Modelling sediment loads in the Swan/Avon River Basin

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Abstract This paper deals with the coupling of a sediment modelling algorithm to an existing conceptual model of water and salt fluxes (LASCAM). In the model sediment generation is based on a modified version of the Universal Soil Loss Equation. The sediment transport processes of channel deposition and re-entrainment, and bed degradation are coupled with the existing stream routing algorithm of LASCAM. The paper highlights some of the scientific issues involved in quantifying these processes in this catchment and presents validation results comparing model predictions with observations of sediment transport at different locations in the catchment. The results indicate that despite the strongly nonlinear relationship between streamflow and sediment load, both are predicted well by the model. The model further highlights that in the Avon River Basin, disproportionately more stream sediment is generated in the wheatbelt region than in the lower catchment.

1. INTRODUCTION

The estuary of the Swan River in Western Australia is shallow and poorly flushed. These properties, coupled with increasing nutrient transport to the estuary have lead to increasingly severe algal blooms in recent years. The transport of nutrients from the catchment to the estuary is strongly linked to the transport of sediment, with a large percentage (especially phoshorus and organic nitrogen) being adsorbed to sediment particles [Donohue et al. 1994].

To investigate and propose solutions to these water quality problems the Western Australian government has initiated a multi-disciplinary research project to study the physical, chemical and biological structure of the estuary. Part of this response involves a hydrological modelling project to predict the impact of potential land use remediation efforts on the transport of water, salt, sediment and nutrients from the catchment.

The Swan/Avon catchment is extremely large (119,000 square kilometres), relatively flat and dry. Most of its annual average 400 mm of rainfall occurs during winter and exhibits a pronounced west-east gradient. About 65 percent of the catchment has been cleared of native forest to allow cereal production and sheep grazing. Much of this has involved broadacre clearing since the 1950s, and has lead to substantial increases in soil erosion.

In this paper, an existing water and salt balance model, LASCAM, has been adapted to include a sediment generation and transport algorithm. LASCAM [Sivapalan et al. 1996a, 1996b, 1996c] was originally developed to predict the effects of land use and climate change on the daily trends of water yield and quality in the forested water supply catchments of southwest Western Australia. Its application to these catchments has been described by Viney and Sivapalan [1994].

2. THE WATER BALANCE MODEL

2.1 Basic features

The LASCAM model uses gridded topographic information to define a stream network and to disaggregate the catchment into a series of interconnected subcatchments of area 1–5 km^2. The subcatchments are the basic building blocks of the model. It is at the subcatchment scale that the hydrological processes are modelled, before being aggregated to yield the response of the entire catchment.

The hydrosalinity of each subcatchment is modelled in terms of three interconnected conceptual stores of soil water and salt (Figure 1) representing a perched near-stream aquifer (the A store), the permanent groundwater (the B store), and an intermediate unsaturated store (the F store). For each subcatchment, a set of global constitutive relations is used to direct water and salt transport among the stores and to distribute new rainfall either into the stores or directly into the stream. Any runoff generated by the constitutive relations is then routed (together with the salt it contains) along the stream network towards the catchment outflow.

The inputs to the model are daily rainfall (distributed), pan evaporation and land use information (e.g., leaf area index, which is allowed to vary with time), while topographic data are needed to define the subcatchments and the stream network. For calibration purposes, measured streamflow records are also required at one or more points in the catchment's stream network. The outputs from the model, for each subcatchment and for the total catchment, are surface and subsurface runoff, actual evaporation, recharge to the permanent groundwater table, baseflow and measures of soil moisture.

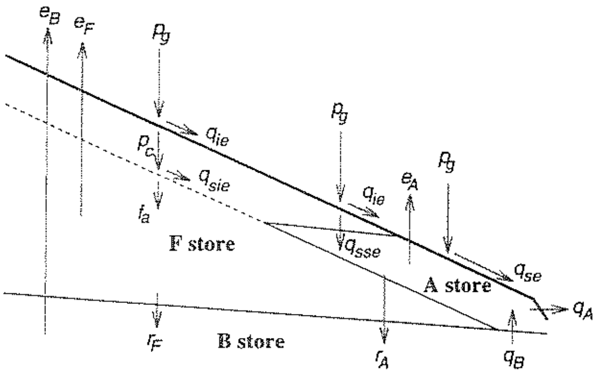

Figure 1. Schematic diagram of an idealized hillslope showing the three conceptual model stores and the principal modelled water fluxes.

