The Structure, Function and Management Implications of Fluvial Sedimentary Systems (Proceedings of an international symposium held at Alice Springs, Australia, September 2002). IAHS Publ. no. 276, 2002.

Flume experiments and modelling of flow–sediment–vegetation interactions

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Abstract Environmental management of rivers requires understanding of the interaction between flow, sediment and vegetation. Flume test results show that the rate of bed load transport through emergent stems is related to bed shear stress, which is influenced by stem drag. Sediment accumulations in partially vegetated rivers are associated with vegetation distribution. Equilibrium storage volumes in vegetation strips are related to the prevailing discharge, and can be attained by erosion or deposition of bed load. Bed load also accumulates in the lee zones of patches, attaining equilibrium volumes related to sediment supply and discharge. The interaction between sediment and vegetation dynamics can be effectively simulated by rule-based modelling.

Key words sedimentation; vegetation; bed load; flume study; modelling

INTRODUCTION

Environmental management of rivers requires understanding and prediction of the processes linking management actions to morphological and biological response. Discharge is the fundamental driver in this linkage (Poff *et al.*, 1997), but relating it to ecological functioning and sediment dynamics requires its expression in terms of local hydraulic conditions such as flow depth, velocity, area of inundation, and bed shear.

Hydraulic conditions in a river are determined by discharge and channel form, and are strongly influenced by instream and riparian vegetation. Channel form is determined by sediment supply, local geology, hydraulics, and vegetation. The occurrence of vegetation is determined by habitat conditions defined by hydraulics and channel form. There is therefore a strong, mutual feedback interaction between vegetation, hydraulics and channel form in river function. This paper presents results from a study of this interaction by James *et al.* (2001). The influence of emergent vegetation on bed load transport and storage was investigated in a flume, and a modelling strategy proposed for simulating the interaction between sediment and vegetation dynamics.

BED LOAD TRANSPORT THROUGH EMERGENT VEGETATION

Storage of sediment within stands of vegetation depends on the rates of its supply and removal. The supply rate is externally determined, but the removal rate is controlled by the local hydraulics. Only a few investigations of bed load transport through vegetation have been undertaken (e.g. by Tollner *et al.*, 1982), and no reliable prediction formulations have yet been presented. Bed load transport through emergent stems was investigated in a 15-m-long, 0.38-m-wide tilting flume, using 0.45-mm quartz sediment and stems represented by 5-mm-diameter steel rods at 25 mm longitudinal and transverse centre spacings, in a staggered arrangement. Two series of experiments were performed. In Series A the water discharge was kept constant at 6.5 l s^{-1} m^{-1}, and the sediment feed rate was varied to give four values between 0.005 and 0.0184 kg s^{-1} m^{-1}. In Series B the sediment feed rate was kept constant at 0.0085 kg s^{-1} m^{-1} and the water discharge varied to give five values between 3.4 and 18.5 l s^{-1} m^{-1}. Each experiment was continued until equilibrium of measured sediment input and output rates was attained, after which the flow depth and bed slope were measured. For Series A the bed slope increased consistently with bed load transport rate. For Series B the bed slope decreased with discharge initially, but became constant at higher discharges, suggesting a maximum sediment transport rate for a particular vegetation stand, independent of discharge above some limit.

Prediction of bed load transport rate requires relating it to local hydraulic conditions, commonly in terms of the boundary shear stress (τ_o). In the presence of stems, τ_o can be calculated by subtracting the total stem drag from the downslope weight component of the flow (Thompson & Roberson, 1976; James *et al.*, 2001). The good correlation between the experimental bed load rates and the values of τ_o thus determined (Fig. 1) suggests that bed load transport rates through emergent vegetation can be predicted by conventional equations, provided the hydraulic input accounts for the influence of the stems. The τ_o values for Series B are effectively constant, even beyond the discharge limit where the bed slope remained the same, suggesting that the additional downslope forces associated with further flow depth increments were carried by stem drag and not transmitted to the bed.

