THE ROLE OF LEAF LITTER AND SMALL WOOD IN THE RETENTION OF FINE PARTICLES DURING STORMS IN AN APPALACHIAN HEADWATER STREAM

by

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(ABSTRACT)

Streams are constantly subject to downstream movement of materials. The role of fallen leaves in resisting downstream transport of particulates is largely unquantified. The litter exclusion study at Coweeta presented the opportunity to study a stream without litter input. I expected removal of leaf litter to reduce the capacity of the stream to retain fine particulate organic matter, FPOM. However, leaves are also a major source of FPOM. I studied the effect of leaf exclusion on FPOM transport by field sampling and by generating computer simulations of particle transport in the stream.

Sampling of suspended particles during storms showed that although litter inputs and subsequent particle generation were greatly decreased (Wallace *et al*. 1997), storm exports did not differ significantly from those of the reference stream. This suggested that the effect of litter exclusion was to reduce FPOM retention. Although there was no new organic matter entering the stream during the exclusion period, entrainment of stored material compensated for it.

The computer simulations predicted higher concentrations of FPOM for storms after litter exclusion than I actually measured except during heavy rains that greatly increased discharge. These results suggested that after litter exclusion, low-intensity storms exported lower concentrations than before exclusion. However, after exclusion, intense storms that greatly increased discharge entrained higher concentrations of FPOM.

Both field studies and computer models indicated that stability of the litter-excluded streambed was lower compared to the reference and pre-treatment streams, and stability was further reduced with increased discharge.

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INTRODUCTION

In many shaded headwater streams, primary production is negligible and the energy base of the system is allochthonous organic material from the riparian forest (e.g., Vannote *et al*. 1980). The role of allochthonous inputs as a food source for stream organisms has been widely studied, and leaf litter and associated microbes constitute the primary food of many aquatic invertebrates in low-order streams (Egglishaw 1964, Kaushik and Hynes 1971, Cummins 1974, Vannote *et al*. 1980, Wallace *et al.* 1997). The fluvial system is constantly subject to downstream movement of materials. In order for leaf litter and the associated microbes to be used by stream organisms, they must remain in place long enough to be used.

Retention

The capacity to resist the downstream transport of materials is termed retention efficiency and is an important factor in stream ecosystem function. Retention efficiency of a stream ecosystem may be evaluated by measuring the transport of substances suspended in the water column, but the amount of material entrained and exported does not occur at a constant rate. For example, in a study of particulate and solution losses from a forested watershed, Bormann *et al*. (1969) noted that 70% of the total material moved downstream in one year occurred during the late winter-spring runoff, and 66% of particulates were transported during one storm. A number of indices have been proposed to measure retention in streams, including measures of Production/Respiration and Fisher's (1977) Stream Metabolism Index (SMI). The concept of nutrients in a stream moving downstream as they cycle, rather than remaining in place, was described as "spiraling" by Webster and Patten (1979). The tightness of the spirals was proposed as an indicator of retention efficiency. The concept was further refined as an index of the spiraling process in which spiraling length was defined as the average distance required to complete one loop of the imaginary spiral and could be measured by comparing upstream-downstream ^{32}P loss (Newbold *et al*. 1982). The retention efficiency of a stream ecosystem may also be evaluated by measuring the amount of small particles transported in the water column.

Particle Sources

Biological particle generation in streams occurs by microbial decomposition and the activities of shredders. Sedell *et al*. (1978) found that streams effectively retain coarse particulate organic material (CPOM) and process it into smaller sizes. This fine particulate organic matter (FPOM), 0.45µm - 1 mm in size, comprises most of the particulate organic material in transport in streams (Sedell *et al*. 1978, Naiman and Sedell 1979, Minshall *et al*. 1983, Webster *et al*. 1987, Wallace *et al*. 1993). The experimental removal of leaf-shredding insects and their litter processing functions, in conjunction with significantly higher accumulations of leaf litter resulting from lower rates of leaf-litter processing, reduced export of FPOM in a North Carolina mountain stream by 56% during the three year treatment period. In addition, much more POM was suspended during the rising hydrograph of storms in reference streams than in the insecticide-treated stream (Wallace *et al*. 1991).

Some particles may originate outside of the stream. In areas where litter and humus layers have been eroded and soil has been exposed, overland flow may carry soil particles into the stream (Ward *et al*. 1990). Sollins *et al*. (1985) used C/N ratios to conclude that the majority of the detrital carbon and nitrogen in the stream channel and floodplain samples were composed of plant debris adsorbed onto mineral surfaces but were unable to determine whether this adsorption had occurred prior to or after entering the stream bed.

Factors Affecting Fine Particle Dynamics

Factors affecting retention and transport of fine particles include fall velocity, deposition velocity, and presence of retention structures.

Fall Velocity and Deposition Velocity

Fall velocity, V_{fall}, is the downward movement of particles in still water. Fall velocity of particles larger than 0.0002 mm in still water can be determined by using Stokes' law for spherical particles at very low Reynolds numbers:

$$V_{fall} = \frac{2gr^2}{9\mu}\left(\rho_s - \rho\right), \qquad (1.)$$

where ρ is the density of the fluid, ρ_s the density of the particle, r the radius of the sphere and μ the viscosity of the fluid (Gordon *et al*. 1992). In water, Stokes' Law does not apply to particles smaller than 0.0002 mm, since the settling of this size class of particles is influenced by Brownian motion.

Reynolds (1979) examined the fall velocity of *Lycopodium* spores in still water conditions (intrinsic sinking rate) and in turbulent conditions in a lake (effective sinking rate). The mean intrinsic sinking rate was 1.0 to 1.4 m day^{-1}, while the effective sinking rates under turbulent conditions ranged from 0.19 to 0.50 m day^{-1}. The only experiment in which the intrinsic sinking rate approached the effective sinking rate was when the water column was stably stratified. He concluded that the relative delay in settling at other times was probably due to the overriding effects of physical entrainment of the particles within turbulent eddies.

Reynolds' conclusion was further supported by Smith's (1982) model of algal deposition which suggested that algae settle at their intrinsic, still-water rate only when the period of complete calm lasts at least as long as a quarter of the column clearance time, resuspension does not occur, and interaction between particles does not occur. In a fully turbulent water column, the amount in suspension is independent of the intensity of turbulence as measured by the frequency of mixings. Smith concluded that in still water, deposition corresponds to a zero order reaction, and in fully turbulent conditions, the amount of material remaining in suspension corresponds to a first-order (exponential) reaction.

Deposition velocity (V_{dep}) can be used to indicate the rate of particle loss from the water column. This term accounts for the resuspension that may occur in turbulent flow. According to Smith (1982), in flowing water V_{dep} is a function solely of depth and V_{fall} if:

1) a laminar sublayer is present whose depth exceeds particle size; and
2) particles entering this layer are not resuspended.

These two assumptions are not usually met in natural streams. In most parts of a stream, flow is turbulent (Davis and Barmuta 1989, Carling 1992, Gordon *et al*. 1992) and the laminar sublayer can be completely disrupted for flow characterized by high turbulence (Carling 1992).

In the absence of a laminar sublayer, V_{fall} and V_{dep} are not theoretically equal (Smith 1982, Reynolds 1979, Cushing *et al*. 1993). Deposition velocity is usually much less than fall velocity, due to concurrent resuspension or entrainment of particles from the streambed. Cushing *et al*. (1993) reported V_{dep}/V_{fall} of 7-12%, and Reynolds (1990) reported 50-60%.

