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Sediment Routing Through Reservoirs, Wyresdale Park Reservoir, Lancashire, U.K.

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ABSTRACT

The proportion of the catchment sediment yield stored in a reservoir is a measure of the system's trap efficiency. The use of empirical relationships, such as Brune (1953), has been widespread but in many cases is found to be inappropriate because of local hydrodynamic conditions. Wyresdale Park Reservoir, Lancashire, has been instrumented to evaluate the present suspended sediment transmission and trapping characteristics of the system. A data-based mechanistic approach to modelling suspended sediment routing and deposition at the event scale has been adopted by applying a transfer function model generated by the microCAPTAIN computer software package developed at Lancaster University. The analysis of hysteresis loops from storms provides a method for analysing the delivery of suspended sediments from the catchment as well as the relationship between suspended sediment concentration and discharge at the reservoir outflow.

KEYWORDS

Reservoir sedimentation; sediment transmission; trap efficiency; transfer function modelling.

INTRODUCTION

Reservoirs by their inherent design provide a trap for sediment delivered from the catchment. Reservoir sedimentation has implications for maintaining water quality and for reducing the operational life span of the reservoir. Therefore it is of vital importance that the transmission of sediments through reservoirs is understood so that sediment management programmes can work effectively.

Much time was spent developing trap efficiency models for reservoir sedimentation based on empirical relationships such as Brown's (1944) design curves for sedimentation and the capacity/inflow ratio developed by Brune (1953). Application of these models to UK sites finds that in many cases these models are found to ineffective in predicting sedimentation in reservoirs due to local hydrodynamic conditions and the questionable validity of extending such empirical relationships beyond the environments from which the data originates (Butcher *et al.*, 1992). There are many factors that control the deposition of sediment in any given reservoir. At present there is insufficient quality data available to validate fully physically-based models for reservoir sedimentation. Young & Lees (1993), argue that where such models exist they are over parameterised, instead advocating the use of transfer functions as a first approach to characterising the systems dynamics. This considered, a time-series, 'data-based' mechanistic approach to modelling sediment transmission through Wyresdale Park Reservoir at the event level has been adopted. Utilisation of the powerful recursive identification techniques provided by the microCAPTAIN computer software package, developed at Lancaster University, allows the derivation of a transfer function (TF) model (Young & Benner, 1991). The model output can be interpreted in terms of the mechanisms of sediment transmission within the reservoir as well as being used as a predictive tool once the system has been characterised (Young, 1992).

LOCATION & INSTRUMENTATION

Wyresdale Park Reservoir (Grid Ref: SD512493) is situated 10 km South of Lancaster in the North West of England (Fig.1). It was constructed in 1895 as a private fishery. The reservoir has a surface area of 0.08 km^2 and is fed by one major inflow the Tythe Barn Brook. The catchment surface area is approximately 1.3 km^2 and geological investigations suggest that there would be little if any extended subsurface contribution. The original capacity of the reservoir has been calculated to be 155,000 m^3. A bathymetric survey conducted in June 1994 calculates the present capacity of the lake as 120,000 m^3. Therefore 35,000 m^3 or 23% of the original capacity has been lost as a result of sediment deposition. Depositional patterns are non-uniform and concentrated in two areas. The first is a small subaerially exposed prograding delta at the inflow, the second is a distally located fine sediment accumulation; here maximum sediment thickness exceeds 1m and is likely to be the result of focusing processes.