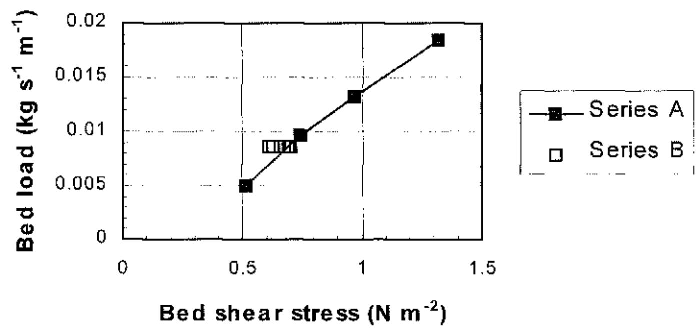

Fig. 1 Relationship between bed load transport rate through stems and bed shear stress.

SEDIMENTATION IN PARTIALLY VEGETATED CHANNELS

Discontinuous regions of vegetation in a river give rise to spatially varying hydraulic conditions, resulting in spatial patterns of sediment erosion and deposition. Sediment accumulations associated with vegetation result from enhanced deposition through modification of the flow field, and stabilization of deposits by reduction of bed shear amongst stems. Experiments were carried out to investigate sediment accumulation associated with vegetation strips (such as commonly occur along river banks) and isolated instream vegetation patches. The experiments were done in the same flume and using the same sediment as in the bed load experiments described above. The same stems were used in the strip experiments, but extended over only one third of the flume width. Two series of strip experiments were conducted: in the first, sediment was fed into the flume and the deposition in the strips was monitored; in the second, sediment was placed within the strips and its erosion was monitored.

For the deposition experiments, sediment was introduced to the clear width of the flume at a rate of 8.4 g s^{-1} under uniform flow conditions at discharges of 5.2 and 7.5 l s^{-1}. The sediment leaving the flume was collected and measured over time intervals of 20 or 30 min, enabling the cumulative volume of lateral diffusion and deposition of bed load into the strips to be determined (dotted lines, Fig. 2). It is clear that the deposition rate decreases with time as the sediment accumulates towards some equilibrium volume at which net deposition would cease.

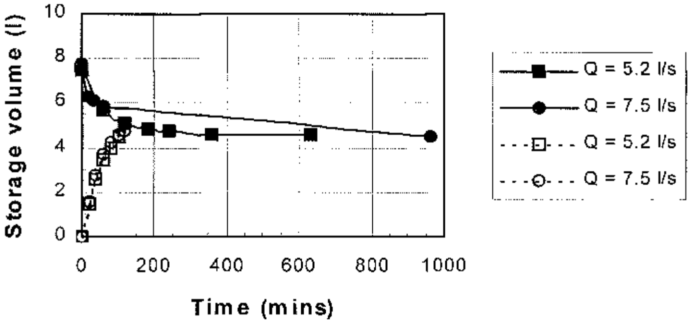

Fig. 2 Change with time of sediment storage in vegetation strips through deposition (dotted lines) and erosion (solid lines).

For the sediment retention experiments, excess sediment was placed within the strips and allowed to erode under the same flow conditions as for the deposition experiments, but with no sediment supply. In each case flow was continued until erosion was effectively completed. Again, the change in storage is initially rapid (Fig. 2, solid lines) and becomes progressively slower as the storage asymptotically approaches an equilibrium state, which appears to be quite similar to that approached by deposition.

The experiments with isolated vegetation patches were carried out at a smaller scale than the others, to obviate flume side effects on flow and deposition around the patches. The patches were formed with 1.6 mm diameter copper rods spaced at 14 mm centres, representing the same stem density as used in the other experiments (with density defined as the stem area projected in the flow direction per unit volume of water). The width of the patch was 70 mm in every case, but three different lengths of 140, 280 and 560 mm were used. Increased sediment mobility was required at the smaller scale, and coal sediment with a median grain diameter of 1.0 mm was used.

