An Appropriate Streamflow-Sediment-Pollutant Model for use by Non-specialist Landcare Groups

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Abstract: Australian government-sponsored Landcare/Catchment Management programs have recently stimulated strong interests in environmentally significant catchment processes by non-specialist local resident groups. Advanced and sophisticated mathematical models for quantitatively analysing such processes are not usually appropriate for Landcare purposes because, in general, applications of these models require data, computing facilities, expertise and financial resources not available to most groups. However, such difficulties should be overcome with the model to be described. This has been developed for the Ourimbah Creek Landcare Group located in the Central Coast region of NSW to enable their investigation of the likely environmental effects of proposed catchment changes and management practices. The model is operated with daily rainfall and streamflow data and with irregular or very intermittent measurements of sediment and pollutant concentration. Each of the five compatible components of the model can be operated separately, comprising only two or three simple mathematical equations easily handled by any computer with spreadsheet software. Despite this simplicity most of the model parameters have recognisable and estimable physical significance, and may be evaluated directly from the data or from catchment survey measurements. No parameter optimization procedures are necessary but, if desired, small trial and error adjustments may be made to some parameter values to improve the performance. Although to date the model has been applied only to the 83 sq km Ourimbah Creek catchment there seems no reason why it should not be suitable for the same purposes with other perennial stream systems of similar size.

Keywords: Catchment management; Rainfall-runoff modelling; Sediment transport; Environmental flows.

1. INTRODUCTION

Since the United Nations 'Rio Conference' in 1992 Government policies in many countries, have increasingly favoured the direct participation of local communities in the management of land and water resources. In Australia, New Zealand and elsewhere this has resulted in the formation of Catchment Management, Landcare and similar groups comprised mainly of non-specialist volunteers.

Although these groups receive some professional assistance from local councils and government agencies, their activities emphasize decision-making and practical action by the group members themselves. Through their interactions and experience many group members acquire an excellent understanding of environmental processes, and often tackle tasks in this area that, in the past, have been undertaken only by professionally trained specialists. Moreover, in some cases, specialist advice from 'outside experts' is unwelcome, especially if it ignores the 'non-scientific' aspects of local problems [see Davis et al, 2001]. These circumstances have some relevance to the following modelling effort which was strongly influenced by the needs, resources and outlook of a particularly progressive and well-informed group.

As a local landholder and active member of the Ourimbah Creek/Palm Grove Landcare Group, the author agreed to look for a mathematical model of catchment processes that might assist the group with their land management problems. Such a model was expected to be suitable for operation by several group members who are home computer enthusiasts but with mathematical knowledge only at senior high school level.

It was also expected that the model would allow the participation of other group members willing to carry out fieldwork such as water quality sampling, channel surveying and the identification of sediment sources. All these items were perceived as directly relevant and it was desirable to fit them into the model.

As none of the readily available models seemed to meet the above requirements, the author attempted to formulate something more appropriate, as outlined below.

2. SPECIAL FEATURES OF MODEL

2.1 Catchment to be Modelled

Ourimbah Creek is a perennial stream on the NSW Central Coast. About 75% of the 83 km^2 catchment area is undulating to moderately steep terrain under forest. The other 25% is largely cleared and used for agriculture, horticulture and grazing.

2.2 Problems to be Addressed

The local problems of Ourimbah Creek are probably typical of the problems addressed by other Landcare groups. They include:

- expected reductions in dry weather flows due to proposed increases in upstream water extractions.
- excessive stream sediment loads from new mining and forestry activities, and
- potentially unacceptable nutrient and pesticide concentrations from existing and proposed land use practices.

2.3 Data Constraints

There is a 21-year record of daily average streamflows at the catchment outlet, some of which is of poor or doubtful quality. Daily rainfall records are available for 5 stations on or near the catchment, as shown in Figure 1.

Water quality and suspended sediment loads have been measured by the local council at very irregular intervals. These are mainly for dry weather flows and provide little usable data for the more relevant wet weather flows.

