Predicting sediment rating curves with a cellular landscape model

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Abstract Sediment rating curves are used frequently to estimate suspended sediment concentration for the subsequent calculation of sediment fluxes and to establish sediment budgets. This paper discusses a cellular model (Cascade 6) of erosion and sediment transport in a drainage basin that is used to derive sediment rating curves. In Cascade 6, water and sediment are routed from each cell to its lowest neighbour, and ultimately, to the drainage basin outlet. The sediment flux from one cell to the next is a nonlinear function of discharge and slope. The Cascade 6 model was applied to the 45-ha Catsop basin, a loess-covered agricultural basin with a gently to moderately sloping topography located in South-Limburg, The Netherlands. The Cascade 6 (a partly empirical model) results compare favourably with those generated by LISEM (a fully physically-based model). However, Cascade 6 is far less demanding in terms of input data, which gives it a distinct advantage as the interpretation of the modelling results is much more straightforward.

Key words Cascade 6; erosion; erosion model; LISEM; sediment rating curve; sediment transport

INTRODUCTION

In many basins, a sediment rating curve, and the data used to construct it, constitutes the only type of information available, as the more detailed data required as input for physically-based, distributed erosion models are not routinely collected. As a result, reproducing the sediment rating curve should be an important aspect of the calibration and verification of erosion models. The sediment rating curve is typically a power function:

$$C = aQ^b \tag{1}$$

where C is sediment concentration (e.g. mg l^{-1}), Q is discharge (e.g. l s^{-1}), a is a coefficient, and b is an exponent (Asselman, 2000; Syvitski *et al.*, 2000). The objective of this study was to compare sediment load estimates generated with Cascade 6, a drainage basin-scale erosion model that is partly physically-based and partly empirical, with sediment load estimates obtained previously using the distributed, physically-based erosion model LISEM (De Roo & Jetten, 1999).

THE CASCADE 6 MODEL

Cascade 6 is an erosion model that operates at the drainage basin scale. It is based on an earlier model, Cascade 5, which was developed to investigate self-organization and emergence in synthetic, erosional landscapes over long time scales (De Boer, 2001; De Boer & Ali, 2002; Favis-Mortlock & De Boer, 2003). Cascade 6, on the other hand, is aimed at modelling the erosional response of a drainage basin to a rainfall event.

Cascade 6 is grid-based, and for each grid cell requires data on elevation, saturated conductivity, surface roughness, and soil cohesion. Cascade 6 uses a time step, with a length in seconds, equal to the grid cell size in metres, i.e. the time step is 10 s for 10 m × 10 m grid cells. For each time step, precipitation is added to all grid cells in the basin. The calculation of infiltration and runoff rates is highly simplified. It is assumed that all rainfall infiltrates as long as the cumulative infiltration is less than $P_{\min}$. The rainfall threshold $P_{\min}$ represents the initial loss due to interception, depression storage, and the initially high infiltration capacity of the soil. It is assumed that once $P_{\min}$ is exceeded, the infiltration rate is equal to K_{sat}, and excess water runs off.

Water is routed from a cell to its lowest neighbour using the Manning equation:

$$v = 1/n\, d^{2/3}\, S^{1/2} \tag{2}$$

where v is the flow velocity (m s^{-1}), d is the flow depth (m), and n is the Manning coefficient. The flow velocity and depth are used to calculate the discharge from a cell to its lowest neighbour, and the sediment flux is calculated as:

$$Q_s = k\, Q^m\, S^p \tag{3}$$

where Q_s is the sediment flux (kg time step^{-1}), Q is the discharge (m^3 time step^{-1}), S is the slope (elevation difference divided by distance), k is a measure of the soil erodibility in a grid cell, and m and p are constants (Howard, 1994; Dietrich *et al.,* 2003). Following Kirkby (1993), Tucker & Slingerland (1997) and others, it is assumed that the sediment flux varies linearly with S, so that $p = 1$. The relationship between the discharge and the sediment flux, however, is nonlinear, and $m > 1$. This results in proportionally greater sediment fluxes in grid cells where the discharge concentrates. In the current version of Cascade 6, sediment transport is assumed to be transport-limited (i.e. the sediment concentration is controlled by the flow conditions).