In the first series of isolated patch tests, sediment was introduced to the flume at a rate of 9.0 g s^{-1}. For the two shorter patches, deposition was all in the form of a lee bar; for the longest patch, deposition also occurred within the patch, and this increased with

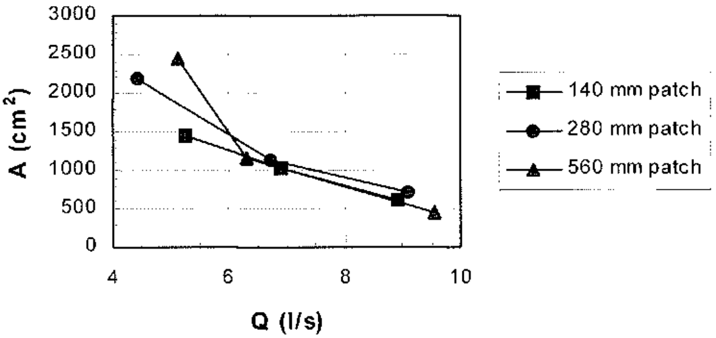

Fig. 3 Relationship between equilibrium plan area of lee bar deposits (A) and discharge (Q) for isolated vegetation patches.

decreasing discharge. Once an equilibrium deposit had formed (i.e. its plan area had stabilized), the flow was stopped and the plan area and weight of the deposited sediment were measured. The experiment was performed for each of the three patch sizes, with three discharges ranging from about 5 to 9 l s^{-1}. The results show that the plan area of equilibrium deposit decreases with increasing discharge (Fig. 3). At relatively low discharges the area of the deposit is proportional to the length of the patch, but the curves converge as the discharge increases. Although plan area is similar for the different patch lengths at higher discharges, the measured weights increase with patch length for all discharges, indicating that the deposits are deeper for longer patches.

Although the deposits stabilized at a constant equilibrium size, they were always active, with continuous deposition and erosion taking place. If sediment supply ceased, erosion continued until a new stable equilibrium state was attained. A further series of experiments was carried out to monitor the storage depletion after cessation of sediment supply. For each patch length, an active deposit was formed for a common discharge of 5.1 l s^{-1}. The sediment supply was then cut off and the deposit area monitored until it stabilized once more, this time at a static condition with no sediment movement. The depletion curves (Fig. 4) show that, whereas the size of active deposit depends strongly on patch length at this discharge, the static deposits are very similar in size. These results suggest that sizes of relic deposits after short flood events depend on the local sediment supply rate during the event as well as the discharge magnitude.

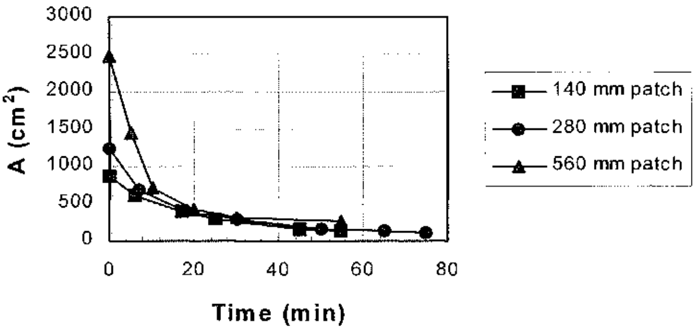

Fig. 4 Storage–depletion curves for lee bar deposits.

MODELLING FLOW–SEDIMENT–VEGETATION INTERACTION

The experiments described above contribute to understanding the influence of vegetation on hydraulic and sedimentation processes. The feedback response of vegetation is more difficult to determine experimentally, however, and requires simulation. Current knowledge of vegetation response to dynamic river form is insufficient to provide the quantitative description required by conventional modelling techniques, but a wealth of qualitative understanding exists that is potentially useful in predicting system dynamics. New, non-computational modelling approaches are therefore being explored, which are able to incorporate qualitative expert opinion.

The core of all models for simulating sediment dynamics in rivers is the sediment continuity equation:

$$Q_{s\,in} - Q_{s\,out} = \frac{\Delta S}{\Delta t} \tag{1}$$

in which $Q_{s\,in}$ and $Q_{s\,out}$ are the sediment input and output rates, and ΔS is the change in storage in time Δt. In conventional modelling $Q_{s\,in}$ is known at any time step, $Q_{s\,out}$ is calculated using an equation relating sediment transport to local hydraulic conditions, and ΔS is then calculated from equation (1). Where river form is made complex by the presence of bedrock and vegetation, this approach requires higher resolution description of local hydraulics than is normally practicable, and other approaches are required.