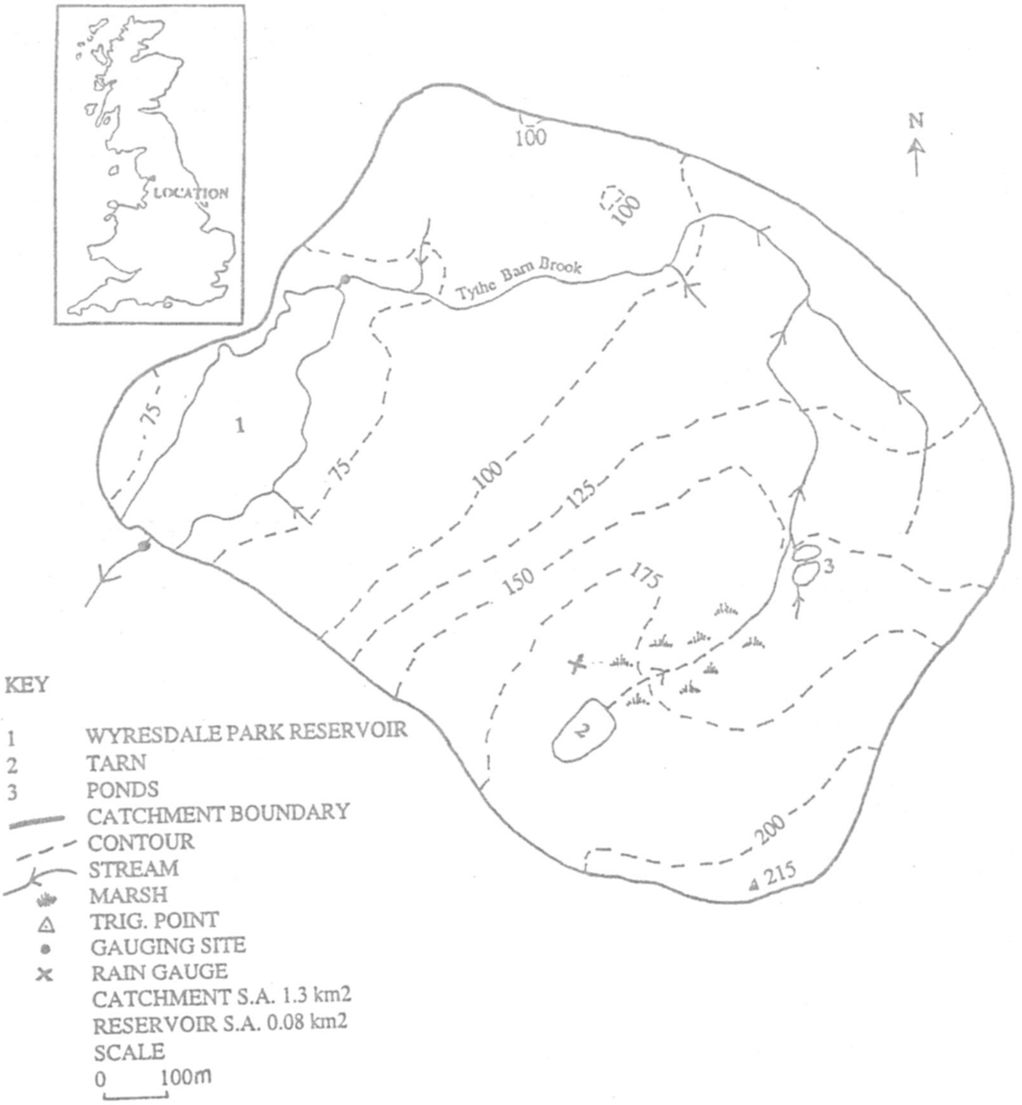


Fig.1 General location and Wyresdale Park Reservoir catchment.

In February 1994 the influent and effluent streams of the reservoir were instrumented with Keller pressure transducers, housed in stilling wells to record water level, and Partech IR40C infra-red turbidity meters to measure suspended solids. These are connected to dataloggers which take readings at 15 minute intervals. Stage/discharge equations were derived using dilution gauging and current metering methods. The turbidity meters at the inflow and the outflow have been calibrated separately to account for changes in the particle size distribution of the sediment. Both laboratory and field calibration of the meters has ensured reliability in the results obtained.