2.2 Amendments for the Avon Catchment

The Avon catchment includes several attributes and characteristics that are not present in any of the catchments to which LASCAM has previously been applied. These present considerable challenges for water balance modelling and have led to the incorporation of several changes to the model described by Sivapalan et al. [1996a].

The most obvious difference is that the notional Avon basin (119 000 km^2) is much larger than any catchment encountered previously. It is nearly two orders of magnitude larger than the previous largest Western Australian catchment (Collie, 2500 km^2). Consequently the "building block" subcatchments on which the water balance modelling is based are considerably larger than those used previously. The assumption of rainfall homogeneity over the subcatchment scale is therefore questionable. An analysis of spatial scaling of rainfall across the Avon River catchment has demonstrated that subcatchments of the order of 1600 km^2 or less are adequate. This limit has been adopted for the wetter western half of the catchment. A subcatchment disaggregation consisting of 134 subcatchments has been constructed. Subcatchments below Northam have a mean area of 87 km^2, those between Northam and Yenyenning Lakes have a mean area of 560 km^2, while the remainder have a mean area of 2300 km^2. It was felt that since the easternmost subcatchments contribute negligibly to basin streamflow, there was little benefit in their conforming to the rainfall scaling limit.

Secondly, the catchment size, together with its relative aridity, ensures that transmission losses are much greater than in catchments in the Darling Ranges for which LASCAM was originally developed. A re-infiltration parameter and a more comprehensive stream evaporation algorithm have been incorporated into LASCAM to account for transmission losses.

A further modelling problem arose during calibration of the water balance component. It was found that the model overestimated streamflow generation in the wheatbelt region. It is thought that this overprediction stems from the relative flatness of the terrain, which contrasts with the well-defined V-shaped valley and hillslope topography of the Darling Ranges. In the wheatbelt, where stream density is much smaller, a significant proportion of rainfall is likely to be diverted away from the main stream channels by the local topography. Consequently, a diversion parameter depending on mean annual rainfall (since regional geomorphology is largely dependent on rainfall climate) has been incorporated into the model.

3. THE SEDIMENT MODEL

A large number of sediment models has been proposed in the literature, but the range of applicability of each is uncertain. None have been developed to describe sediment processes in Western Australia. Indeed, there even appears to have been very little work in Western Australia on characterising or measuring sediment yields in semi-arid catchments. This is despite there being considerable evidence that erosional processes are important and have caused much stream channel damage and siltation in the Avon River.

One of the main requirements of a new LASCAM sediment model is that it should be compatible with the existing water transport model. In particular, it must be capable of operating on a daily timestep and preferably should not utilize any water pathway or store that is not already explicitly modelled by LASCAM. Given our incomplete understanding of sediment processes at the catchment scale and the overwhelming number of unresolvable factors involved, the sediment model should remain as conceptually simple as possible, whilst retaining the capacity to model the effects of land use change.

Sediment modelling is a much more difficult task than salt balance modelling, since the latter is a conservative tracer whose observed concentration in a particular reach seldom varies by as much as an order of magnitude. In contrast, the rates of sediment mobilisation and transport are strongly affected by streamflow volume, and in consequence, so is sediment concentration. Furthermore, there does not appear to be any simple rating curve solution to the modelling of sediment concentration in the Avon River.

In the model that has been developed, sediment generation in the subcatchments is assumed to occur by erosion processes associated with infiltration-excess (Hortonian) overland flow. The model that has been adopted is a conceptualisation of the Universal Soil Loss Equation [Wischmeier and Smith 1978], giving daily hillslope sediment generation, E (tonnes) as

$$E = \gamma C q_{ie}^{\delta} \qquad (1)$$

where q_{ie} is the daily infiltration-excess runoff (ML) and C is the USLE crop factor, and is assumed to be linearly related to leaf area index. The variables γ and δ are optimisable parameters. Equation 1 assumes that the remaining USLE variables are incorporated into the parameter γ and, as a consequence, are uniform across the catchment. Whilst this assumption is possibly reasonable for the soil factor, it will not necessarily be true for the slope length or erosion mitigation factors that are commonly employed in the Modified USLE [Williams and Berndt, 1977]. These factors however, depend on variables which are difficult to prescribe for a large subcatchment. For instance, it is difficult to specify a slopelength and steepness factor for a large subcatchment with perhaps hundreds of hillslopes. The model assumes that hillslope sediment generation is not limited by raindrop detachment processes.