FIELD AREA

The 45-ha Catsop basin is located in the province of South-Limburg, The Netherlands (De Roo, 1996). This loess-covered basin has a gently to moderately sloping topography, and land use is predominantly agricultural. Data from the Catsop basin have been used in a variety of earlier modelling exercises, enabling comparison of the Cascade 6 results with those from other models (e.g. De Roo *et al.*, 1996a,b; De Roo & Jetten, 1999; Jetten *et al.,* 1999).

CALIBRATION

Infiltration and runoff generation

Cascade 6 has five parameters that can be adjusted during calibration. Two of these relate directly to runoff generation: the rainfall threshold $P_{\min}$ and the saturated conductivity K_{sat}. It is assumed that $P_{\min}$ is the same for all cells, regardless of surface characteristics. Conversely, K_{sat} is spatially variable and depends on landuse or soil type. The values of K_{sat} used in this study were determined in a laboratory with a soil-water permeameter and were included in the Catsop data set. Cascade 6 uses a K_{sat} calibration factor to change K_{sat} by the same percentage for all cells, thus preserving the spatial pattern in K_{sat}. During calibration, the K_{sat} calibration factor is varied to adjust the peak discharge (Q_{peak}), as this was deemed the most important variable for controlling sediment load.

Data collected during five calibration storms were used to select the optimal values for the rainfall threshold P_{min} and the K_{sat} calibration factor (Table 1). The values for P_{min} and the K_{sat} calibration factor differed for the calibration storms because of changes in initial soil moisture conditions (Table 1). For storms under wet antecedent moisture conditions (initial soil moisture = 100%, initial head = 0 cm) excellent results were obtained with a P_{min} of 2 mm and a K_{sat} calibration factor of 0.38 (Table 1). Under drier conditions, these values were changed to match the shape of the hydrograph (Table 1).

Runoff routing

The Manning coefficient is spatially variable in Cascade 6 to reflect, for example, differences in land-use or vegetation type. The values of the Manning coefficient used in this study were determined using a rainfall simulator on runoff plots with the kinematic wave time of concentration model for overland flow and also were included in the Catsop data set. In addition, Cascade 6 uses a Manning coefficient calibration factor to vary the Manning coefficients by the same percentage for all cells so that the spatial pattern of surface roughness is retained. The Manning coefficient calibration factor was altered during calibration to adjust the shape of the modelled hydrograph and the timing of Q_{peak}. During calibration, optimal results were obtained with a Manning coefficient calibration factor equal to 0.08.

Sediment transport

During calibration, the sediment transport parameters *m* and *k* are adjusted so that the modelled and observed sediment rating curves match. The parameter *m* indicates how rapidly the sediment flux increases with discharge, and is adjusted so that the slopes of the modelled and observed sediment rating curves match. The same value of *m* is used for all cells. The other parameter, *k*, reflects soil and sediment properties such as erodibility and particle size distribution, and is spatially variable, depending on land-use and soil type. For this study, *k* is inversely proportional to the soil cohesion provided in the Catsop data set. A *k* calibration factor is used to reduce or increase *k* by the same percentage for all cells so that the spatial pattern is preserved.

Calibration procedure

The dataset for the Catsop basin includes sediment transport for 1987 and 1993. For two calibration storms (870626 and 870818) and two validation storms (930530 and

Table 1 Storm characteristics, hydrological factors, and modelling results.