In streams, radio-labeled particles, corn pollen, and glass beads have been used to examine both transport distance and deposition velocity of fine particles and the physical and hydraulic factors affecting them (Jones and Smock 1991,Cushing *et al*. 1993, Miller and Georgian 1992, Ehrman 1994). Cushing *et al*. (1993) showed that particles deposited on the bottom of two Idaho streams exchange rapidly with the water column and were alternately deposited and resuspended over long distances. Using an advection-dispersion model, they estimated that approximately 99% of the ^{14}C-labeled particles were initially deposited within three hours and subsequently resuspended and exported from the study reach. Cushing *et al*.'s study (1993) also showed that the pool of surficial FPOM represents particles that originated relatively recently at varying distances upstream.

Particle Retention Mechanisms

Hydrologic and substrate features keep pieces from rapidly flushing downstream, so that the materials are available for stream organisms to use. Debris dams formed by large woody materials are important retention mechanisms (e.g., Keller and Swanson, 1979). Debris dams form when tree trunks, fallen limbs, and rootwads partially or completely span the channel. Smaller twigs and leaves then fill in the gaps, making debris dams nearly watertight, which greatly enhances retention (Bilby 1981). Where debris dams have been removed, the stream has lost the capability to retain leaf-sized material (Bilby and Likens 1980). In studies following logging, removal of trees from the watersheds caused a decrease in organic matter accumulations in the streams (Webster *et al*. 1987). This resulted in a decreased capacity to resist downstream transport of seston, particularly during storms or seasons of high discharge (Webster *et al*. 1987). During baseflow, particle transport depends on the rate of biological particle generation and the retention characteristics of the streambed (Webster *et al*. 1987). During high flow, particle concentration is more strongly correlated with discharge, as concentration increases rapidly on the rising limb of the hydrograph.

In shallow headwater streams of the Appalachian Mountains, there are large numbers of obstructions including rocks, boulders, logs, and sticks. Most particles travel only a few meters upon entering the stream, although they may move further during storms (Webster *et al*. 1994). Thus, particles are often retained quite close to their points of entry rather than being carried long distances downstream.

Connection with Leaves

A number of studies have experimentally measured the retention of leaves in streams. By releasing and recovering leaves of an exotic tree *Gingko biloba*, Speaker *et al*. (1984) identified hydrologic features and substrate structures responsible for short-term retention of leaves in streams in the Cascade Mountain Range of Oregon. All of the streams they studied retained 90% of released leaves within 10 to 210 meters. Stream reaches with major debris dams were much better at retaining leaves than reaches without dams. Riffles were more efficient at retaining leaves than pools, regardless of substrate type, and the trapping efficiency of sticks (wood less than 10 cm in diameter) was between one and two orders of magnitude greater than that of inorganic substrates.

A similar method was used by Cummins *et al*. (1989) in a low-gradient stream in the Appalachian Mountains in Maryland. Ninety percent of autumn-shed *G. biloba* leaves were retained within 250 meters of the point of release in Piney Run.

In a study of two high-gradient streams in South Africa, spray-painted leaves were released and their locations of stranding noted. The occurrence of wood and leafpacks was rare in this shrub-dominated region, occupying less than eight percent of each of the reaches. However, these features contributed significantly to retention at both sites. Boulders and backwaters were also very effective at retaining leaves (Snaddon *et al*. 1992).

The above studies found that hydrologic features including debris dams, riffles, boulders, and backwaters were very effective in retaining leaves, an important factor in ecoystem functioning. A number of studies have shown that leaf litter that falls into a stream is retained close to the point of entry, where it is slowly degraded into smaller particles while at the same time functioning to retain those and other fine particles (e.g., Webster et al. in press). Webster *et al*. (1994) suggested that the increased retention of artificial leaves they observed in Big Hurricane Branch in October 1990 may have been due to the presence of many newly fallen leaves.

The role of fallen leaves in resisting downstream transport of particulate matter is largely unquantified. Experimental elimination of insects, in addition to reducing export of FPOM in North Carolina streams as discussed above, resulted in amassed leaf litter that enhanced retention of particulate inorganic material (PIM) over the six-year treatment and post-treatment period (Wallace *et al*. 1993). Annual PIM export decreased by more than 70% during treatment, despite the fact that discharge in the treatment stream exceeded that of the reference streams during two of the three treatment years. The authors concluded that retention of particles by accumulations of leaf litter is the most logical explanation for reduced inorganic export in the treated stream.

The litter exclusion study on Satellite Branch (Watershed 55) at Coweeta Hydrologic Laboratory (Wallace *et al.* 1997) presented the opportunity to study a stream with no leaf litter input. This study is a multi-year project to assess changes in organic matter standing crop, food quality, and benthic community structure in response to the decrease in resources and the degree to which organic debris contributes to substrate stability. The experimental design is such that leaf litter is excluded from the stream while the vegetation itself remains unaltered. Research objectives of the litter-exclusion study include assessing effects of reducing the resource base on community structure, ecosystem processes, response to short-term episodic events, the strength of upstream-downstream linkages in headwater streams, and the degree to which organic debris contributes to substrate stability. My study of the role of leaves as a physical retention mechanism was a portion of this study.

I expected the removal of leaf litter to reduce the capacity of the stream to retain materials. This led to two predictions:

1) the transport of fine particles should increase in Watershed 55 (WS 55) in the absence of leaf litter; and
2) the organic fraction of the particles transported in Watershed 55 (WS 55) should eventually decrease due to the lack of FPOM processed from leaf litter.

STUDY SITE

My studies were conducted in two first-order streams at Coweeta Hydrologic Laboratory, a Forest Service facility in the Appalachian Mountains of southwestern North Carolina, USA. Satellite Branch, which drains Watershed 55 (WS 55), has been covered with netting since August 1993. The netting excludes 95% of the litter that would otherwise enter the stream channel (Wallace *et al*. 1997b). It extends from the headwater spring to a gauging site 175 m downstream. In September 1996, the exclusion study was carried a step further when all small woody debris (< 10 cm) was removed from the channel.

Bee Tree Branch, draining Watershed 53 (WS 53), has been relatively undisturbed for 60 years, except for a 1980-1982 invertebrate manipulation study in which the insecticide methoxychlor was used (Wallace *et al*. 1982). Physical characteristics of the catchments are similar (Table 1). Both catchments are forested, and the dominant trees are typical of the southern Appalachian Mountains: tulip poplar (*Liriodendron tulipifera*, L.), chestnut oak (*Quercus montana*, Willd.), beech (*Fagus grandifolia*, Ehrh.), white oak (*Quercus alba*, L.), and red maple (*Acer rubrum*, L.). Rhododendron (*Rhododendron maxima*, L.) forms a dense riparian understory, which shades most of the streams year-round (Wallace *et al*. 1993). Both streams are gauged with H-flumes, and stage-recorders operate continuously.

Table 1. Physical characteristics of the study sites (after Wallace *et al.* 1991, Wallace *et al*. 1997a).

	WS 55 (Litter-excluded stream)	WS 53 (Reference stream)
Catchment Area (ha)	7.5	5.2
Elevation (m asl)	810	820
Gradient (cm/m)	20	27
Length (m)	175	145
Bankfull Area (m^2)	373	327
Discharge Range (L/sec)	0.05 - 46.9	0.14 - 30.3
Temperature Range(°C)	1.6 - 19.5	0.8 - 19.5

METHODS

Field Sampling

Because the majority of particle transport occurs during periods of high discharge (e.g. Borman *et al*. 1969), field sampling was carried out over a two-year period during storms occurring in all seasons. Seasonality was important because the amount of available organic matter in the stream is not constant throughout the year. Also, summer storms are often brief, intense, and highly localized; while winter storms are generally widespread in area, less intense, and of longer duration. These seasonal differences produce dissimilar storm hydrographs.

