unsaturated zone has also been improved. Finally a conceptual physical description of the deeper groundwater system has been implemented. The paper presents the results of the application of the revised model to a first order catchment within Collie catchment (Western Australia) and assesses the exportability of the set of parameters thus obtained to the whole Collie catchment.

***Keywords:*** *conceptual model; model improvement; VIC model; landscape heterogeneity*

## 1. INTRODUCTION

Two alternative approaches are usually adopted for the modelling of large catchments: i) the lumped, conceptual model; or ii) the physically-based spatially-distributed model. However, modelling large catchments using either of these approaches is difficult, due either to the requirement of calibration to mimic the flow or to the non-linearity of the governing equations (Grayson et al., 1992). Moreover the use of physically based spatially distributed models is also compromised by their extensive data requirements which are rarely met by the type, quantity and quality of available data, and the use of physics-based equations that are inappropriate at length scales considered by the models.

A third category exists which combines some aspects of both these modelling approaches. These models are simple enough to be practical and yet physically-sound enough to predict the consequences of alternative strategies for managing the land surface. Nevertheless, their conceptual framework still necessitates model calibration. There remain two major problems with the resultant parameterisations: i) the set of parameters is non-unique and tends to be site specific; and ii) parameter extrapolation and regionalisation is problematic. As a result, the application of such models to ungauged catchments is not feasible without further development of their conceptual framework.

In this paper we propose a step-by-step procedure based on the "downward approach" to overcome these difficulties. Rather than focusing on the complexity of the model, the suggested procedure involves incorporating, in steps, improved process descriptions into the model. Explicit inclusion of subcatchment variability of landscape attributes and each hydrological process is achieved by addressing two basic questions: i) what is the physics behind a process; and ii) how can the process be parameterised in a physically meaningful way based on catchment attributes. This methodology has been applied successfully to the large-scale conceptual model LASCAM (Sivapalan et al., 1996 a,b,c).

To test the applicability of the revised version of LASCAM to an ungauged catchment, the model is calibrated on Lemon, a small first-order catchment within the Collie catchment. The whole Collie catchment is then treated as an ungauged catchment and the revised LASCAM is used to simulate streamflow and salt loads with the parameter set obtained from calibration on Lemon. The success of the model revisions and the capacity for regionalisation and extrapolation of parameters may thus be judged by comparison between simulated and observed flows and salt loads throughout the catchment.

## 2. REVISED VERSION OF LASCAM

The Large Scale Catchment Model (LASCAM) has been developed to predict the impact of land use and climate change on the daily trends of streamflow and salinity in large catchments over long time periods (Sivapalan et al., 1996 a,b,c).

LASCAM is a complex conceptual model with a daily time step. The basic building blocks are subcatchments organized around the river network. All hydrological and water quality processes are modelled at the subcatchment scale; the resultant flows and loads are aggregated via the stream network to yield the response of the catchment at the main outlet and at any number of intermediate points on the stream network.

The inputs to the model are daily rainfall and potential evaporation, landscape attributes relating to the A and B soil horizons, leaf-area index, percentage of deep-rooted vegetation and percentage of impervious area, for each og the subcatchments. The last three inputs are determined from landscape attributes and are distributed in space and time. Potential evaporation is assumed to follow a sinusoidal trend with season rather than being derived from observed pan data.

Calculation of the daily fluxes of water and salt through the soil and discharge to the stream is based on four soil moisture stores representing the near-stream perched aquifer (A store in Figure 1), the top-soil unsaturated zone (D store), the permanent deep groundwater system (B store), and the intermediate unsaturated zone (F store). In order to represent the large mass of salt stored in the soil profile just above the water table (typical of the south west of Western Australia) the model incorporates an additional salt store, called the P store. For each subcatchment, a set of physically based constitutive relations is used to direct water and salt between stores and to distribute rainfall either into the stores or directly into the stream. The associated parameter set is global, however the impacts of some parameters are modified in an objective way by local landscape attributes for application to individual subcatchments.