Sediment transport involves the processes of channel deposition and re-entrainment, and bed degradation. The model assumes that these processes are governed by a stream sediment capacity that is a function of stream power. The stream sediment capacity Z (t) is adapted from the SPNM model [Williams 1980] and is given by

$$Z = \alpha v^{0.5} (q/v)^{\beta} \qquad (2)$$

where q is the daily streamflow volume (ML), v is the stream velocity (km d^{-1}) and α and β are optimisable parameters. In Equation 2, it is assumed that the term q/v approximates the stream cross-sectional area and that stream depth is proportional to $(q/v)^{0.5}$. Streamflow of a given volume is able to carry a mass Z of sediment in suspension, provided sufficient material is available either from the hillslope, from upstream or from previously deposited channel sediment.

In such a case, sediment re-entrainment R (t) is thus given by

$$R = \min\{Z - Y_i - E,\ S\}$$

where Y_i is the sediment inflow from upstream subcatchments (t) and S is the amount of loose sediment on the channel floor available for re-entrainment. Obviously R will be zero if $Z < Y_i + E$. If there is still insufficient readily available sediment to satisfy Z then bed degradation is assumed to occur at a rate governed by stream power and the USLE crop factor [Williams, 1980]. In such circumstances, bed degradation B (t) is

$$B = \min\{\epsilon CZ, Z - Y_i - E - R\} \qquad (3)$$

and is zero otherwise. In Equation 3, ϵ is an optimisable parameter. Any available sediment in excess of the sediment capacity is assumed to remain in the subcatchment as bed deposition.

Sediment in suspension within a subcatchment is subject to a delivery ratio which describes the settling rate for sediment particles. The sediment delivery ratio ψ is conceptualised from Arnold et al. [1995] by assuming that the potential fall distance is much greater than the stream depth, and is given by

$$\psi = \zeta (q/v)^{0.5}$$

The delivery ratio is the proportion of suspended sediment that leaves the subcatchment with the current day's streamflow. The remainder is assumed to settle to the channel bottom where it is available for ready reentrainment on subsequent days.

The sediment yield Y_o (t) from a subcatchment is then given by

$$Y_o = \psi (Y_i + E + R + B)$$

The change in channel sediment store (t) is therefore

$$\Delta S = (1 - \psi)(Y_i + E + R + B) - R$$

The LASCAM sediment model thus requires optimisation of six new parameters (α, β, γ, δ, ϵ and ζ) and also requires the maintenance of a channel sediment store for each subcatchment.

4. APPLICATION TO THE SWAN/AVON BASIN

For application of the LASCAM water and sediment balance models, the Avon River catchment was disaggregated into a network of 134 subcatchments. Long-term observations of streamflow and sediment yield were available at the catchment outlet (the Walyunga gauging station, 616011; area 119 000 km^2) and at the outlets of several internal subcatchments. Model calibration was achieved in two stages. Firstly, the water balance parameters were optimised subject to an objective function that represented a weighted least squares minimisation of streamflows at several gauging stations. Secondly, the calibrated water balance model was used to optimise the six sediment parameters against the observed sediment load record for Walyunga only. Sufficient spin-up time was allowed for the channel sediment stores to reach equilibrium values prior to the calibration period in order to avoid the need to specify initial storage values.

Calibration predictions for the water balance component of LASCAM are shown in Figures 2 and 3. Clearly the model is predicting streamflow well for such a dry, ephemeral catchment. In particular, it copes well with the atypical summer storm of early 1990. Figure 3 also indicates that recession rates are well represented, but there is a tendency to underpredict the peak flows. This calibration also produced excellent agreement between predictions and observations on many of the internal gauged subcatchments (not shown here).

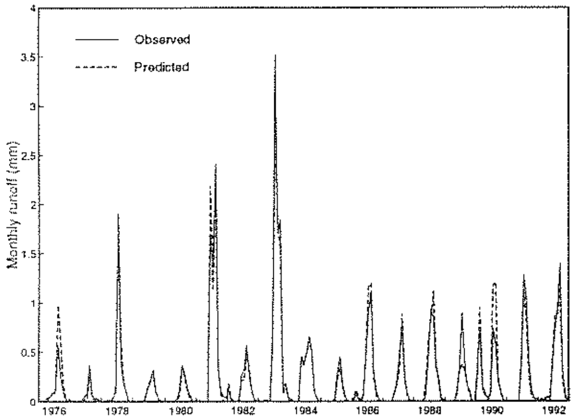

Figure 2. Monthly streamflow observations and predictions for the Avon River at Walyunga, 1976–1992.