2.4 Spatial Variability of Processes

Because of the data constraints and the need for model simplicity it is difficult to avoid 'lumping' or aggregation of processes. Nevertheless, the model allows for some degree of spatial distribution and variability, as indicated in Figure 1.

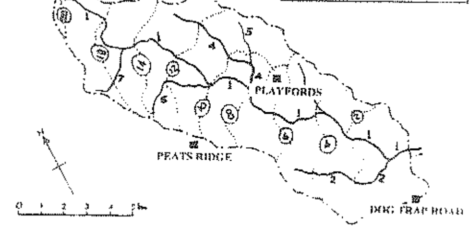


Figure 1. Major channel network in Ourimbah Creek catchment.

Channel locations in the model are specified by (X,N) where X = flow distance (km) upstream of the catchment outlet, and N = the channel reference number.

2.5 Variables and Notation

The catchment and all relevant subcatchments are treated as mathematical-physical systems with the following time-dependent variables:

2.5.1 Input Variables

R (T,X,N) = catchment or subcatchment rainfall (mm/day)
U (T) = potential or energy-limiting evapotranspiration (mm/day)

2.5.2 State Variables

D (T,X,N) = average streamflow depth at (X,N) (m)
I (T) = moisture index (mm)
M (T,X,N) = mass of sediment/pollutant in transit upstream of (X,N) (kg)
Q (T,X,N) = streamflow at (X,N) (Ml/day)
S (T,X,N) = total potential streamflow storage upstream of (X,N) (Ml)
V (T,X,N) = average streamflow velocity at/upstream of (X,N) (km/day)
W (T,X,N) = potential streamflow input upstream of (X,N) (mm/day)

2.5.3 Output Variables

Q (T,X,N) = streamflow at (X,N) (Ml/day)
P (T,X,N) = sediment/pollutant flow at (X,N) (kg/day)

It should be noted that streamflow, Q, is treated as both a state variable and an output variable, and that it is not a unique function of the potential streamflow storage S (as for many other simple models). Different combinations of Q and S represent different spatial distributions of the flows and storages.

Corresponding to each location (X,N) is a unique set of system constants or model parameters with notation as follows:

A = area of catchment/subcatchment (km^2)
B, H, J = constants in D-Q and V-Q relationships
G = site factor for sediment generation
K = storage delay time for streamflow or sediment/pollutant flow (days)
L = channel or slope length for streamflow or sediment/pollutant flow (km).

All the above variables and parameters may be used with subscripts to specify particular times or locations.

3. COMPONENTS OF MODEL

3.1 Rainfall-Streamflow Generation

The potential streamflow (W) generated from a daily rainfall (R) on the catchment or any subcatchment (X,N) of Ourimbah Creek is given by:

$$W = \begin{cases} (I/380)^{2.64}(R - U) & \text{if } R > U \\ 0 & \text{if } R \leq U \end{cases} \qquad (1)$$

Daily changes in the catchment moisture index (I) are given by:

$$\Delta I = \begin{cases} R - Q/83 - 0.013\, I & \text{if } 0.013\, I < U \\ R - Q/83 - U & \text{if } 0.013\, I \geq U \end{cases} \qquad (2)$$

The following concepts and assumptions are implied in Equations (1) and (2):

- I is a measure of the total water content of the catchment, including soil moisture and potential streamflow.
- Only rainfall exceeding the energy-limiting evapotranspiration rate (i.e. R-U) is efffective in generating streamflow.
- Evapotranspiration from the catchment is either at the energy-limiting (potential) rate or at the water-limiting rate.

The mathematical form of (1) is based on the 'variable contributing area' concept of Bevan and Kirkby [1979].