Seston concentrations during storms were sampled on the litter-excluded stream (WS 55) and the reference stream (WS 53) simultaneously. Seston was collected using ISCO Model 2100 automated water samplers with the intake hoses positioned in plastic troughs placed below the H-flumes permanently installed on each stream. Leaf litter-excluded samples were taken during seven storms between March 1994 and November 1995. Four additional sets of storm data were taken between September and November 1996, after woody debris < 10 cm diameter was removed from the channel on 31 August - 1 September 1996. Pre-exclusion storm sampling on these two streams was carried out in the late 1980's as part of another study (J.R.Webster, VA Tech, unpub).

The samplers were turned on manually and background samples taken when rain appeared imminent. The frequency of sampling changed over the storm hydrograph (Figure 1). At the onset of rain, the autosamplers were programmed to take samples at 10 or 15 minute intervals, depending on rainfall intensity. After rainfall ceased, samples were taken less frequently on the falling limb of the hydrograph. Sampling was discontinued when discharge approached pre-storm levels.

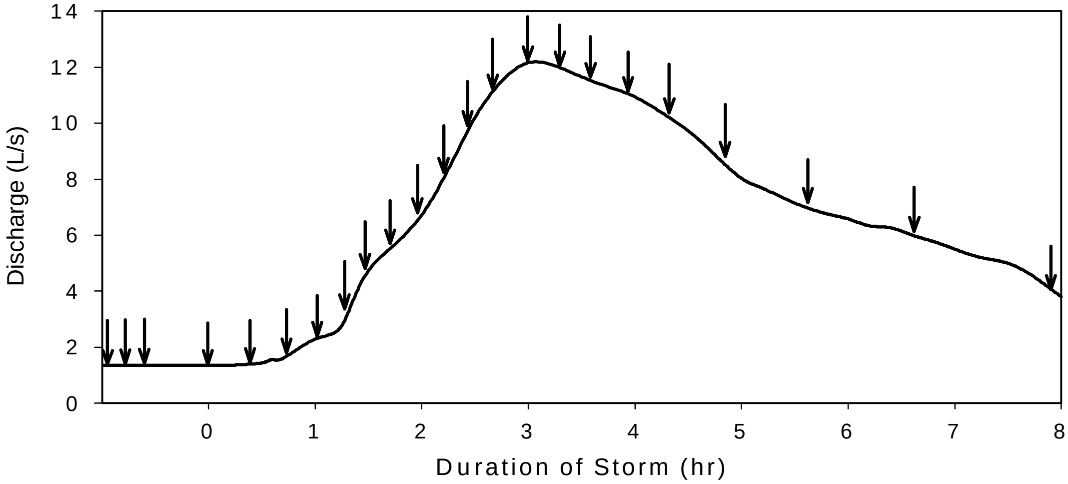

Figure 1. Frequency of sampling over storm hydrograph. Arrows indicate times of sample collection over the course of the storm.

The approximately 1-L water samples were returned to the laboratory, measured to the nearest half milliliter, and filtered onto ashed and weighed glass fiber filters (Gelman Type AE). The samples were oven-dried (>48 h), desiccated, weighed, ashed (20 min at 550°C), rewetted to restore water of hydration, and again oven-dried (>48 h), desiccated, and weighed. Fine particulate organic (FPOM) concentration was calculated as weight loss on ashing.

The Transport Model

A computer model of the litter-excluded stream (WS 55), patterned after several existing stream models (Webster 1983 and unpub), was written in FORTRAN (Appendix I). In the model, the mean velocity of a unit of FPOM was equivalent to the instantaneous discharge (Bagnold 1966). The program modeled the concentration of FPOM during the rising hydrograph of a storm by increasing the concentration according to the rate of change of discharge by means of a regression equation. The model was calibrated using data collected during nine storms on WS 55 prior to leaf litter exclusion. The value for the FBOM concentration at the start of each storm simulation was obtained from benthic organic matter samples from the closest routine sampling date prior to each storm (Wallace, unpub). Entrainment rates and deposition rates were determined by iteration and matching of simulated FPOM concentrations to the concentrations measured during each of the pre-exclusion storms. The seven post-litter exclusion storms and four post-wood removal storms were then simulated using the entrainment and deposition rates determined for pre-exclusion storms similar in season and discharge.

Physical Variables

Geomorphic variables were based on empirical equations relating gradient, stream channel width, and streamflow to stream distance. Elevation of the mainstream channel was measured every five meters. Logarithms of slope were regressed on stream distance (r^2=0.97 , n=36), and the derivative of that line produced the equation for gradient:

$$G = (0.000292) * (852.80)^{-0.00292X} \qquad (2.)$$

where G is stream gradient (m/m) and X is stream distance (m) measured from the headwaters.

Measurements of bankfull channel width (BFW, in m) were made every 5 m along the stream. Each measurement was read into the model and distances between measurements were calculated by linear interpolation.

In order to widen the wetted width of the stream as discharge increased, a linear equation was developed correlating discharge to BFW. Wet width values measured during 1995 hydraulic tracer studies were expressed as the percentage of the BFW at that location. BFW was estimated to occur at the flood magnitude that occurs in two years out of three (Allan 1995), so after ln-transforming the dependent variables, the data were fitted to a linear equation that reached 100% BFW at a discharge (Q_{max}) of 25 L/s. The value of 25 L/sec was selected from 1985 - 91 maximum daily discharge data provided by Wallace (unpub). The best fit (r^2=0.98, n=5) equation was:

$$\ln(\%BFW) = 0.0363936\,(Q) - 0.91624 \qquad (3.)$$

where Q = discharge in L/s.

An equation relating streamflow to stream distance was obtained by digitizing a topographical map to determine the watershed area above the stream's source and the total watershed area above the flume at the bottom of the study reach. The discharge measured at the flume was then multiplied by the proportion of watershed area above the source in order to estimate a value for discharge at the source. Streamflow was then increased exponentially over distance downstream according to Equation 4:

$$Q = \left(0.19 * QWEIR\right)^{0.0095\,X} \qquad (4.)$$

where *Q* is discharge (L/s) at distance *X* (m), and *QWEIR* is the measured discharge at the flume (L/s).

Velocity and mean depth were calculated from the above equations using the Manning and flow continuity equations. The Manning equation,

$$Q = \frac{1}{n} A R^{2/3} S^{1/2} \qquad (5.)$$

was rearranged as:

$$Depth = \frac{Q / 1000 * n}{\left(Width * S^{1/2}\right)^{2/3}} \qquad (6.)$$

where Q = discharge (m^3/s), n = "Manning's n", A = cross-sectional area (width times depth) of the flow (m^2), R = hydraulic radius (m), and S = slope.

The roughness coefficient (Manning's n) was determined from hydraulic tracer studies carried out in 1991 (Webster, unpub):

$$n = 2.0784^{-0.000534X} \tag{7.}$$

where X is stream distance (m).

Velocity was then calculated from the flow continuity equation:

$$V = Q/A \tag{8.}$$

where V = velocity, Q = discharge, and A = cross-sectional Area.