Date	Soil moisture (%)	Initial head (cm)	Total rainfall (mm)	Maximum intensity (mm h^{-1})	P_{min} (mm)	K_{sat} calibration factor	Manning calibration factor	Q_{peak} observed (l s^{-1})	Q_{peak} LISEM (l s^{-1})	Q_{peak} Cascade 6 (l s^{-1})	Q_{total} observed (m^3)	Q_{total} LISEM (m^3)	Q_{total} Cascade 6 (m^3)
Calibration:													
870626	100	0	8.9	31.0	2	0.38	0.08	226.7	216.6	226.6	487	379	454
870818	44	–300	18.1	36.2	10	0.36	0.08	174.9	177.1	175.4	499	310	451
880928	75	–100	27.2	36.0	6	0.30	0.08	194.0	185.2	199.4	1968	448	708
890807	50	–200	17.0	23.3	4	0.38	0.08	129.9	48.1	129.6	417	97	288
891222	100	0	16.8	12.0	2	0.38	0.08	21.6	4.0	174.4	296	44	1600
Validation:													
870513	100	0	11.3	23.8	2	0.38	0.08	86.6	51.0	48.1	651	133	135
891215	100	0	23.0	18.0	2	0.38	0.08	28.5	10.4	129.5	412	68	493
930122	100	0	11.8	103.1	2	0.38	0.08	95.6	356.2	71.0	433	949	246
930530	50	–200	14.2	144.9	4	0.38	0.08	343.6	345.4	332.6	378	539	1336
931014	100	0	18.4	28.8	2	0.38	0.08	153.8	6.7	128.2	646	60	794

931014), discharges and sediment concentrations are available at the same points in time. However, for one storm (870513), discharge and sediment concentration were not measured simultaneously; hence, discharge at the time of the sediment concentration measurement has to be determined by interpolation.

Because sediment concentrations in 1987 are substantially lower than in 1993, separate sediment rating curves were derived for the two years. The 1987 rating curve is given by:

$$C = 0.977\, Q^{0.248} \tag{4a}$$

with $n = 7$ and $r^2 = 0.52$, whereas the 1993 rating curve is:

$$C = 3.695\, Q^{0.570} \tag{4b}$$

with $n = 36$ and $r^2 = 0.38$. Sediment concentrations and loads are not modelled for 1988 and 1989 because data for these years are not included in the dataset.

RESULTS AND CONCLUSIONS

The hydrological parameters (rainfall threshold, K_{sat} calibration factor, and Manning calibration factor) are adjusted to reproduce the magnitude and timing of the peak discharge. Figures 1 and 2 show the observed and modelled discharge for the 870626 calibration storm and the 931014 validation storm, respectively. These storms have similar antecedent moisture conditions, with soil moisture at 100% and an initial head of 0 cm (Table 1). It should be noted that soil moisture and initial head are not