The water and salinity balance model has 42 parameters, which describe each of the 13 potential flux paths. Among these parameters, 19 represent the initial volume of the stores (9) and their disaggregation on the basin (10); 3 relate to routing processes; 12 are physically-based parameters and can be directly estimated by regional hydrogeological or soil texture maps; and 8 are fully conceptual parameters (6 relate to the evaporation process, 2 to the salt modelling). The model is calibrated using a Shuffled Complex Evolution algorithm to optimise an objective function relating one or more pairs of observed and predicted fluxes. The objective function is based on the daily model efficiency statistic with a Box-Cox transformation (Box and Cox, 1964) of data values.

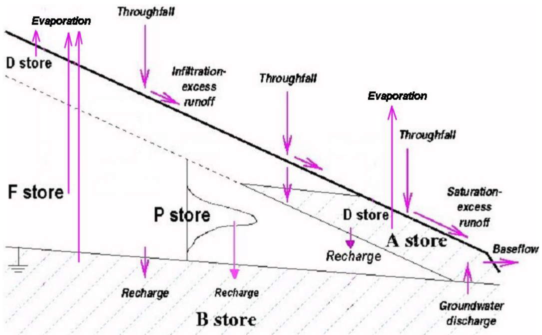


**Figure 1.** Schematic of a hill slope cross-section assumed in LASCAM and the definition of the subsurface water store.

## 3. APPLICATIONS TO THE COLLIE CATCHMENTS

### 3.1. Characteristics of the Collie catchment

The Collie catchment, located in southwest Western Australia, has an area of 2,545 $km^2$ above the stream gauging station at Mungalup Tower and contains 21 rain gauges and 16 stream gauges distributed throughout the catchment. Several small forested subcatchments (including Lemon catchment) were instrumented in the 1970's to quantify the changes in the input and output of salt and water that occurred when land use changed from forest to agriculture in some of those subcatchments. Details of soils, geology and landscape attributes are described by Williamson et al. (1987) and Jothityangkoon et al. (2001).

The Collie catchment has a Mediterranean climate with cool, wet winters (June-August) and warm to hot, dry summers (December-February). The average annual rainfall decreases from 1100mm to 550mm, and the average annual potential evaporation increases from 1400mm to 1600mm, from west to east across the catchment. Correspondingly, the average annual runoff decreases from 150 mm in the west to less than 20 mm in the east. Until the mid-1970s, Collie catchment was subjected to a gradual reduction in forest cover. This clearing occurred mainly in the southeast, where several catchments were reduced to between 20% and 50% forest cover. When clearing bans were imposed in 1976, the Collie catchment was 72% forested. The forest cover in Lemon catchment was reduced from 100% to 47% in 1976–77.

The native vegetation in the Collie River Basin consists of open forest dominated by Jarrah (*Eucalyptus marginata*) and Marri (*Eucalyptus calophylla*). These two species are located mainly on the mid and upper slopes. Increasing proportions of *Eucalyptus wandoo* and *Eucalyptus rudis* occur on the valley floors. Clearing in the experimental catchments took place between December 1976 and March 1977, when forest was replaced by annual pasture (mainly rye grass and subterranean clover).

The soils consist of a 1–10 metre thick A-horizon of predominantly gravely and sandy laterites with high hydraulic conductivity. The A-horizon overlies less permeable deep sandy loam and kaolinitic clays (the B-horizon) to an average depth of 30 metres.

In order to test the applicability of the revised version of LASCAM to an ungauged catchment (in particular to assess parameter extrapolation), it was decided: i) to calibrate the model on the Lemon catchment (area 3.44 km$^2$); and then ii) to simulate the stream flow and salt load on the whole Collie catchment (area 2,545 km$^2$) with the parameters deduced in exercise (i).

## 3.2. Lemon catchment calibration

Lemon catchment was disaggregated into two subcatchments. The model was applied and calibrated over a 24-year period (1 January 1975 to 31 December 1998). The calibration period thus includes both forested and pastured conditions. In the absence of suitable spatial data, all 20 water and salt balance parameters, including the physically-based parameters, were calibrated.

### *Hydrological model calibration*

Some results from the model calibration are presented in Figure 2, which displays daily observed and predicted stream flow values, for 1981 and 1998. Good model reproduction of streamflow volume and timing (model efficiency 0.83) is demonstrated, especially during the recession periods.

Analysis of monthly simulations demonstrates also that the long-term water balance of Lemon catchment, including its transition from a fully forested to a 53% pastured catchment, is modelled accurately.