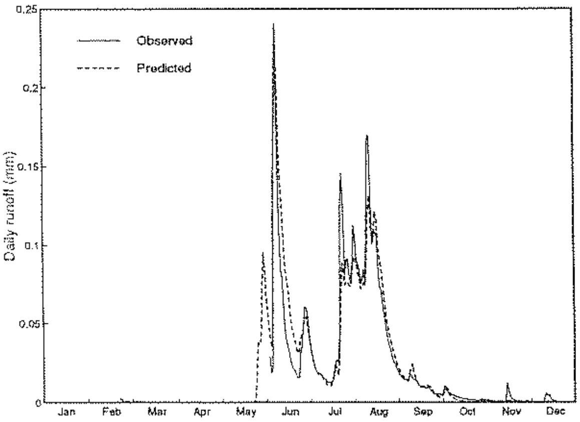

Figure 3. Daily streamflow observations and predictions for the Avon River at Walyunga, 1981.

Predictions of sediment yield at Walyunga are shown in Figures 4–6. Comparison of the monthly sediment (Fig-

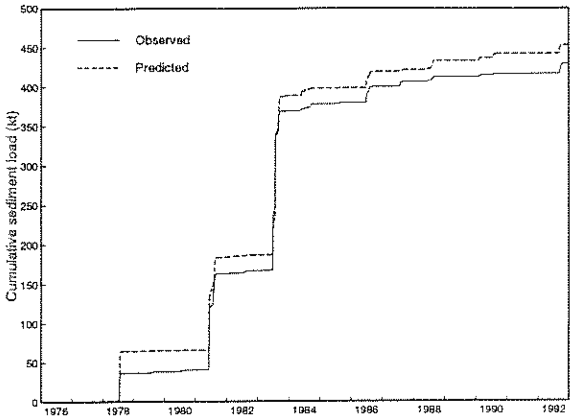

Figure 4. Cumulative sediment yield observations and predictions for the Avon River at Walyunga, 1976–1992.

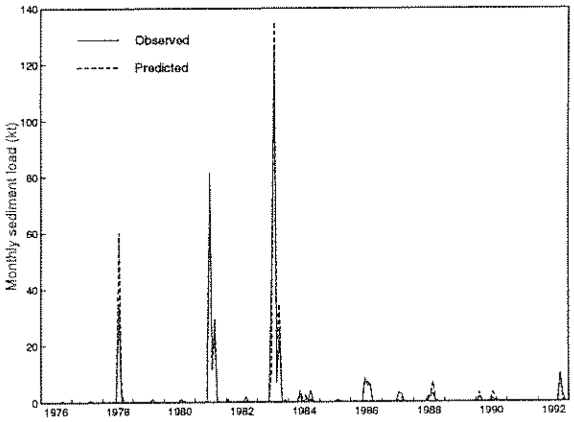

Figure 5. Monthly sediment yield observations and predictions for the Avon River at Walyunga, 1976–1992.

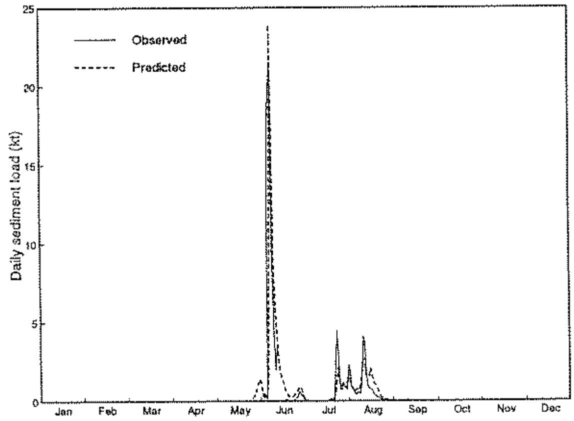

Figure 6. Daily sediment yield observations and predictions for the Avon River at Walyunga, 1981.

ure 5) and water (Figure 2) yields indicates clearly the importance of extreme events in dominating sediment yield. Sediment concentrations are comparably much greater in the large streamflow years of 1978, 1981 and 1983 than in small streamflow years. Also evident in Figures 2, 4, 6 and 7 is a seasonal bias in sediment transport, whereby a greater mass of sediment is transported by a given streamflow early in the winter than by a streamflow of similar magnitude later in the winter. Two possible reasons may be advanced to explain this seasonal bias. One is that wheat cropping across much of the catchment leads to strong seasonality in leaf area index with peak values occurring in spring following a build-up of biomass during winter. Consequently, one might expect greater erosion during the more sparsely vegetated autumn and early winter periods. Secondly, it is possible that more loose sediment is available for re-entrainment by early-season streamflows after having been deposited by receding flows at the end of the previous winter. Whatever the reason, the modelled sediment yields clearly reflect this seasonal bias remarkably well.