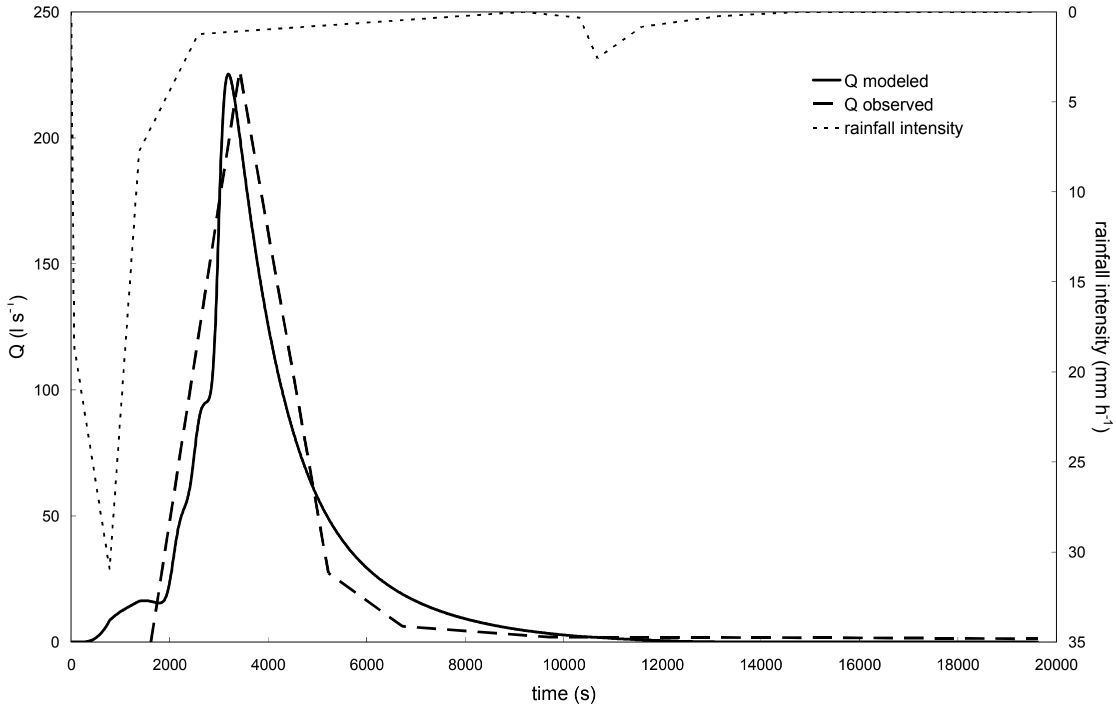

Fig. 1 Modelled and observed discharge for the Catsop basin on 870626 (calibration storm), with rainfall threshold = 2 mm, K_{sat} calibration factor = 0.38, and Manning calibration factor = 0.08.

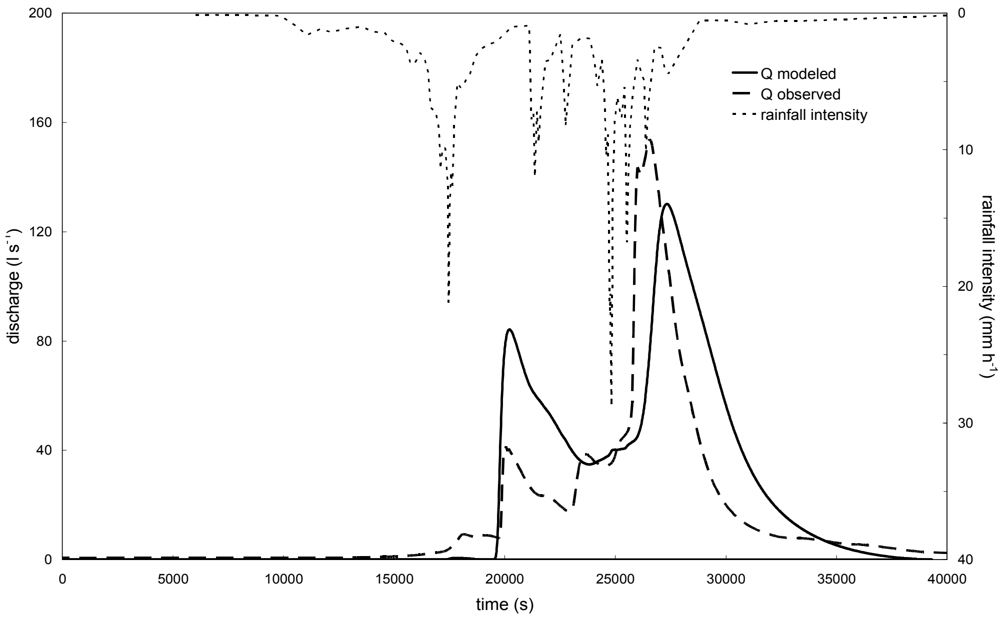

Fig. 2 Modelled and observed discharge for the Catsop basin on 931014 (validation storm), with rainfall threshold = 2 mm, K_{sat} calibration factor = 0.38, and Manning calibration factor = 0.08.

explicitly incorporated in Cascade 6. Instead, the similarity in antecedent moisture conditions allows the hydrological parameter values derived from the 870626 calibration storm to be used for the 931014 validation storm. Figure 2 shows that Cascade 6 reproduces the general shape of the hydrograph for the 931014 storm, even though there is some difference in the magnitude and the timing of the peak discharges. A comparison of all the observed and modelled peak discharges indicates that Cascade 6 works well at peak discharges greater than about 100 l s^{-1}, but tends to overestimate smaller peak discharges (e.g. 891215 and 891222, (Table 1, Fig. 3)). Of course, the overall good match between the observed and modelled peak discharges is not surprising given that the model was calibrated on peak discharge. For comparison, Table 1 and Fig. 3 also show the modelled peak discharges obtained using LISEM (De Roo & Jetten, 1999).