Two features can be noted in these results. Firstly, there is an underestimation of the infiltration-excess process (for example, December 1998). This is thought to be associated either with the relatively simplistic formulation of the infiltration capacity of the soil in the model (described by two parameters related to vegetation and land use), or some process identification issues in the calibration. The latter is linked to the time step used in the model, which implies that all the processes occur at a daily time step, whereas infiltration-excess runoff occurs at a smaller time scale.

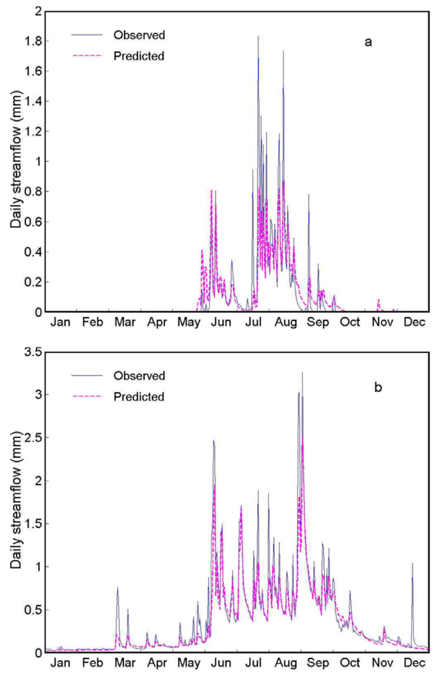


**Figure 2.** Observed and modelled daily stream flow for Lemon catchment (a) 1981, (b) 1998.

Secondly, some years exhibit a timing problem (e.g., 1981—the onset of stream flow is two weeks early). This is thought to be associated either with the use of a constant vegetation index throughout the simulation period, or the use of a constant vegetation seasonality decomposition throughout the year. The first problem would be solved by derivation of the vegetation index from satellite imagery. Solution of the latter would require the vegetation seasonality to be related to antecedent rainfall.

Analysis of the storage variations over the 24-year period (not shown) indicates that the B store exhibits the most dramatic effects of the land use change. As a result of the clearing in the summer of 1976-1977, the catchment reaches a new wetter equilibrium level (+65% of volume of water in the B store) twelve years after clearing. This new equilibrium is the result of an increase in subsurface runoff in the cleared area. This result is corroborated by piezometric data from several bores in Lemon catchment (Croton and Bari, 2001).

***Salinity modelling***

The daily salt load variations in Lemon catchment for 1992 are presented in Figure 3 and show reasonable fit between observed and modelled salt loads (model efficiency 0.59).

The most sensitive parameters for the modelling of the chloride fluxes are the initial values of the F and B salt stores. The initial value of P store is taken from the work of Johnston (1987). The initial values of the chloride storage in the saturated and unsaturated zones, obtained by calibration, are 4.2 and 1.6 $kg.m^{-2}$ respectively. These values are nearly one order of magnitude less than the observed values obtained from salt cores by Johnston (1987). This result is thought to be associated with scaling issues from the core storage value to the catchment-scale storage value.

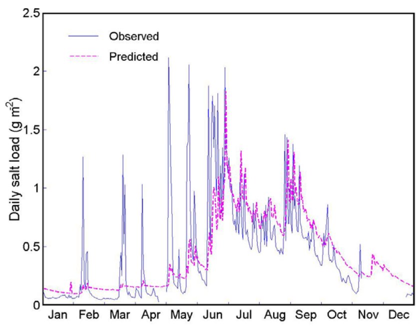


**Figure 3.** Observed and modelled daily salt load for Lemon catchment, 1992.

Discrepancies in the modelled salt load occur in the early winter flows, peak flow events, the winter/spring recessions and summer loads. There may be three reasons for this: i) there is a lack of fit in the streamflow model; or ii) the model ignores accumulation, by evaporation, of salts in the surface soils during the spring and summer period and their leaching during subsequent autumn and early winter storms; or iii) the assumption of fully-mixed salt stores is not valid throughout the year.