INFLOW-OUTFLOW DATA

Almost 60% of the annual flow and sediment delivery to the reservoir occurs during the winter months. During these months the total outflow exceeds the total inflow. This is a result of the majority of flow occurring during storm events when there is direct precipitation onto the reservoir, with additional sources of input being seepage and flow from storm activated streams around the reservoir margins. The total suspended sediment yield over the 12 month monitoring period was 55 t giving a delivery of 42 t km^{-2} yr^{-1}.

The trap efficiency over the monitoring period, calculated from mass balance is 91%. The majority of sediment is delivered during events which exceed a critical threshold of $0.2m^3sec^{-1}$ peak discharge and have an average trap efficiency of 75%. The annual trap efficiency of the system is elevated as a result of the 100% trapping of background levels of suspended sediment during low flow and the high trap efficiency of sediments delivered from storms below the stated critical threshold. Considering that the majority of sediment is delivered from large scale events ,this emphasises the need for event-based modelling of sediment transmission.

microCAPTAIN TF MODELLING

The TF model generated by microCAPTAIN is based on the Box-Jenkins (1970) approach to recursive analysis and has the form,

$$y(k)=\frac{B(z^{-1})}{A(z^{-1})}u(k-\delta)+\xi(k) \qquad (1)$$

where,
$y(k)$ is the time-series composed of N equi-spaced samples (k=1...N); $u(k)$ is a single, deterministic input; δ is the pure time delay between changes in the input and the output series; $\xi(k)$ represents 'coloured noise'; and $A(z^{-1})$ and $B(z^{-1})$ are polynomials. After Young & Benner (1991).

There are several stages in identifying the TF model using microCAPTAIN. The first stage is to pre-process the raw data. This is used to filter any noise which might cause problems during model identification. Next the program derives the most suitable values of A, B and δ for parameter estimation using one of three recursive techniques: least squares, basic instrumental variable (IV) and simplified refined instrumental variable (SRIV) (Young & Benner 1991). The basic IV approach is generally most attractive as this yields unbiased transfer function parameter estimates without the need for noise model identification and estimation. The model order is judged using two statistics; the coefficient of determination (R_T^2) which gives an indication of how well the model explains the data, and the Young Identification Criterion (YIC) which is a measure of how well the parameter estimates are defined. The most appropriate model generally has an R_T^2 close to unity and a highly negative YIC. Once the final parameter estimates have been calculated the model is evaluated by assessment of the model fit data, the parameter estimates and the time (impulse) response.