Calculated velocity was verified by comparison with that measured from a conservative tracer (chloride) study in WS 55 in May 1995 (Webster, unpub), using the equation:

$$\text{Velocity} = \text{reach length} / T_n, \tag{9.}$$

where T_n (Nominal Transport Time) was the time for ½ of the released solute to pass the downstream end of the reach (Triska *et al*. 1989).

The calculated mean depth of the channel was also validated against mean depth surveyed during the May 1995 hydraulic tracer study.

Entrainment and Deposition of FPOM

Several equations were needed to model the concentration of FPOM in transport. The amount of FPOM in transport at a point is equal to the water column concentration at the stream source plus entrained FPOM, minus deposited FPOM. Concentrations of particulate organic matter in soil water and springs were extremely low (Webster and Golladay 1984, Golladay *et al*. 1987) so the concentration at the stream source was fixed at a constant 0.8 mg/L. Equations for entrainment and deposition were derived from collected data.

The FPOM entrainment equation was based on storm data collected from 1986 to 1989 (Webster, unpub). Using data from a typical storm, an equation was fitted to the line produced by plotting FPOM concentration against the rate of change of discharge (Figure

2). FPOM increased with the rate of change of Q up to a maximum concentration of 400 mg/L, which was the highest concentration recorded in the stream during the study period. If the concentration increased to a point where it was greater than or equal to the maximum concentration of 400 mg/L, the entrainment rate became zero. Otherwise, fine particle entrainment was the entrainment rate times the deficit (maximum minus actual concentration) if there was enough FPOM available on the benthos. If this entrainment over the next ten minutes would have depleted storage, then the entrainment rate was just what it took to deplete storage over the next ten minutes. The entrainment rates (min^{-1}) used to calibrate the model were obtained by fitting the measured and simulated FPOM concentrations for each storm by iteration and comparison of the graphed data.

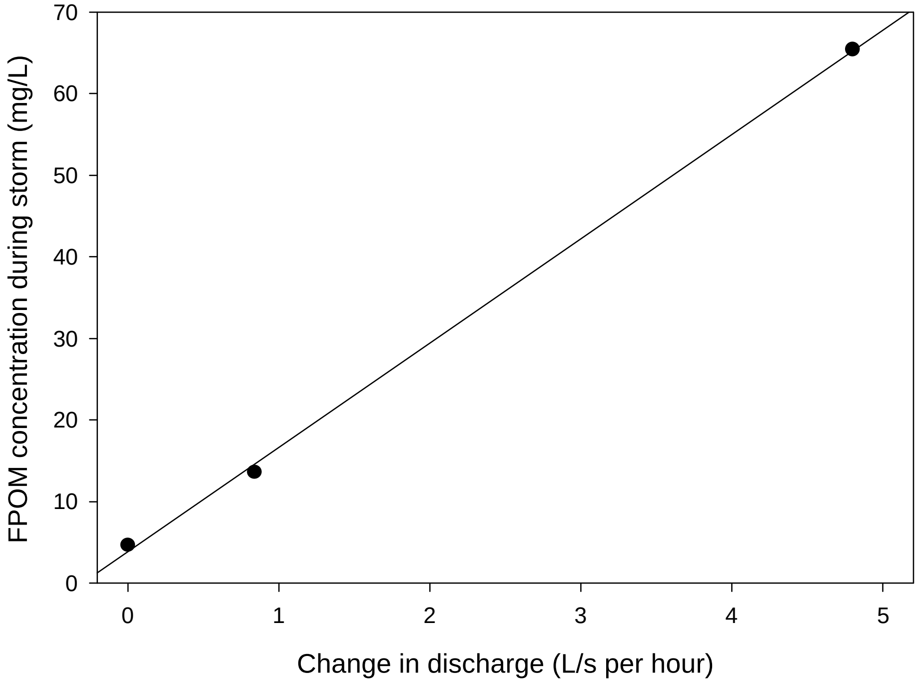

Figure 2. Regression of FPOM concentration and change in discharge per hour for a typical storm. The equation is y = 12.79x + 3.88, $r^2 = 0.99$, where y is FPOM and x is change in Q. The rate was calculated from discharge measured at five-min intervals and converted to an hourly rate.

The travel time of fine particles is equal to half the water depth divided by the particle deposition velocity. Deposition velocity (m/min) was adjusted by iteration to fit the data for each pre-exclusion storm. The deposition subroutine read the water depth at distance and calculated travel time. The deposition rate was equal to the inverse of travel time and this rate was used in the following transport equations.

Transport Equations

To model FPOM in transport (F_T), I used a partial differential equation with two variables, distance (X) and time (t):

$$\frac{\partial F_T}{\partial t} = -\frac{\partial QF_T}{\partial X} + E_F - D_F \tag{10.}$$

where E_F is the entrainment of fine particles and D_F is the deposition of fine particles.

This equation was converted to an ordinary differential equation by assuming that transport occurs at the velocity of water, so that distance = velocity x time (e.g. Webster 1983). The resultant equation was then solved using the Runge-Kutta technique for numerical integration with a time step of 0.01 min. The time between each downstream run was 10 minutes. The entrainment of FPOM was limited so that benthic FPOM was not exceeded during an integration interval.

Because benthic FPOM (F_B) was not moving, a partial differential equation was not applicable. For this parameter, it was necessary to model the downstream change in standing crop by partitioning the streambed into a series of benthic compartments within which there was no change with distance. The 175-m reach was divided into 10 benthic boxes, each with a differential equation:

$$\frac{dF_B}{dt} = F_B - E_F + D_F \tag{11.}$$

where E_F is fine particle entrainment and D_F is fine particle deposition. The equation is solved by Euler integration between each downstream run. The benthic compartments are updated between runs using average exchange rates over the distance of the benthic compartment.

RESULTS

Field Data

Sampling from one manipulated stream presented statistical problems because the data sets were pseudoreplications in time (Hurlbert 1984). This issue is common to ecosystem-level studies because manipulation of multiple streams is not economically feasible. I used a BACI design to analyse my data, which detects disturbance effects by testing whether differences between a particular measure at a control site and an impact site change once the disturbance begins (Stewart-Oaten *et al.* 1986). According to Stewart-Oaten *et al.* (1986), the pseudoreplication problems raised by Hurbert (1984) can be overcome by taking samples, replicated in time, Before the disturbance begins and After it has begun, at both the Control and Impact sites (hence the term, BACI).

Samples collected at both baseflow and stormflow from the litter-excluded stream before and after litter-exclusion were compared with samples collected from the reference stream at the same times (Table 2). Means of from one to three samples at baseflow and the one to five samples having the highest values during peak stormflow were used in all comparisons. I used paired t-tests to compare samples collected from the two streams at the same time, and t-tests assuming unequal variances to test samples collected from the same stream before and after litter-exclusion.

Total Particle Concentration

The concentrations of total (organic + inorganic) particles suspended in the streams were examined at baseflow and during stormflow.

Baseflow concentrations of particles ranged from 2.84 to 28.52 mg/L in the litter-excluded stream before exclusion, from 4.02 to 19.98 mg/L after litter exclusion, and from 3.52 to 30.25 mg/L after wood removal. Concentrations in the reference stream ranged from 1.45 to 16.36 mg/L. Baseflow concentrations after litter exclusion were not significantly different from before-exclusion concentrations or from reference stream concentrations (t-test assuming unequal variances, ln-transformed data). The particle concentrations were not significantly related to discharge, and no seasonal trends were apparent.