Nicolson (1999) proposed a rule-based modelling approach in which equation (1) is used to predict dynamic sediment storage states in a succession of reach scale cells (James *et al.*, 2001). The driving hydrograph is specified coarsely in terms of the occurrence of "small", "medium" or "large" events. Sediment discharge capacity (for $Q_{s\,out}$) is predefined for particular channel reach types and event classes through laboratory, field or higher resolution analytical studies. Rather than by solution of differential equations, the simulation is carried out by logical rules of the form: IF(certain conditions hold) THEN(the system state is altered accordingly). In this way sediment can be transferred downstream and stored at different rates, as determined by the applied hydrograph, sediment availability and reach type. A significant advantage of this approach is that it is able to account for sediment distribution pattern within cells and the interaction between sediment and vegetation through rules that may be based on theory, empirical evidence or expert opinion.

A prototype model of this type has been formulated to simulate interaction between reeds and sedimentation. Stages of reed growth are defined in terms of four possible states: "none" representing bare sediment, "rhizomes" representing presence of rhizomes without aerial shoots, "young stems" representing early stage aerial stems, and "dense reedbed" representing full development. Changes between these states are driven by the hydrograph through logical rules; for example, "young stems" can develop to "dense reedbed" in a year including a minimum number of "medium" flow events to provide water and nutrients, but can be reduced to "none" if ripped out by a "large" event. The relationship between the states is shown in Fig. 5. The rules are primitive, but are easy to refine or replace as new knowledge is gained. The effect of reedbed state on sediment dynamics can also be described by rules that modify the transport capacity, reduce availability of sediment in storage, or increase deposition. A model incorporating these rules, and allowing sediment storage separately on the channel bed or in bars, was used to describe the annual change in sediment storage in a hypothetical sequence of 10 cells under the influence of an 8-year flow sequence. The effect in one cell of including rules to account for the influence of reed dynamics on sedimentation is shown in Fig. 6 (the upper and lower parts of each block represent storage in bars and on the bed respectively): once the reeds have become established (year 84) they have a significant influence on the sedimentation dynamics.

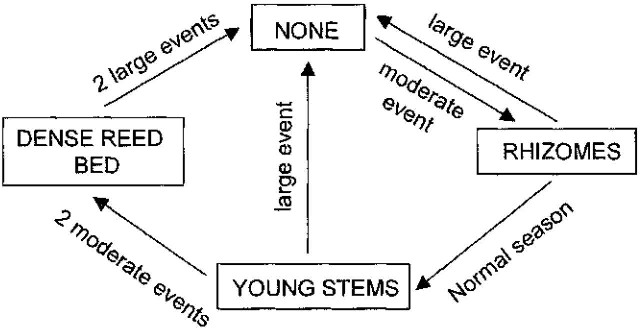

Fig. 5 Simulated reedbed states with event-driven changes.

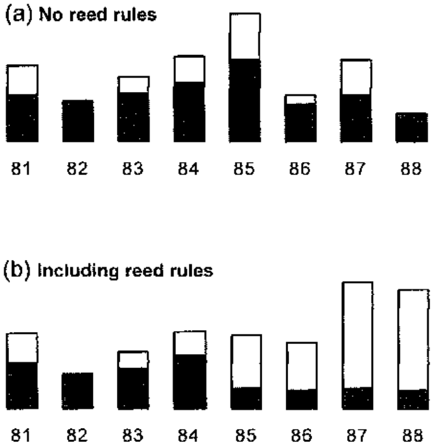

Fig. 6 Simulated effect of reedbed dynamics on sedimentation in a cell.

CONCLUSIONS

The rate of bed load transport through emergent vegetation can be related to bed shear stress, but this must be calculated with allowance made for stem drag.

Sediment accumulates in river channels in association with instream vegetation distribution patterns. Bed load diffuses transversely into longitudinal strips of vegetation (such as occur along banks), and within and in the lee of isolated vegetation patches. An equilibrium volume of sediment stored in these situations exists, associated with discharge magnitude, and is approached through either erosion or deposition.

Conventional computational modelling is unsuitable for describing sediment vegetation interactions in river morphology dynamics. A rule-based approach can simulate sediment movement and storage, allowing for sediment–vegetation interaction, and has the facility for incorporating non-quantitative information and knowledge.

Acknowledgements This work was funded by the Water Research Commission (South Africa). The isolated patch experiments were carried out by Warren Brusse.

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