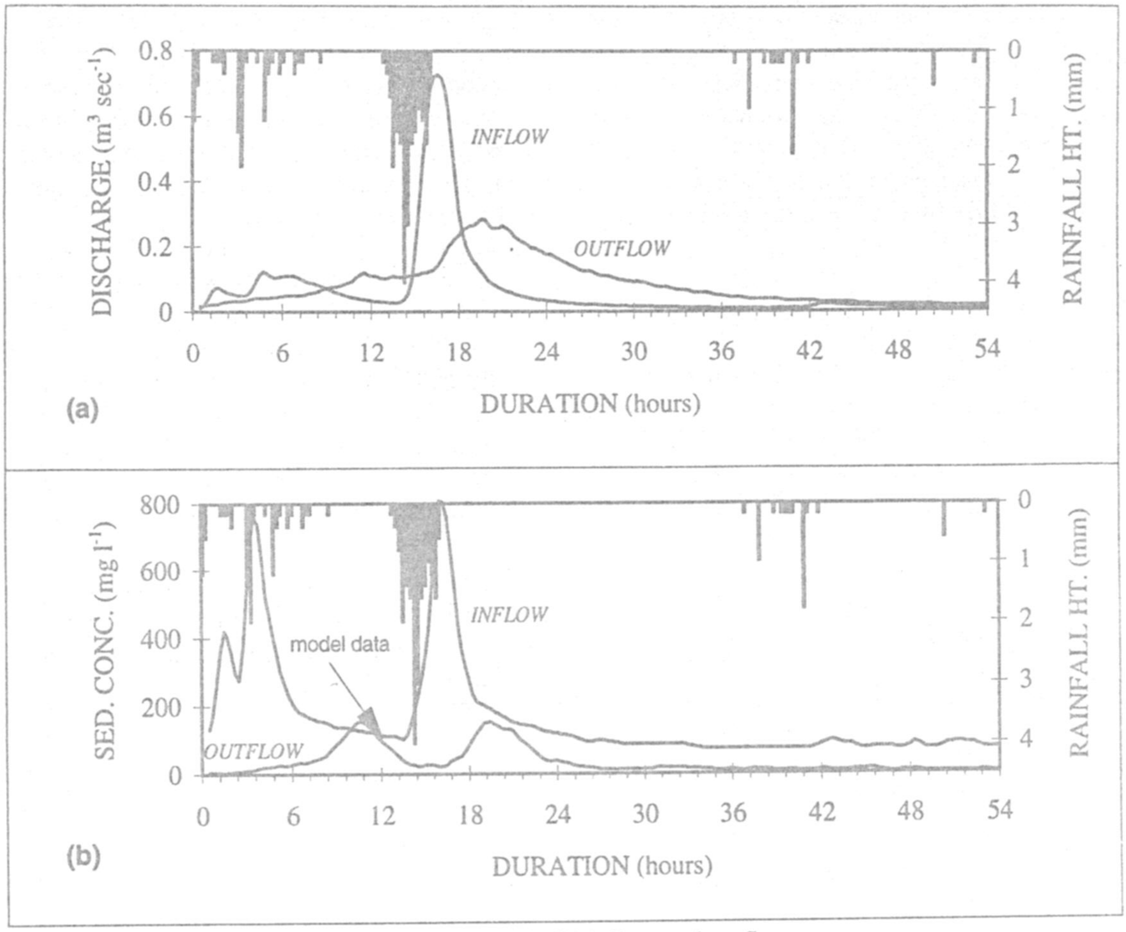


Fig. 2(a) inflow and outflow discharge 13/11/94, **(b)** inflow and outflow suspended sediment 13/11/94