Paired t-tests using ln-transformed data were also used to compare the reference stream with the litter-excluded stream. Mean particle concentrations were not significantly different between streams at baseflow or during storms. However, particle concentrations in each stream were higher during storms than at baseflow both before and after litter exclusion ($p<0.0002$).

During storms, total particle concentrations before exclusion increased to between 24.06 and 450.31 mg/L in the litter-excluded stream. In the reference stream, storm concentrations ranged from 17.46 to 303.40 mg/L during the same period. After litter exclusion, storm concentrations in the litter-excluded stream ranged from 29.98 to 1429.01 mg/L and increased to 1365.23 mg/L after wood removal. The comparatively high value of 1429.01 mg/L on 7 August 1995 in the litter-excluded stream occurred during a very localized thunderstorm that was much more intense than in the reference watershed. During the exclusion period, storm concentrations ranged from 15.20 to 525.79 mg/L in the reference stream. Neither the baseflow concentrations of particles nor the storm concentrations (Table 2) in these two streams were significantly different before or after litter exclusion (t- test assuming unequal variances, ln-transformed data). There was no relationship between measured particle concentration and maximum discharge occurring during each storm.

Table 2. Total suspended particle (organic + inorganic) concentrations. Figures shown are means of from one to three samples at baseflow and the one to five samples having the highest concentrations during peak storm discharge.

Date	Litter-excluded Stream Baseflow mg/L ± SE	Litter-excluded Stream Storm mg/L ± SE	Reference Stream Baseflow mg/L ± SE	Reference Stream Storm mg/L ± SE
11Sep 86	9.40 (2.63)	383.64 (218.07)	3.36 (0.86)	238.38 (43.91)
25Jun 87	4.06 (0.56)	343.25 (35.63)	1.45 (0.37)	303.40 (84.89)
3Mar 88	2.84 (0.50)	53.20	4.85 (1.49)	36.18
13Jul 88	9.45 (1.09)	450.31 (159.62)	13.78 (4.72)	260.99 (138.02)
21Jul 88	28.52 (7.38)	307.34 (6.69)	10.61 (1.13)	102.22 (13.03)
6Jan 89	5.25 (1.46)	38.95 (4.50)	11.65 (8.22)	27.10 (1.52)
18Mar 89	3.53 (0.05)	24.06 (1.62)	2.86	17.46 (5.46)
12Jun 89	10.32 (0.96)	62.50 (18.25)	2.93	67.41 (11.52)
1Aug 89	16.61 (3.07)	43.29 (2.56)	6.59 (0.89)	38.99 (10.85)
litter exclusion				
9Mar 94	19.98 (6.41)	112.25 (16.96)	5.59 (0.56)	66.56 (0.36)
20Nov 94	8.36 (2.42)	38.78 (7.33)	6.19 (0.46)	72.75 (12.84)
27Jan 95	4.02 (0.59)	29.98 (2.88)	2.35 (0.27)	15.20 (2.53)
21Jun 95	7.83	238.23	8.21 (0.78)	58.55 (12.34)
26Jul 95	6.07 (1.03)	45.94 (13.36)	--	36.02
7Aug 95	7.26	1429.01 (168.21)	16.04	456.97 (52.87)
11Nov 95	9.02 (2.01)	181.47 (5.89)	7.44 (1.48)	145.55 (13.83)
wood removal				
2Sep 96	6.07 (1.15)	19.95 (3.48)	16.36 (3.21)	69.35 (1.65)
3Sep 96	3.52 (0.41)	275.66 (71.87)	5.67 (0.16)	281.47 (8.85)
28Sep 96	30.25 (0.56)	1365.23 (101.34)	10.96 (0.74)	525.79 (159.82)
7Nov 96	10.79 (1.79)	1329.26 (374.24)	7.36 (0.82)	347.24 (165.40)

Organic Particle Concentrations

Like total particle concentrations, the concentrations of fine particulate organic material (FPOM) at baseflow were also highly variable (Table 3). Litter-excluded stream concentrations of FPOM were generally low, ranging from 1.46 to 10.78 mg/L prior to exclusion, from 1.34 to 6.51 mg/L after exclusion, and reached 13.70 mg/L after wood removal, while those of the reference stream ranged from 1.15 to 10.88 mg/L during the same periods. Storm FPOM concentrations in the litter-excluded stream ranged from 8.92 to 158.01 mg/L before exclusion, 7.66 to 369.51 mg/L after litter exclusion, and reached 389.42 mg/L after wood removal. Storm FPOM concentrations in the reference stream ranged between 6.93 and 231.67 mg/L during the study period. Although baseflow concentrations of FPOM were lower than storm concentrations in each stream ($p<0.0001$, paired t-tests, ln-transformed data), there was no significant difference among streams before or after litter exclusion.

Table 3. Organic particle concentrations in the litter-excluded and reference streams. Figures shown are means of from one to three samples at baseflow and the one to five samples having the highest concentrations during peak storm discharge.

	Litter-excluded Stream		**Reference Stream**	
Date	Baseflow mg/L ± SE	Storm mg/L ± SE	Baseflow mg/L ± SE	Storm mg/L ± SE
11Sep 86	4.22 (1.07)	158.01 (86.04)	2.45 (0.58)	156.99 (28.84)
25Jun 87	1.69 (0.19)	110.48 (11.51)	1.15 (0.13)	188.60 (54.69)
3Mar 88	1.46 (0.37)	19.30	1.30 (0.32)	19.14
13Jul 88	2.90 (0.65)	138.66 (28.71)	7.87 (3.17	147.77 (80.49)
21Jul 88	10.78 (2.29)	133.92 (8.83)	5.18 (0.47)	60.94 (8.26)
6Jan 89	3.09 (1.46)	17.10 (0.78)	5.10 (3.21)	16.91 (0.98)
18Mar 89	1.96 (0.00)	8.92 (0.21)	2.55	10.67 (2.90)
12Jun 89	4.44 (0.55)	21.01 (6.21)	1.99	40.28 (6.01)
1Aug 89	7.03 (2.34)	14.76 (1.54)	2.22 (0.23)	22.66 (6.47)
litter exclusion				
9Mar 94	2.37 (0.33)	16.62 (4.18)	2.42 (0.23)	32.93 (17.39)
20Nov 94	6.51 (2.06)	14.30 (2.00)	2.73 (0.77)	34.25 (6.32)
27Jan 95	1.34 (0.20)	7.66 (1.08)	1.32 (0.13)	6.93 (1.11)
21Jun 95	3.49	101.67	3.60 (0.37)	28.12 (2.98)
26Jul 95	3.55 (0.85)	28.84 (10.42)	--	18.19
7Aug 95	3.71	369.51 (25.84)	2.79	231.67 (18.97)
11Nov 95	3.82 (0.94)	37.35 (0.39)	4.47 (0.97)	60.66 (8.83)
wood removal				
2Sep 96	2.81 (0.34)	8.65 (1.44)	10.78 (2.21)	36.59 (0.31)
3Sep 96	2.45 (0.34)	114.74 (19.75)	3.59 (0.09)	133.17 (0.55)
28Sep 96	13.70 (3.09)	193.79 (96.92)	6.05 (0.18)	185.22 (70.28)
7Nov 96	8.43 (1.40)	389.42 (112.85)	3.43 (0.55)	132.90 (57.08)