3.2 Streamflow in Channels

Daily changes in streamflow (Q) and potential streamflow storage (S) at any location (X,N) on the channel system are given by:

$$\Delta Q = F_1 W - F_2 Q_0 + F_3 S_0 \qquad (3)$$

$$\Delta S = W - Q_0 - \Delta Q/2 \qquad (4)$$

A is the catchment area above (X,N), Q_0 and S_0 are the values of Q and S at the start of the day, and values of W are obtained from (1). The constants F_1, F_2 and F_3 depend on the location (X,N) as explained in 4.2

Equations (3) and (4) have evolved from some of the past modelling efforts of the author [see Bell and Chowdhury, 1981]. They are derived from the assumption that streamflow behaviour in channels is approximated by the outflow from a system of three linear, concentrated storages interacting as shown in Figure 2.

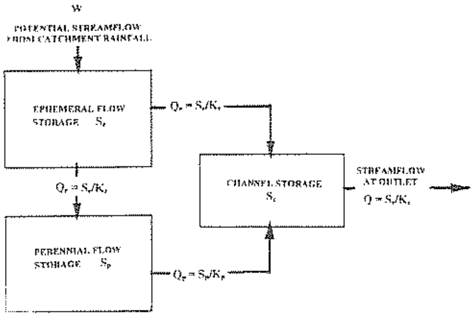


Figure 2. Assumed storage system for streamflow component.

In the above system $S_e+S_p+S_c= S$ in Equations (3) and (4). It can be shown that the scheme has similarities to some other models, including IHACRES [see Jakeman et al, 1990].

3.3 Sediment Generation

The mass of sediment (M_G) generated in a day by rainfall (R) from a localised source is expressed by:

$$M_G = G\, A_s\, R^{1.12} \qquad (5)$$

This is an adaptation of the Modified Universal Soil Loss Equation [Williams, 1975]. The value of M_G is used in Equations (6) and (8) to estimate downstream sediment loads.

Factors G and A_s are briefly explained in 4.3

3.4 Sediment/Pollutant Transportation

The model uses the same set of equations for the transportation of both suspended sediments and conservative pollutants, namely:

$$P = K_S P_0 + \Sigma M_G + P_B \qquad (6)$$

$$C = P/Q \qquad (7)$$

$$M = K_S M_0 + \Sigma(L\, M_G / V) \qquad (8)$$

$$K_S = ((2M_0/P_0) - 1)/((2M_0/P_0)+1) \qquad (9)$$

These are based on the continuity principle, assuming there are no sources/sinks in transit. Such a gross assumption will obviously need revision when more experience is gained with this part of the model.

Equations (6) and (7) enable estimates of the sediment/pollutant discharge (P) and concentration (C) at the end of each day.

Equation (8) provides an estimate of the total mass of sediment/pollutant remaining in transit upstream of (X,N) at the end of the day. P_0 and M_0 are corresponding values at the start of the day. K_S is an 'effective delay time' for M_0.

ΣM_G is the total mass of sediment/pollutants generated from localised sources during the current day. For sediments, Equation (5) is applied to each source to give individual values of M_G. L is the flow distance and V the average velocity of streamflow between each source and (X,N).

P_B is intended to account for 'background' sediments or pollutants in the water.

3.5 Environmental Flows

For the survival of critical species in the aquatic ecosystems of Ourimbah Creek it is assumed that certain minimum depths (D) and velocities of flow (V) must be maintained at particular times of the year [see Gippel and Stewardson, 1995]. These are estimated at key locations by:

$$D = B_1 Q^H \qquad (10)$$
$$V = B_2 Q^J \qquad (11)$$

The constants B, H and J vary with (X,N).

4. EVALUATION OF PARAMETERS

The methods used for evaluating the parameters involve mainly graphical plotting and field surveying. Although advantageous and appropriate for Landcare participants, some of these techniques would be regarded as subjective and crude by current scientific standards. More efficient and academically acceptable techniques may be introduced later.

4.1 Rainfall-Streamflow Generation

Log-log graphical plots of W/(R-U) against I were used to estimate the constants of Equation (1). The values of W were calculated from the streamflow data with (3) and (4).