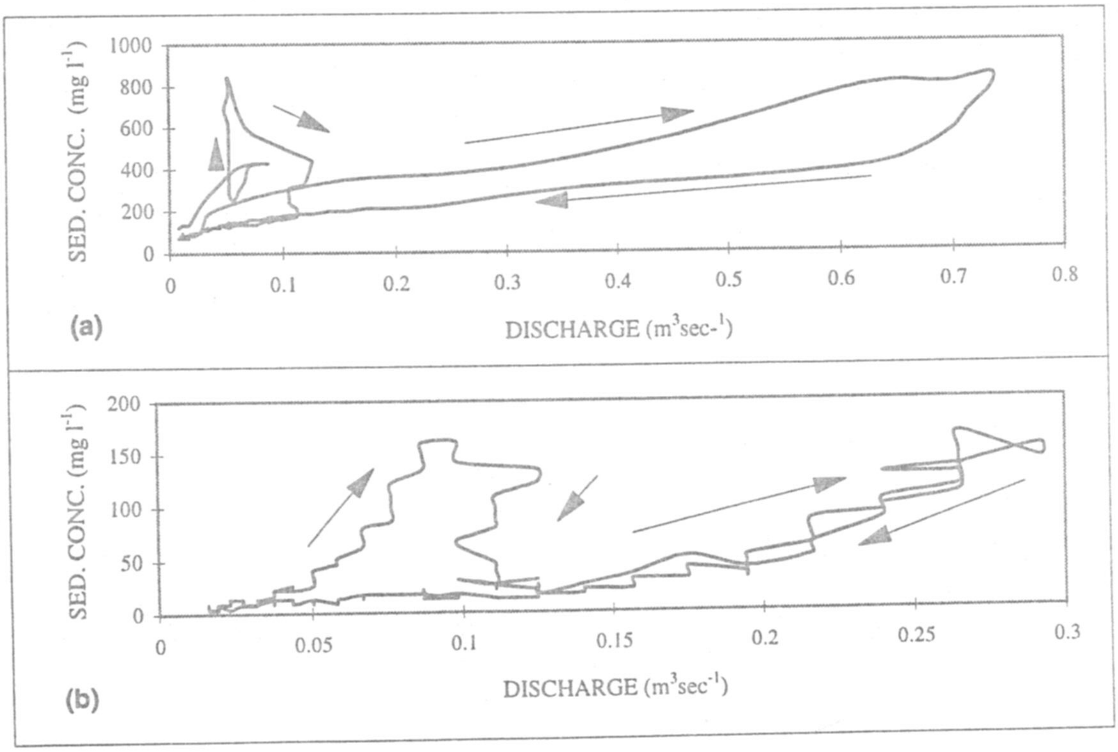


Fig. 3(a) inflow hysteresis plot, **(b)** outflow hysteresis plot

microCAPTAIN TF MODELLING RESULTS

The event being modelled started 13/11/94 (Fig.2). The catchment has a flashy response to rainfall with a lag time of less than 2 hours to peak discharge at the inflow and a further 3 hours for the propagating flood wave to reach the outflow. The total suspended sediment delivered by the event was 476 kg, with a maximum suspended sediment concentration of 820 mg l^{-1}. This compared with a total outflow 132 kg and a maximum suspended sediment concentration of 270 mg l^{-1}. The hysteresis plot (Fig.3a) of the inflow shows clockwise loops indicating flushing and a shift to the right signifying suspended sediment exhaustion (Rieger *et al* 1988). It can also be seen that sediment depletion occurs temporally where events occur in close succession as has also been found by Labadz *et al* (1991). The hysteresis of the outflow shows a more complicated relationship, but the linear component of the second loop indicates a close relationship between the suspended sediment and discharge.

The data being used for this model run starts 13 hours into the event. The baseline of this data was removed during pre-processing to remove unwanted background noise which would reduce the quality of the model output. The best model structure identified was first order, having 1 A, 1 B parameter and a pure time delay of 10 sample intervals (Table 1). The R_T^2 of 0.947 is close to unity indicating that although it is only first order it explains the data very well. The YIC is large and negative showing that the parameter estimates are well defined. The model output (Fig.4a) does contain some residual noise due to underestimation of the peak outflow and under estimation of the recession, and refinement techniques are being explored.

BASIC IV IDENTIFICATION: 1,1,10 MODEL STRUCTURE

Coeff. of Detn:	0.94734
YIC:	-6.98440
Output mean:	29.3063
Variance:	1655.40
Noise variance:	87.1682
Time Delay:	10
Parameter Estimates:	A 1: -0.85459 +/- 0.03188 B 0: 0.04454 +/- 0.00818