Because the sediment load also is affected by the total discharge, Fig. 4 shows the observed and modelled total discharges for all storms (Table 1). Clearly, Cascade 6 does not perform as well for total discharge as it does for the peak discharge. Cascade 6 overestimates the total discharge for the 891222 and 930530 storms by factors of 5.4 and 3.5, respectively. The 891222 event is a low intensity storm under high antecedent moisture conditions, whereas the 930530 event is a high intensity storm under low antecedent moisture conditions (Table 1). Conversely, Cascade 6 underestimates the total discharge for the 880928 and 870513 events by factors of 0.36 and 0.21, respectively. The 880928 event is a large rainstorm with a total rainfall of 27.2 mm under relatively low antecedent moisture conditions. The 870513 storm is a long-duration storm, with multiple rainfall and discharge peaks, that is very different from the simpler, single peaked calibration storm of 870628, even though it occurred under similar antecedent moisture conditions. Better results for these types of storms might be obtained if more calibration data were available.

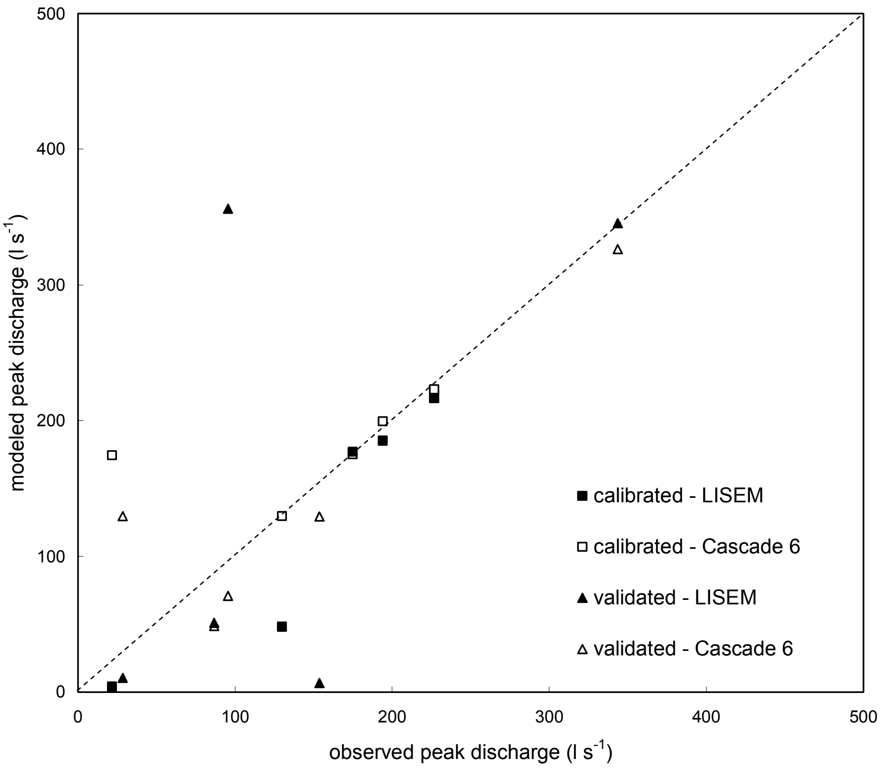

Fig. 3 Modelled and observed discharge for the Catsop basin on 931014 (validation storm), with rainfall threshold = 2 mm, K_{sat} calibration factor = 0.38, and Manning calibration factor = 0.08.