Figure 4 presents the comparison between modelled and observed daily stream salinity, estimated from grab samples taken at different time of the day. Three features can be noted. Firstly, there is a good agreement between the stream salinity observed and predicted in winter. This result demonstrates that in winter the assumption of well-mixed stores is valid. Secondly, each rainfall event seems to generate dilution of the stream salinity. Even if this process occurs during the winter period, it does not correspond to the “reality” of the rest of the year. The peaks in observed stream salinity in late-summer and autumn could either be associated with leaching of the salt accumulated at the surface, or indicate that the assumption of well-mixed A and D stores is not valid at this time of the year. The latter is thought to be responsible for the overestimation of stream salinity in summer.

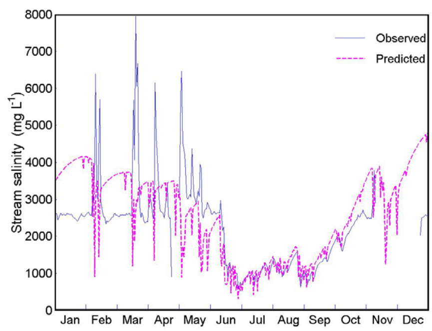


**Figure 4.** Observed and modelled daily salinity for Lemon catchment, 1992.

## 3.3. Collie catchment prediction

Collie catchment has been disaggregated into a network of 114 subcatchments. The model is applied over a 14-year period (1 January 1977 to 31 December 1990). Because of the lack of spatial information, the complete set of parameters obtained in the calibration of Lemon catchment (including the physically-based parameters) is applied, without recalibration, to the whole catchment. The applicability of the model is then judged by reference to observed streamflow and salt load records at the different gauging stations.

***Hydrological prediction***

Results for the application of the Lemon parameter set to the whole Collie are presented in Figures 5 and 6. Figure 5 presents the comparison between observed and predicted monthly flow hydrographs at Mungalup Tower (2,545 $km^2$) and at Coolangatta (1,344 km$^2$), an internal flow gauge.

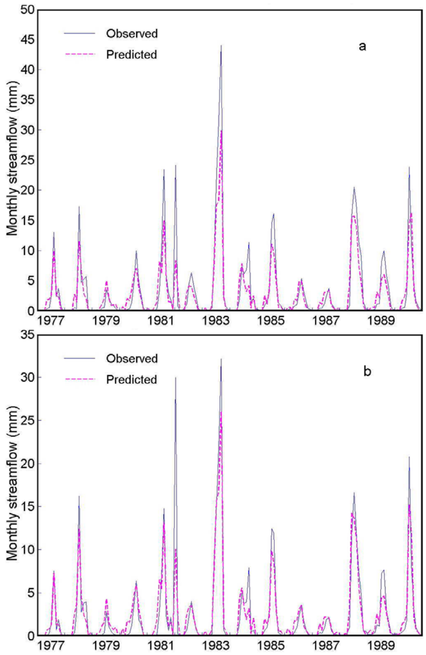


**Figure 5.** Observed and Predicted monthly runoff at (a) Mungalup Tower catchment, 1977-1990, and (b) Coolangatta Farm, 1977-1990.

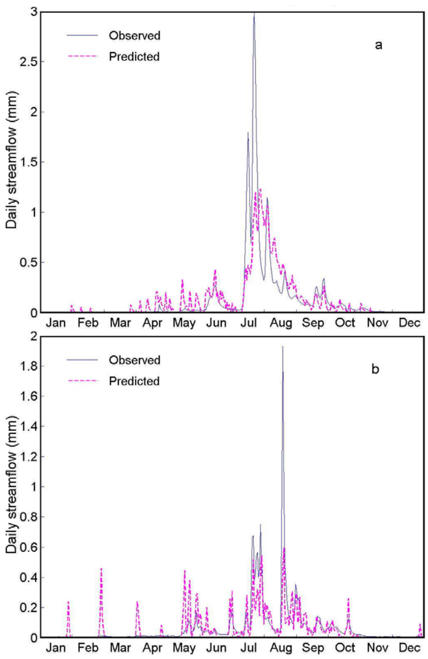


**Figure 6.** Observed and predicted daily runoff at (a) Mungalup Tower, 1990, and (b) Coolangatta Farm, 1989.

Analysis of the predicted monthly hydrographs shows good model predictions of streamflow (model efficiency 0.79 at Mungalup Tower, 0.82 at Coolangatta). Most subcatchments display these characteristics. However in two of the smaller subcatchments, James Well (169 km$^2$) and Maringee Farm (13 km$^2$), peak flows are consistently underestimated. This result is thought to be associated with the uncertainty in the estimation of the soil depth in these subcatchments, or with a routing problem. As Lemon catchment is a small first order catchment (3.44 km$^2$), the stream routing parameters were not calibrated.