Inorganic Particle Concentrations

The concentrations of fine particulate inorganic material (FPIM) at baseflow were also highly variable (Table 4). Concentrations ranged from 1.38 to 17.74 mg/L in the litter-excluded stream and 0.30 to 6.55 mg/L in the reference stream before exclusion. During this study, inorganic particle concentrations at baseflow ranged from 1.85 to 17.61 mg/L in the litter-excluded stream and from 1.03 to 13.25 mg/L in the reference stream. The storm FPIM concentrations before litter exclusion ranged from 15.14 to 311.65 mg/L in the litter-excluded stream. After litter exclusion, storm inorganic concentrations ranged from 17.10 to 1059.49 mg/L in the litter excluded stream. Like the total particle concentration, the unusually high value of 1059.49 mg/L in the litter-excluded stream was due to the very intense storm on 7 August 1995. After wood removal, the storm FPIM concentration ranged between 11.30 to 1171.44 mg/L. The storm concentration of FPIM in the reference stream ranged from 6.79 to 340.57 mg/L during the study. Baseflow concentrations of FPIM were lower than storm concentrations in each stream ($p < 0.001$, paired t-tests, ln-transformed data). Among streams, FPIM concentrations at baseflow were significantly lower in the reference stream than in the litter-excluded stream before litter exclusion, but not after exclusion ($p=0.04$, paired t-test, ln-transformed data). FPIM concentrations during storms were always lower in the reference stream than in the litter-excluded stream ($p<0.02$, paired t-tests, ln-transformed data).

Table 4. Inorganic particle concentrations in the litter-excluded and reference streams. Figures shown are means of from one to three samples at baseflow and the one to five samples having the highest concentrations during peak storm discharge.

Date	**Litter-excluded Stream**		**Reference Stream**	
	Baseflow mg/L ± SE	**Storm mg/L ± SE**	**Baseflow mg/L ± SE**	**Storm mg/L ± SE**
11Sep 86	5.18 (1.58)	225.63 (132.14)	0.90 (0.28)	81.39 (15.07)
25Jun 87	2.37 (0.37)	232.78 (28.11)	0.30 (0.25)	114.80 (30.20)
3Mar 88	1.38 (0.19)	33.90	3.55 (1.17)	17.04
13Jul 88	6.55 (0.44)	311.65 (163.43)	5.92 (1.56)	113.22 (57.53)
21Jul 88	17.74 (5.09)	173.42 (2.13)	5.43 (0.71)	41.28 (4.76)
6Jan 89	2.16	21.85 (3.76)	6.55 (5.01)	10.19 (0.54)
18Mar 89	1.57 (0.06)	15.14 (1.41)	0.31	6.79 (2.56)
12Jun 89	5.88 (0.55)	41.49 (12.07)	0.94	27.13 (5.53)
1Aug 89	9.58 (0.73)	28.53 (1.06)	4.37 (0.77)	16.34 (4.37)
litter exclusion				
9Mar 94	17.61 (6.35)	95.63 (20.79)	3.17 (0.15)	33.63 (17.75)
20Nov 94	1.85 (0.37)	24.49 (5.42)	3.45 (0.38)	38.50 (6.73)
27Jan 95	2.70 (0.60)	22.32 (1.80)	1.03 (0.14)	8.27 (1.43)
21Jun 95	4.34	136.56	4.61 (0.45)	30.43 (9.89)
26Jul 95	2.52 (0.19)	17.10 (2.93)	--	17.84
7Aug 95	3.54	1059.49 (145.88)	13.25	225.31 (39.67)
11Nov 95	5.21 (1.37)	144.12 (5.98)	2.97 (0.53)	84.89 (20.57)
wood removal				
2Sep 96	3.26 (0.81)	11.30 (2.04)	5.58 (1.03)	32.76 (1.96)
3Sep 96	1.07 (0.15)	160.92 (52.12)	2.08 (0.07)	148.30 (9.40)
28Sep 96	16.55 (2.53)	1171.44 (4.43)	4.90 (0.55)	340.57 (89.79)
7Nov 96	2.36 (0.40)	939.85 (261.39)	3.93 (0.53)	214.34 (108.44)

Particle Composition

Before litter exclusion, %FPOM in each sample at baseflow ranged between 33.7% and 56.0% in the litter-excluded stream and from 27.9 to 83.0% in the reference stream (Table 5). After exclusion, baseflow %FPOM ranged from 14.4 to 55.8% in the litter-excluded stream and 42.9 to 59.7% in the reference stream. After wood removal, baseflow %FPOM increased to as high as 78.2% in the litter-excluded stream. Baseflow %FPOM was significantly higher in the reference stream than in the litter-excluded stream when all sampling dates were analyzed together ($p<0.03$, paired t-test, arcsine-transformed data). It appears that FPOM in the litter-excluded stream, WS 55, before litter exclusion was generally higher than in the reference stream, WS 53. Wallace *et al*. (1991), in an invertebrate manipulation study using WS 55 as a reference, also reported that average instantaneous FPOM concentrations were higher in WS 55 than in WS 53. These results suggest that litter exclusion reduced the surficial FPOM available, and thus reduced the %FPOM transported during baseflow in the litter-excluded stream, which made the values more similar to those of the reference stream.

During storms, the proportion of organic matter in transported particles decreased compared to that at baseflow (Table 5). Storm %FPOM ranged from 21.8 to 73.6% in the reference stream and from 5.0 to 73.4% in the litter-excluded stream. For all sampling dates combined, the storm %FPOM in each stream was significantly lower than the baseflow %FPOM ($p<0.0007$, paired t-test, arcsine-transformed data). When the storm data were separated into pre-treatment and post-treatment sets in each stream, the storm %FPOM was lower than baseflow %FPOM in the litter-excluded stream before exclusion ($p=0.0003$, paired t-test, arcsine-transformed data) and in both streams after litter-exclusion ($p<0.007$, paired t-tests, arcsine-transformed data).

Table 5. Fine particulate organic matter, FPOM, in the litter-excluded and reference streams, expressed as percentage of total particles. Figures shown are means of from one to three samples at baseflow and the one to three samples having the highest values during peak storm discharge.

Date	**Litter-excluded Stream**		**Reference Stream**	
	Baseflow % ± SE	**Storm % ± SE**	**Baseflow % ± SE**	**Storm % ± SE**
11Sep 86	46.17 (1.37)	40.27 (0.23)	72.35 (1.38)	58.63 (4.73)
25Jun 87	41.65 (1.15)	25.22 (1.67)	82.99 (9.80)	58.18 (1.37)
3Mar 88	50.51 (5.70)	36.67 (0.41)	27.86 (1.68)	56.56 (2.03)
13Jul 88	33.72 (3.93)	25.39 (5.27)	54.92 (3.26)	45.51 (2.52)
21Jul 88	38.65 (1.15)	33.61 (0.33)	49.04 (1.83)	42.00 (2.06)
6Jan 89	56.01 (13.09)	37.35 (0.78)	48.50 (6.71)	50.09 (1.83)
18Mar 89	54.72 (1.06)	37.24 (0.84)	79.01 (7.87)	61.25 (1.76)
12Jun 89	42.86 (3.01)	30.66 (1.59)	71.22 (2.67)	54.18 (2.58)
1Aug 89	40.45 (3.81)	28.00 (1.26)	34.49 (4.29)	23.41 (6.21)
litter exclusion				
9Mar 94	14.40 (5.28)	5.01 (0.68)	42.92 (3.13)	29.33 (3.48)
20Nov 94	55.81 (0.00)	33.68 (1.27)	42.96 (9.83)	44.22 (0.31)
27Jan 95	29.82 (3.84)	15.65 (0.60)	55.83 (1.61)	42.02 (1.06)
21Jun 95	43.71 (1.60)	33.56 (0.91)	47.37 (3.78)	39.88 (1.14)
26Jul 95	57.75 (4.10)	73.40 (90.76)	N/A	73.57 (4.22)
7Aug 95	51.17 (0.00)	2.40 (0.06)	59.10 (0.00)	34.67 (1.22)
11Nov 95	42.34 (5.45)	6.67 (0.15)	59.69 (1.46)	21.80 (1.71)
wood removal				
2Sep 96	47.85 (4.14)	43.29 (0.52)	65.76 (1.26)	53.00 (1.50)
3Sep 96	69.59 (3.55)	43.33 (2.38)	63.27 (0.26)	51.49 (2.33)
28Sep 96	41.76 (6.39)	36.16 (8.17)	54.02 (1.80)	36.64 (1.09)
7Nov 96	78.18 (0.06)	29.22 (0.26)	46.48 (4.31)	37.34 (0.84)