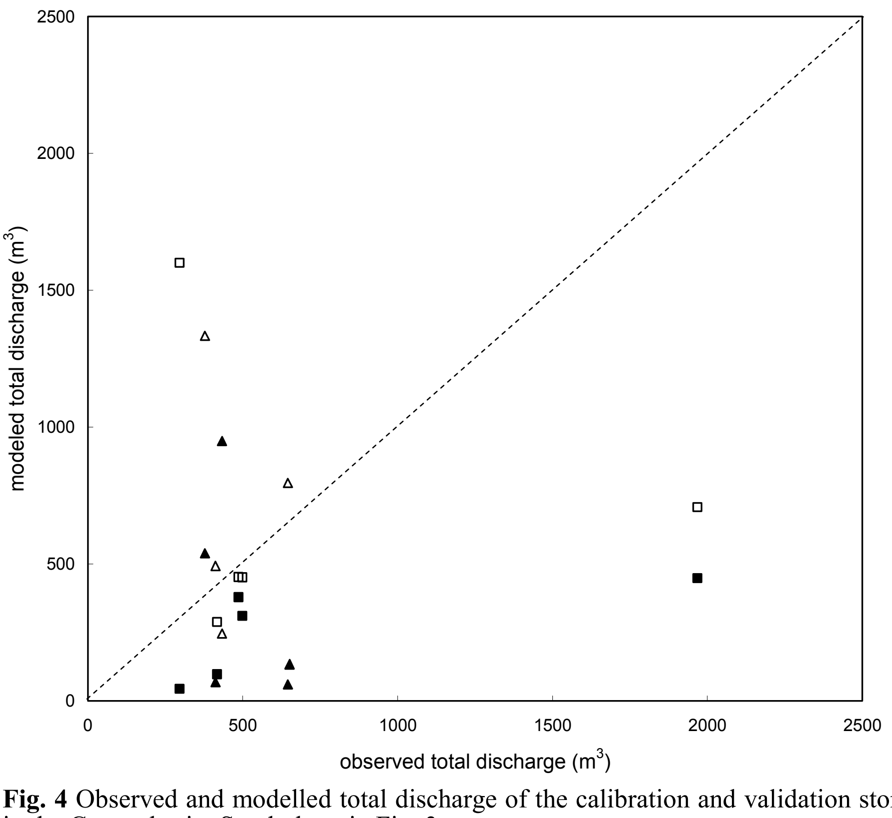

Fig. 4 Observed and modelled total discharge of the calibration and validation storms in the Catsop basin. Symbols as in Fig. 3.

Table 2 and Fig. 5 show the sediment transport modelling results. For the 1987 storms, the sediment rating curves for 870626 and 870818 were used for calibration, resulting in values of 147 for the *k* calibration factor and 1.246 for *n*. Using these values results in a sediment rating curve with a coefficient of 0.9941 and an exponent of 0.2461 for the validation storm of 870513 (Table 2); this compares favourably with the 1987 sediment rating curve (equation (4a)). Because the calibration storms do not include data for 1993, all sediment transport data from 1993 is combined to derive a sediment rating curve for the year (equation (4b)) which subsequently is used for calibration of the individual storms. These calibrations result in a *k* calibration factor of 2800 and a value of 1.556 for *m*. Table 2 shows the coefficients and exponents of the modelled sediment rating curves and the modelled sediment loads. For the two calibration storms (870626 and 870818), the modelled sediment load is 70 and 77% of the observed load (Table 2, Fig. 5). For the 870513 validation storm, the modelled sediment load is only 38% of the observed load. The low value of the modelled sediment load for this storm is a direct result of the low value of the modelled total discharge for this storm. For the three 1993 storms, the modelled sediment loads all exceed the observed loads (Table 2, Fig. 5); even so, the modelled values are of the correct magnitude. The overestimations of sediment load can be attributed, at least in part, to the overestimation of the total discharge for the 930530 and 931014 events (Table 2). However, for the 930122 event, the total discharge is underestimated by a factor of 0.6, whereas the sediment load is overestimated by a factor of 2.9.