Monthly water balance analyses provided estimates of catchment evapotranspiration under both energy-limiting and water-limiting conditions. These analyses enabled the calculation of average daily values of U for each season, and also the water-limiting evaporation constant (0.013) in Equation (2).

4.2 Streamflow in Channels

It may be shown that the three constants in Equation (3) are equivalent to rather complex combinations of other constants with clearer physical significance ie.

$$F_1 = 2AK_pK_r/((2K_pK_r+K_r+K_p)(K_e+K_c))$$

$$F_2 = F_1(K_eK_r+K_pK_r+K_pK_e+K_pK_c)/AK_pK_r$$

$$F_3 = F_1(K_r+K_e+K_c)/AK_pK_r$$

In the above, A is the catchment area above (X,N). K_e, K_p and K_c are the 'delay times' for the ephemeral flow, perennial flow and channel storages respectively (see Figure 2). K_r is an analogous 'recharge delay time' for the perennial flow storage. The interpretation of these constants as delay times follows Laurenson [1964] and other authors.

Values of K_c were estimated for all locations of interest from L/V where L is the average flow distance estimated from map data and V is the average velocity at bankfull stage in the upstream channel system. The Manning Formula with data from field surveys was used to calculate V, along the lines suggested in Bell and Vorst [1981].

There are significant advantages in using V as a measurable parameter varying with location. From geomorphological considerations its range of likely values in the main channels of Ourimbah Creek is relatively small (20 to 180 km/day). Also, with such coarse time increments (days), the modelling is not very sensitive to V, and the adoption of an average of 100 km/day for all (X,N) makes only small differences to the streamflow predictions.

Parameters K_e and K_p were evaluated from streamflow recession analyses (when W = 0). Graphical plots of ΔQ against Q were made for these conditions and linear envelopes drawn above and below the scatter. It may be shown that the slope of the lower envelope is approximately equal to K_p+K_c while the slope of the upper envelope is approximately equal to $K_e+K_c-K_r$.

Parameter K_e was averaged from many values calculated by Equation (3) from the streamflow data.

In the absence of other information, the above values of K_e, K_p and K_r were assumed to apply at every location on the main channel network. Only K_c (evaluated from field and map data) was varied for different locations.

4.3 Sediment Generation

Factor G in Equation (5) depends on soil erodibility, land slope gradient and length, ground cover, and the presence of any erosion control measures. It was evaluated from the tables and maps prepared by the Soil Conservation Service of

NSW [see Rosewell, 1993] for Ourimbah Creek problem sites as identified in field inspections.

Parameter A_s in Equation (5) is the actively eroding area of the sediment source and was also estimated in the field inspections.

4.4 Sediment/Pollutant Transportation

Parameter K_S in equation (6) is updated for each time increment through Equation (9).

The mass of sediment remaining in transit (M) depends on the transport times from the sources to (X,N), as expressed by Equation (8). For each source, these times are assumed equal to L/V, as for K_c in 4.2.

4.5 Environmental Flows

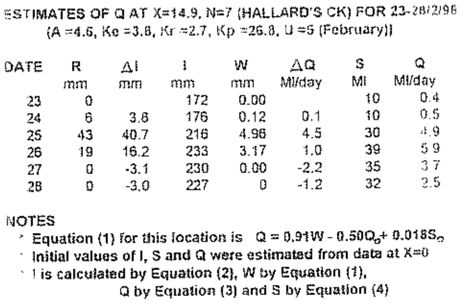
The channel survey locations included two sections identified as key locations for environmental flows. In addition to the surveys for Manning Formula estimates (as outlined in 4.2), a number of low flow gaugings were made at these locations. Plots of the calculated and measured Q values against D and V on log-log graph paper then gave estimates of B_1, B_2, H and J for Equations (11) and (12).

5. OPERATION OF MODEL

5.1 Spreadsheet Computations

In accordance with the specific requirements, each component of the model can be operated separately on any home computer with spreadsheet software. Figure 3 sets out a typical arrangement of spreadsheet computations to predict daily streamflows at an upstream location with Equations (1) to (4).