Storm %FPOM was significantly different between the two streams both before and after exclusion of leaf litter only ($p=0.00$, t-test assuming unequal variances, arcsine-transformed data) and after wood removal in September 1996 ($p<0.0008$, paired t-tests, arcsine-transformed data). Prior to litter exclusion, storm %FPOM ranged from 25.2 to 40.3% in the litter-excluded stream while that of the reference stream ranged from 23.4 to 61.3%. The %FPOM in the litter-excluded stream was significantly lower than in the reference stream when both pre- and post-exclusion dates were analyzed together ($p=0.0001$, paired t-test, arcsine-transformed data). When separated into before and after litter-exclusion sets however, the %FPOM in the litter-excluded stream was lower than in the reference stream both before and after exclusion ($p<0.003$, paired t-tests, arcsine-transformed data). It is noteworthy that particles transported in the litter-excluded stream during the last two litter-excluded storms sampled in 1995, which was prior to wood removal, had a much lower %FPOM than previous storms ($p=0.0004$). This suggested depletion of benthic standing stock of FPOM due to washout (e.g. Bilby and Likens, 1980).

The very high %FPOM recorded during the July 1995 storm was an anomaly. The storm was of very low intensity and short duration, and I believe that the majority of the organic material transported was not of benthic origin. Rather, the material was likely from throughfall, which I did not measure. Golladay *et al.* (1987) reported substantial throughfall amounts from 0.21 to 0.36 g/m^2 during low-intensity storms, with the importance of throughfall OM conversely proportional to storm intensity. They found that during storms of low intensity, as much as 83% of the organic matter exported was potentially contributed by throughfall, while during intense or long storms less than 20% of exported material was potentially washed from the forest canopy.

Storm Export

Storm exports were calculated by trapezoidal integration of the product of total particle concentration and discharge over the duration of each storm (Table 6). These calculated loads of fine particles transported during storms were highly variable, most likely due to differences in pre-storm stream conditions, time since the previous storm, rainfall intensity, and storm duration (e.g. Verhoff *et al.* 1979, Bilby and Likens 1980, Golladay *et al.* 1987).

Table 6. Total particle loads exported during storms, calculated by trapezoidal integration of the product of concentration and discharge over the duration of the storm.

Date	**Litter-excluded Stream(g)**	**Reference Stream (g)**
11Sep 86	1,534	1,322
25Jun 87	4,923	2,076
3Mar 88	1,421	711
13Jul 88	1,246	389
21Jul 88	1,451	385
6Jan 89	5,450	2,611
18Mar 89	2,999	1,424
12Jun 89	1,925	3,215
1Aug 89	1,360	1,025
litter exclusion		
9Mar 94	1,301	345
20Nov 94	742	961
27Jan 95	2078	897
21Jun 95	327	129
26Jul 95	632	--
7Aug 95	79,408	3,443
11Nov 95	7,771	1,867
wood removal		
2Sep 96	508	801
3Sep 96	1196	2,192
28Sep 96	642,964	52,467
7Nov 96	19,412	3,638

To allow for slight size differences between streams, total particle exports during storms were divided by watershed area because the two streams do not drain precisely the same size catchments. Particle export was significantly higher in the litter-excluded stream when all dates were analyzed together (p=0.02), but there were no significant differences before and after exclusion (paired t-tests of ln-transformed data).

Regressions of the particle loads against the maximum discharge measured during each storm were not statistically significant.

Storm loads of transported FPOM were also calculated by trapezoidal integration of the product of FPOM concentration and discharge over the duration of the storm (Figure 7). There were no significant differences in the FPOM loads transported during storms in the two streams before or after litter exclusion and wood removal (t-tests assuming unequal variances, ln-transformed data).

Table 7. Total storm export of FPOM, calculated by trapezoidal integration of the product of FPOM concentration and discharge over the duration of the storm.

Date	**Litter-excluded Stream (g)**	**Reference Stream (g)**
11Sep 86	639	859
25Jun 87	1,765	1,343
3Mar 88	579	437
13Jul 88	570	217
21Jul 88	623	212
6Jan 89	2,326	1,563
18Mar 89	1,303	990
12Jun 89	681	1,957
1Aug 89	474	535
litter exclusion		
9Mar 94	254	208
20Nov 94	307	479
27Jan 95	550	443
21Jun 95	146	60
26Jul 95	888	--
7Aug 95	12,655	1,722
11Nov 95	1,441	766
wood removal		
2Sep 96	232	423
3Sep 96	524	1,009
28Sep 96	52,173	20,556
7Nov 96	5,954	2,254

The average concentrations of FPOM transported, calculated as FPOM load/total storm discharge, were not statistically different before or after litter exclusion and wood removal, due to the high variability among storms (Figure 3). The ratios of reference stream FPOM to litter-excluded stream FPOM transported during each storm also were not significantly different after litter exclusion.

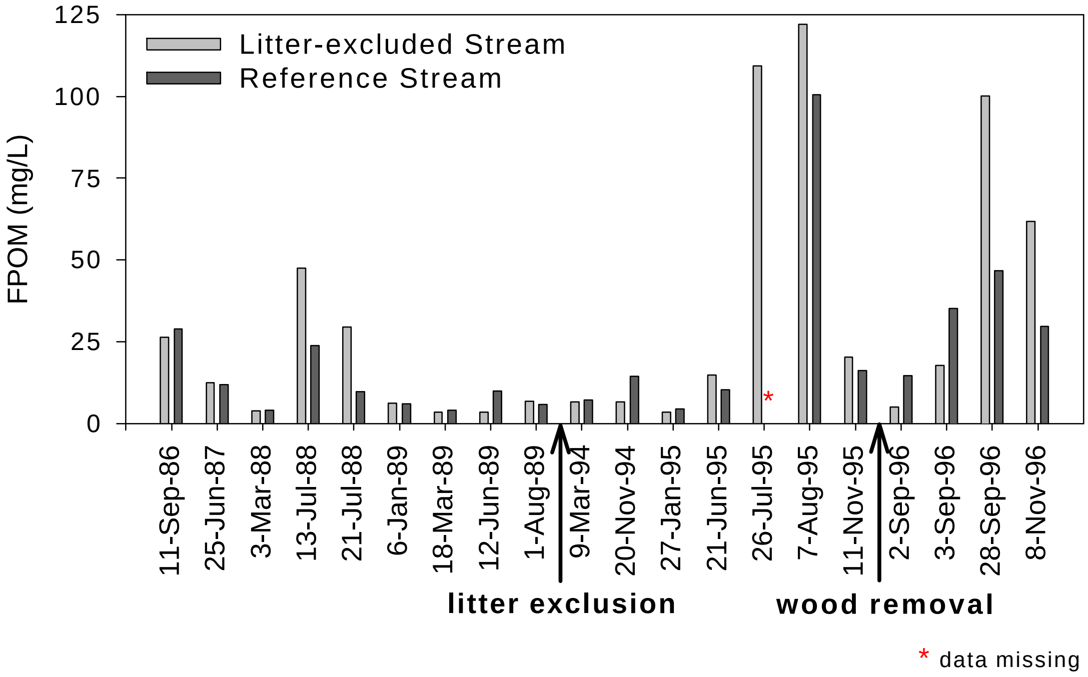

Figure 3. Average FPOM concentration in transport, calculated as FPOM load/total storm discharge.