Analysis of the predicted daily hydrographs shows good model predictions of streamflow timing, especially during the recession periods (model efficiency 0.58 at Mungalup Tower, 0.55 at Coolangatta). Two features can be noted. Firstly, there is a consistent overestimation of the infiltration excess process during summer (January to April). This result simply indicates that extrapolation of the infiltration excess process seems to be governed by non-linear equations. Secondly, one can note that the winter peak flows are consistently underestimated. This result could be linked either to the uncertainty in the estimation the soil depth, or to a routing problem.

### *Salinity modelling*

The monthly salt load variations, which refer to the sum of daily loads during a particular month for days with observed concentration data, are presented in Figure 7 for Mungalup Tower (2,545 km$^2$). Comparisons of daily observed and predicted values, for 1988 for this site are shown in Figure 8.

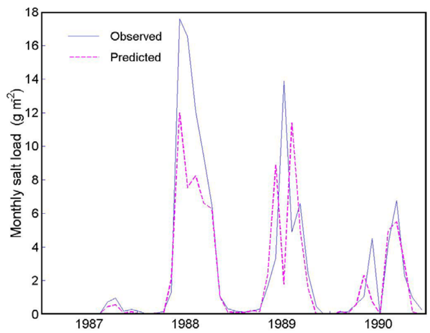


**Figure 7.** Observed and predicted monthly salt load at Mungalup Tower, 1987-1990

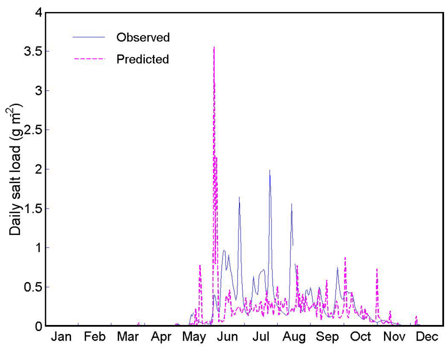


**Figure 8.** Observed and predicted daily salinity at MungalupTower, 1988.

Analysis of monthly and daily salt load signatures clearly demonstrates that the salt loads at Mungalup Tower are not reproduced adequately in terms of volume (model daily efficiency 0.28, monthly efficiency 0.64). Two reasons could explain such a result: i) there is a lack of fit in the streamflow model and ii) the salt model parameters from Lemon catchment are not applicable to the greater Collie catchment. Two (of three) salt parameters are conceptual, and as such, specific to the catchment on which they are calibrated. Lemon catchment is 53% cleared, whereas the remainder of the Collie catchment is mostly native forest.

## 4. CONCLUSIONS

In this paper we have presented an application of a revised physically based version of the LASCAM model. The model was calibrated on the Lemon catchment, a small first-order catchment with an area of just 3.44 $km^2$, and its applicability for ungauged catchment prediction tested on the Collie catchment, which has an area of 2,545 $km^2$.

The application of the revised LASCAM on Lemon shows that daily, monthly and annual stream flows are well reproduced. However the daily, monthly and annual salt load are not correctly reproduced. This indicates that more work is required to improve the performance of the salt modelling and that the assumption of fully mixed salt store throughout the year needs to be revisited.

The exportability of the parameter set from the calibration was tested on the Collie catchment, which was assumed ungauged for this application. The results demonstrate that regionalisation is possible with the physically-based version of LASCAM. The water parameters from the Lemon catchment gave good results when used to simulate the streamflows of the Collie catchment, despite the great diversity in catchment hydro-climatic and physical attributes in the latter. This is because the model revisions have produced a robust physical model for the hydrology. However, the salt model is still of conceptual type and thus the salt parameters are not directly exportable. To regionalise the salt parameters, the landscape attributes have to be considered and the parameters adjusted appropriately.

This modelling has highlighted the crucial importance of the estimation of the catchment landscape attributes. The landscape attributes required by the model include detailed soil data, and the distribution of groundwater in the catchment. Good daily model prediction requires accurate landscape data, whereas good monthly predictions may be achieved with lesser quality data.

## 5. ACKNOWLEDGEMENTS

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