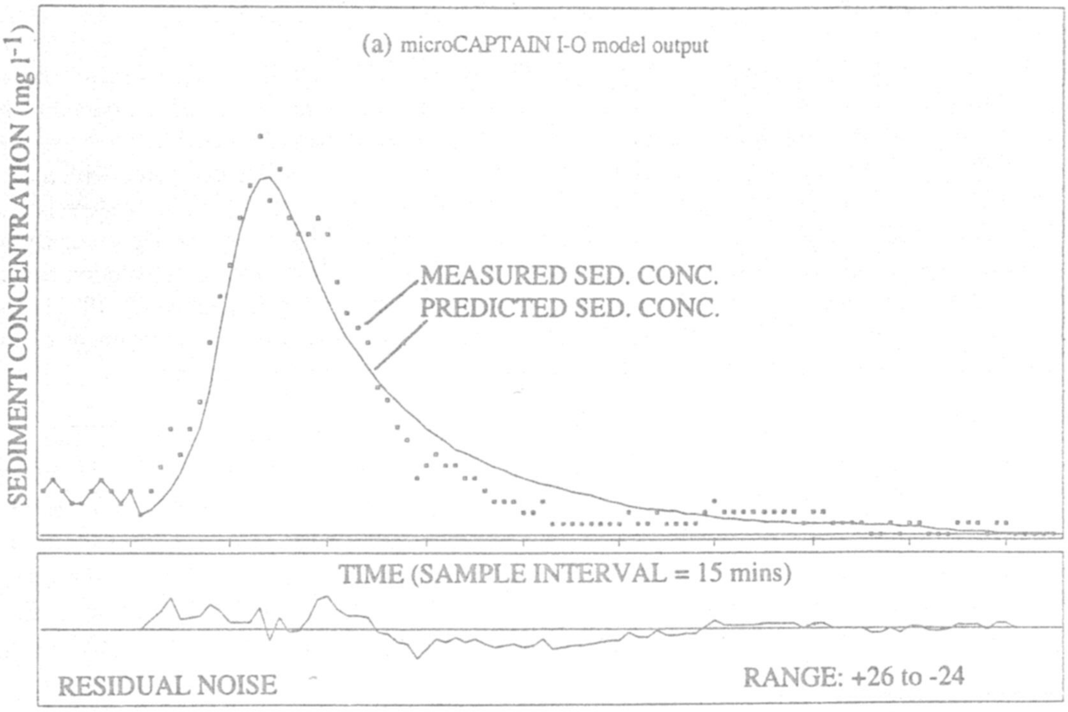
Table 1. microCAPTAIN TF model final iteration results.

The parameter estimation plot (Fig.4b) shows that the parameters converge quickly during recursive estimation, another indication of good model structure. The impulse response (Fig.4c) is the noise-free temporal response of the model to the input sequence (Young & Lees 1993). It provides a means for assessing the models dynamic characteristics and therefore its physical validity. Here the impulse response has no negative or oscillatory components and an exponential recession, validating the model output in physical terms.

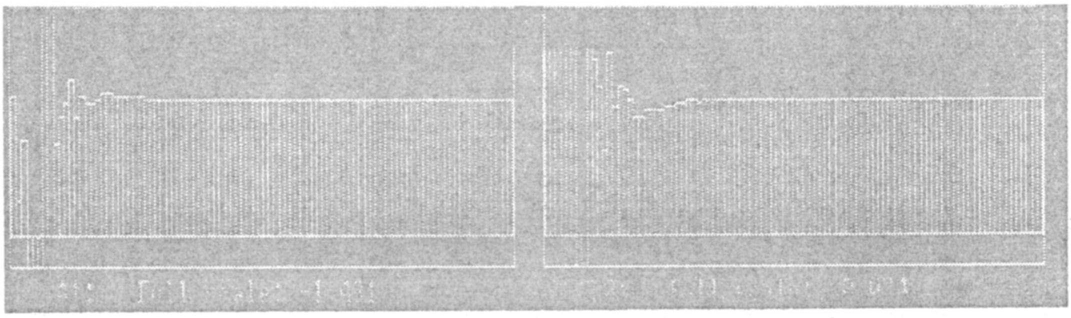
The parameters defined by the model can be expressed,

$$y(k) = \frac{0.044}{1 - 0.85z^{-1}} u(k-10) + \xi(k) \qquad (2)$$

One useful calculation that can be obtained from the parameter estimates is the steady state gain (S.S.G.). This generates a value indicating how much of the input is lost though the output. Thus the amount of suspended sediment deposited from the model output can be calculated:



(b) microCAPTAIN: MODEL PARAMETER ESTIMATION



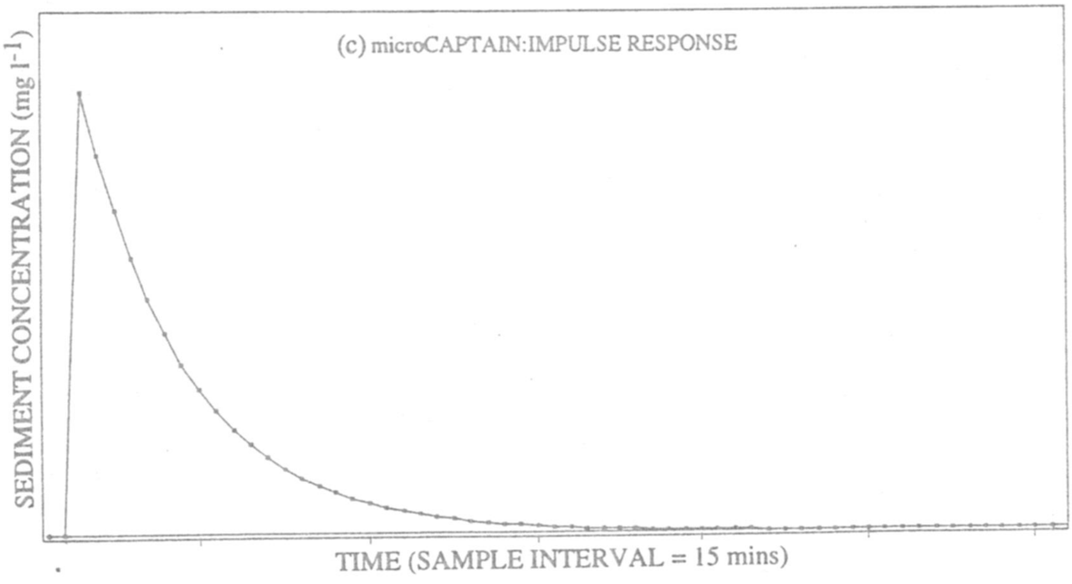


Fig. 4 (a) microCAPTAIN model output and residual noise plot, (b) model parameter estimation (c) impulse response of the model output.

$$S.S.G. = \frac{0.044}{1-0.85} = .29 \times 100 = 29\% \qquad (3)$$
$$\therefore 71\%\ \textbf{\textit{TRAP EFFICIENCY}}$$

Equation 3 shows that 29% of the input signal is lost, which restated in physical terms this means that 29% of the sediment was lost through the outflow. Therefore 71% of the inflowing suspended sediment has been trapped. The empirical trap efficiency of the event calculated from mass balance measurements was is 72%, further indicating how well the model fits the raw data series.

CONCLUSIONS

The TF model for this event indicates that the system is serial, having no identifiable parallel component. The peak velocity of the flow entering the reservoir during this event is 1.22m sec^{-1} which decelerated rapidly upon entering the expanded cross sectional area of the reservoir. The sediment laden flow travelled at 0.037m sec^{-1} taking 3 hours for the peak output to occur. The sedigraph (sediment concentration over time) of the outflow approaches the normal distribution, indicating a high degree of mixing in the reservoir. Observations during several storm events indicates that there is a piston-type mechanism operating whereby a sediment slug enters the reservoir, distally becoming well mixed before passing out of the system leaving a turbid, colloidal suspension in its wake. The first order model structure supports this single transmissive mechanism.

The flow and suspended sediment data already collected at Wyresdale Park Reservoir indicates that the trap efficiency of the system has a seasonal component superimposed on the magnitude of individual events. A comprehensive relationship between the instantaneous maximum inflowing velocity and the sediment trap efficiency of the system has yet to be fully established. However, it is clear that the nature of this piston-type mechanism of sediment transmission indicates that the inflow velocity and discharge are inversely related to trap efficiency. This implies a method for predicting the sediment storage from events of a known magnitude, with the eventual aim of retrospectively defining the minimum event level capable of depositing a discrete sediment unit from rainfall/runoff records.

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