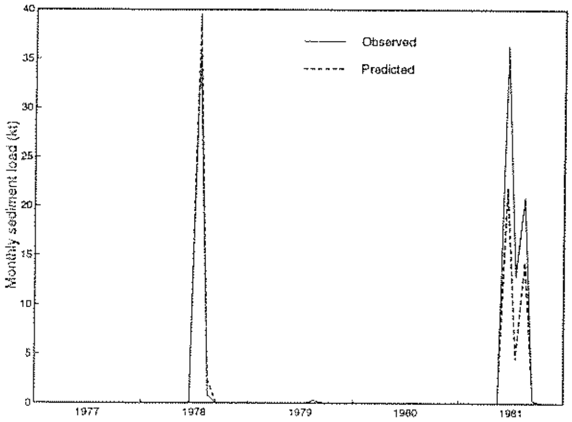

Figure 7. Monthly sediment yield observations and predictions for the Avon River at Dunbarton Bridge, 1978–1981.

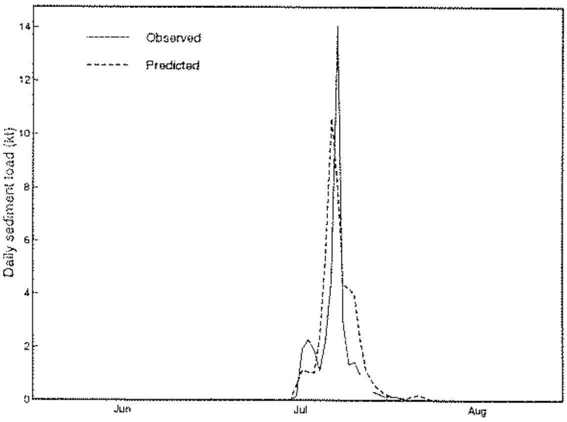

Figure 8. Daily sediment yield observations and predictions for the Avon River at Dunbarton Bridge, 1978.

Sediment yield observations are also available for a few locations within the catchment. One is the Dunbarton Bridge gauging station (station 615021) on the Avon River, about 65 km upstream of Walyunga. Whilst the Dunbarton Bridge gauge has a notional catchment area of more than 115 000 km^2, or about 97 % of the Walyunga catchment area, it records less than 50 % of the flow volume. However, that small flow volume carries with it about 95 % of the sediment yield recorded at Walyunga. Clearly, it is the wheatbelt region, rather than the partly forested Darling Range region downstream of Dunbarton Bridge, which supplies most of the sediment exported by the Avon River to the Swan Estuary. Once again, the sediment model provides good calibration fits of the load at this location (Figures 7 and 8).

5. CONCLUSIONS

Srinivasan and Engel [1994] observed that the utility of many of the common physically-based erosion and sediment transport models is limited by the need for large data and input parameter requirements, for parameters that are difficult to estimate or obtain, and by uncertainty in inputs. These problems inevitably compromise the predictions of even the most rigorously-constructed physical models. Furthermore, the accuracy of observations of sediment data are often questionable. For example, the sediment concentrations used in this study were derived from laboratory analysis of grab samples taken once per day (at irregular times) and converted to a daily sediment load by weighting with the daily streamflow. Given the large intra-day variability of stream heights in the Avon River, the uncertainty of stage heights at the time of sampling and the strong dependence of sediment concentration on streamflow, there is clearly considerable scope for error in estimating the daily sediment loadings.

In the light of these data and parameter uncertainties, there seems little advantage in applying a physically-based sediment model; a simpler conceptual approach is likely to prove adequate. Such an approach has been adopted in this paper and results of its application to the Avon River show that it has considerable potential.

At present, the model does not discriminate among different sediment size classes, largely because the observational data is not available to support its calibration. However, the future coupling of a nutrient transport model is likely to require sediment size class discrimination, since there is observational evidence that some nutrient species attach preferentially to sediment particles of particular size.

Finally, the effects, if any, of the prominent network of playa lakes in the dry, eastern parts of the catchment have not been adequately addressed. While the lakes contribute very little streamflow to the Avon River, their rates of sediment export are poorly quantified and are not well understood. Consequently, no special effort has been taken to amend the sediment model in those subcatchments.

6. ACKNOWLEDGEMENTS

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