The values of Q from the example in Figure 3 were used to predict the corresponding concentrations of suspended sediment with Equations (5) to (9) in a similar spreadsheet format.



ESTIMATES OF Q AT X=14.9, N=7 (HALLARD'S CK) FOR 23-28/2/96
(A =4.6, Kc =3.8, Kr =2.7, Kp =26.8, U =5 (February))

DATE	R mm	ΔI mm	I mm	W mm	ΔQ Ml/day	S Ml	Q Ml/day
23	0		172	0.00		10	0.4
24	6	3.8	176	0.12	0.1	10	0.5
25	43	40.7	216	4.96	4.5	30	4.9
26	19	16.2	233	3.17	1.0	39	5.9
27	0	-3.1	230	0.00	-2.2	35	3.7
28	0	-3.0	227	0	-1.2	32	2.5

NOTES

- Equation (1) for this location is $Q = 0.91W - 0.50Q_o + 0.018S_o$
- Initial values of I, S and Q were estimated from data at X=0
- I is calculated by Equation (2), W by Equation (1),
  Q by Equation (3) and S by Equation (4)

Figure 3. Spreadsheet computations for predicting Q at (14.9,7).

5.2 Testing and Validation

Trial computations with both measured and hypothetical data have verified the general practicability and user-friendliness of all model components. However, because of the limited available data, proper validation has been possible only with the two streamflow components and only at the catchment outlet.

In the above validation, all parameters of the streamflow components (except K_c) were evaluated from the middle half of the streamflow record, i.e. 1984-93. The model was then operated with the same parameter values to compute streamflows for the other half of the record, i.e. 1978-83 and 1994-98.

Comparisons between recorded and computed daily streamflow values with the above procedure showed no positive or negative bias but a mean (absolute) discrepancy of more than 60%. There was little difference between the discrepancies for 1978-83 and those for 1994-98, suggesting that no hydrologically significant catchment changes have occurred since the commencement of records.

More satisfactory comparisons between recorded and computed streamflows were obtained when the daily rainfalls were grouped into 'wet periods' of 1 to 5 days. The corresponding totals of computed and recorded streamflow for each wet period then showed a mean discrepancy of 34%. This was better than expected and seems similar to the discrepancies experienced with some more sophisticated rainfall-runoff models.

5.3 Further Development

In the comparisons of recorded and computed daily values of streamflow a distinct tendency of the model to underestimate high flood flows and overestimate low flood flows was observed. The tendency could have been reduced, and the overall model performance improved by making K_c an exponential function of Q_c (i.e. assuming non-linearity for the ephemeral streamflow storage). This was not done because the resulting increase in model complexity was regarded as undesirable at the present stage. Modifications of this type and a system of trial and error adjustments to improve predictions should be introduced at a later stage.

Much of the work in developing this model to date has been on the rainfall-streamflow components. There is general agreement, however, that the environmental flow and sediment/pollution components are more directly relevant to the catchment problems of highest priority. These latter components will therefore be the main focus of future efforts.

The Ourimbah Creek group has recently joined the NSW Streamwatch Scheme which will assist in the implementation of a new and better program of water quality studies. This should also assist the testing and development of the sediment-pollutant components of the model.

6. CONCLUDING COMMENTS

Various commercially available models were initially considered for the aims of the Ourimbah Creek/PalmGrove Landcare Group. In addition to not meeting the special needs mentioned in 1., these were found generally to require computing facilities, data, and/or financial resources not available to the group. They were therefore regarded as less appropriate than the model described here.

Although the predictive performance of this model is not particularly satisfying, it is still useful for understanding and analysing catchment processes within a quantitative and physically rational framework.

It should be fully recognized that rainfall-streamflow and sediment/pollutant predictions are notoriously fuzzy, even with good data and the most advanced techniques. This seems to be understood and accepted by the Ourimbah Creek community who, hopefully, have no unrealistic expectations or illusions about their model's capabilities.

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