The modelling results shown in Table 1 and 2, and Figs 3, 4, and 5 indicate that even though Cascade 6 is a partly empirical model, it is able to reproduce, after calibration, results that in terms of basin output, compare favourably with those of LISEM, which is a fully physically-based model (De Roo & Jetten, 1999). This latter type of model is very demanding in terms of data input, and in many applications the detailed input data required for these models are not available. A further complicating factor is that interpreting the results of physically-based models can be difficult because of the interactions of the requisite variables and parameters. Conversely, Cascade 6 is far less demanding in terms of input data, which gives it a distinct advantage as the interpretation of the modelling results is straightforward. The trade-off is that calibration is required to use the model. To investigate the physical meaning of the parameters used in Cascade 6, a detailed comparison of Cascade 6 and LISEM currently is underway.

Table 2 Sediment transport factors and modelling results.

Date	Transport equation		Sediment rating curve		Soil loss Observed (kg)	Soil loss LISEM (kg)	Soil loss Cascade 6 (kg)
	k calibration factor	*m*	Coefficient	Exponent			
Calibration:							
870626	147	1.246	0.9745	0.2476	1900	4791	1332
870818	147	1.246	0.9858	0.2420	870	3415	671
Validation:							
870513	147	1.246	0.9941	0.2461	622	308	234
930122	2800	1.556	4.3242	0.5587	2914	6820	8561
930530	2800	1.556	3.6947	0.5680	29348	8269	75373
931014	2800	1.556	4.4854	0.5594	9038	9	15276

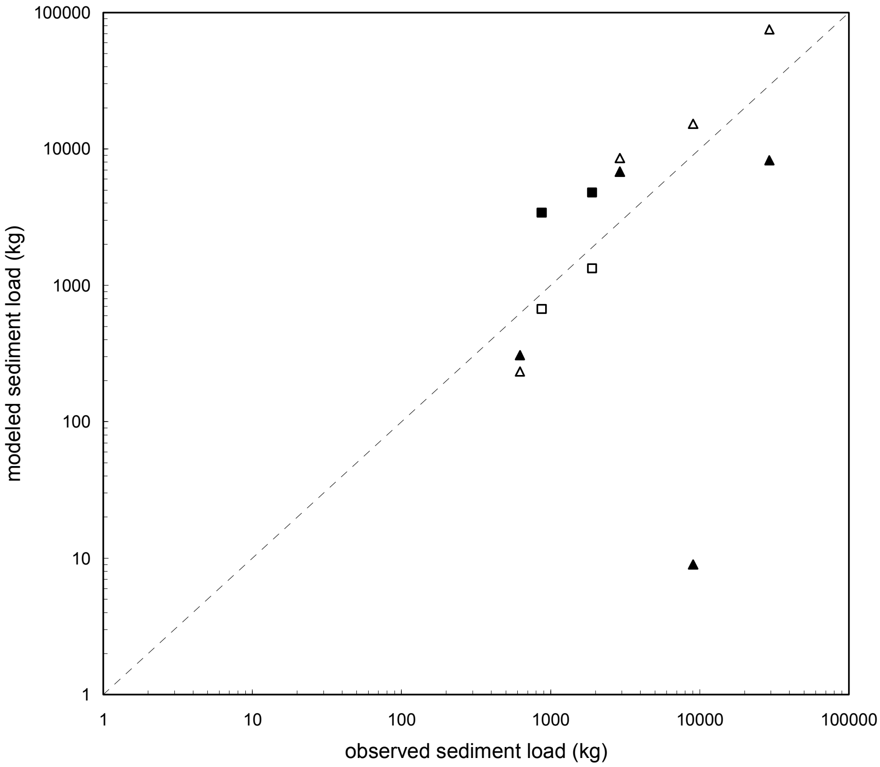

Fig. 5 Observed and modelled sediment load of the calibration and validation storms in the Catsop basin. Symbols as in Fig. 3.

Acknowledgements The author gratefully acknowledges: the hospitality of Coen Ritsema and his Land Use and Soil Processes research group of Alterra at Wageningen University; the comments and insights provided by Victor Jetten; and a sabbatical leave travel grant from the University of Saskatchewan.

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