Average seston concentrations in transport during storms, calculated as total seston exported/total storm discharge (Table 8) were significantly higher in the litter-excluded stream after exclusion than the reference stream (p=0.05, one-tailed t-test assuming unequal variances).

Table 8. Average seston concentrations in transport during storms, calculated as total seston exported/total storm discharge.

Date	**Litter-Excluded Stream**	**Reference Stream**
11Sep 86	63.13	44.54
25Jun 87	34.76	18.22
3Mar 88	9.41	6.42
13Jul 88	125.84	42.49
21Jul 88	68.48	17.53
6Jan 89	14.34	9.91
18Mar 89	7.81	5.69
12Jun 89	9.76	16.27
1Aug 89	19.20	11.15
9Mar 94	33.07	11.70
20Nov 94	15.62	29.01
27Jan 95	12.97	8.77
21Jun 95	33.07	21.83
26Jul 95	77.94	---
7Aug 95	765.29	200.79
11Nov 95	109.28	39.37
2Sep 96	10.97	27.44
3Sep 96	40.21	76.37
28Sep 96	1233.43	118.98
7Nov 96	201.28	47.92

The Transport Model

Fitting the Parameters

As explained in the Methods Section, the parameters for deposition velocity (V_{dep}) of fine particles and the entrainment rate of fine particles were fitted to the pre-exclusion data by iteration, until a plot of the FPOM concentrations generated by the simulation matched a plot of the field data as closely as possible. These simulations yielded deposition velocity between 0.001 and 0.00001 m/min for all of the pre-exclusion storms. Entrainment rates ranged between 0.00165 and 0.04 min^{-1} (Table 9).

Table 9. Deposition and entrainment parameters from pre-exclusion storm data that were used to calibrate the computer model.

Date	Baseflow discharge (L/s)	Peak storm discharge (L/s)	Fine particle deposition velocity (m/min)	Fine particle entrainment rate (min^{-1})
11 Sep 86	0.3	1.6	0.00001	0.0052
25 Jun 87	2.0	10	0.0016	0.04
3 Mar 88	8.0	10	0.001	0.0037
13 Jul 88	0.5	1.1	0.003*	0.04
20 Jul 88	0.8	1.8	0.002*	0.04
6 Jan 89	4.5	12	0.0001	0.00165
18 Mar 89	15	18	0.00001	0.00185
12 Jun 89	2.5	4.0	0.0001	0.0048
1 Aug 89	5.0	7.0	0.0005	0.003

* avg. of 0.003 and 0.002 used as deposition velocity for July post-exclusion simulations

Model Calibration

Because the model did not precisely match baseflow and peak FPOM concentrations during calibration, parameters were selected that yielded the best fit at the peaks because the majority of FPOM is transported during those periods.

Model predictions vs. post-treatment storm data

Simulations of post-exclusion storms were run using parameters determined from pre-exclusion storm data (Table 9). Where possible, the parameters were fitted using the parameters from the pre-exclusion storm that matched both the month and the discharge closely. The time of year was expected to affect the fitting of the parameters for particle deposition and entrainment, because the amount of available benthic FPOM varies throughout the year. Matching the discharge as close as possible was also necessary, because modeled entrainment is determined by the rate of change in discharge. However, there were several dates where this was not possible, so the simulation was run twice, once matching time of year, and once matching discharge (Table 10). If there was more than one storm that matched both time of year and discharge, the simulation was run using the average parameters (e.g. July 95).

Table 10. Parameters used in FPOM transport simulations. The first column shows post-exclusion storm dates and the second shows pre-exclusion storms most closely matched in season and/or discharge. The third and fourth columns show FPOM deposition and entrainment parameters determined from pre-exclusion data and used in the transport simulations. The final column summarizes the comparisons of post-exclusion empirical FPOM concentrations with those predicted by simulations.

Post-exclusion storm date	Pre-exclusion storm date	Discharge range during storm (L/s)	FPOM deposition velocity (m/min)	FPOM entrainment rate (min^{-1})	Model prediction relative to empirical concentration
9 Mar 94		**2.9 - 6.1**			
	Mar 88	8 - 10	0.001	0.0037	slightly lower
	Mar 89	15 - 18	0.00001	0.00185	slightly higher
20 Nov 94		**0.80 - 1.8**			
	Sep 86	0.3 - 1.6	0.00001	0.0052	higher
	Jun 89	2.5 - 4	0.0001	0.0048	higher
27 Jan 95		**1.8 - 2.9**			
	Jan 89	4.5 - 12	0.0001	0.00165	slightly higher
	Sep 86	0.3 - 1.6	0.00001	0.0052	much higher
21 Jun 95		**0.65 - 0.81**			
	Jun 89	2.5 - 4	0.0001	0.0048	higher, poor fit
	Jul 88	0.5 - 1.1	0.003	0.04	higher, poor fit
26 Jul 95		**0.41 - 0.50**			
	Jun 89	2.5 - 4	0.0001	0.0048	higher
7 Aug 95		**0.49 - 23**			
	Aug 89	5 - 7	0.0005	0.003	lower
	Jun 87	2 - 10	0.0016	0.04	lower
11 Nov 95		**1.4 - 13**			
	Sep 86	0.3 - 1.6	0.00001	0.0052	higher
	Jan 89	4.5 - 12	0.0001	0.00165	lower
2 Sep 96		**0.50 - 0.75**			
	Sep 86	0.3 - 1.6	0.00001	0.0052	higher
3 Sep 96		**0.50 - 2.0**			
	Sep 86	0.3 - 1.6	0.00001	0.0052	higher; damped peaks
28 Sep 96		**2.8 - 16**			
	Sep 86	0.3 - 1.6	0.00001	0.0052	lower
	Jan 89	4.5 - 12	0.0001	0.00165	lower
7-8 Nov 96		**0.70 - 11**			
	Sep 86	0.3 - 1.6	0.00001	0.0052	lower
	Jan 89	4.5 - 12	0.0001	0.00165	much lower

In general, the model predicted higher FPOM concentrations in storms after litter exclusion than were measured except during very heavy rains that greatly increased discharge. The one exception to this was for the first storm sampled after litter exclusion, in March 1994. During this storm, discharge rose from 2.9 to 6.1 L/s. The two pre-exclusion storms in March, 1988 and 1989, differed in discharge and the simulations using these parameters illustrate the effect that discharge has on FPOM concentrations (Figure 4). The March 1988 parameters (simulation 1), which match the 1994 storm increase in Q most closely, predicted slightly lower peak concentrations than the March 1989 parameters that predicted slightly higher concentrations than were measured (simulation 2).

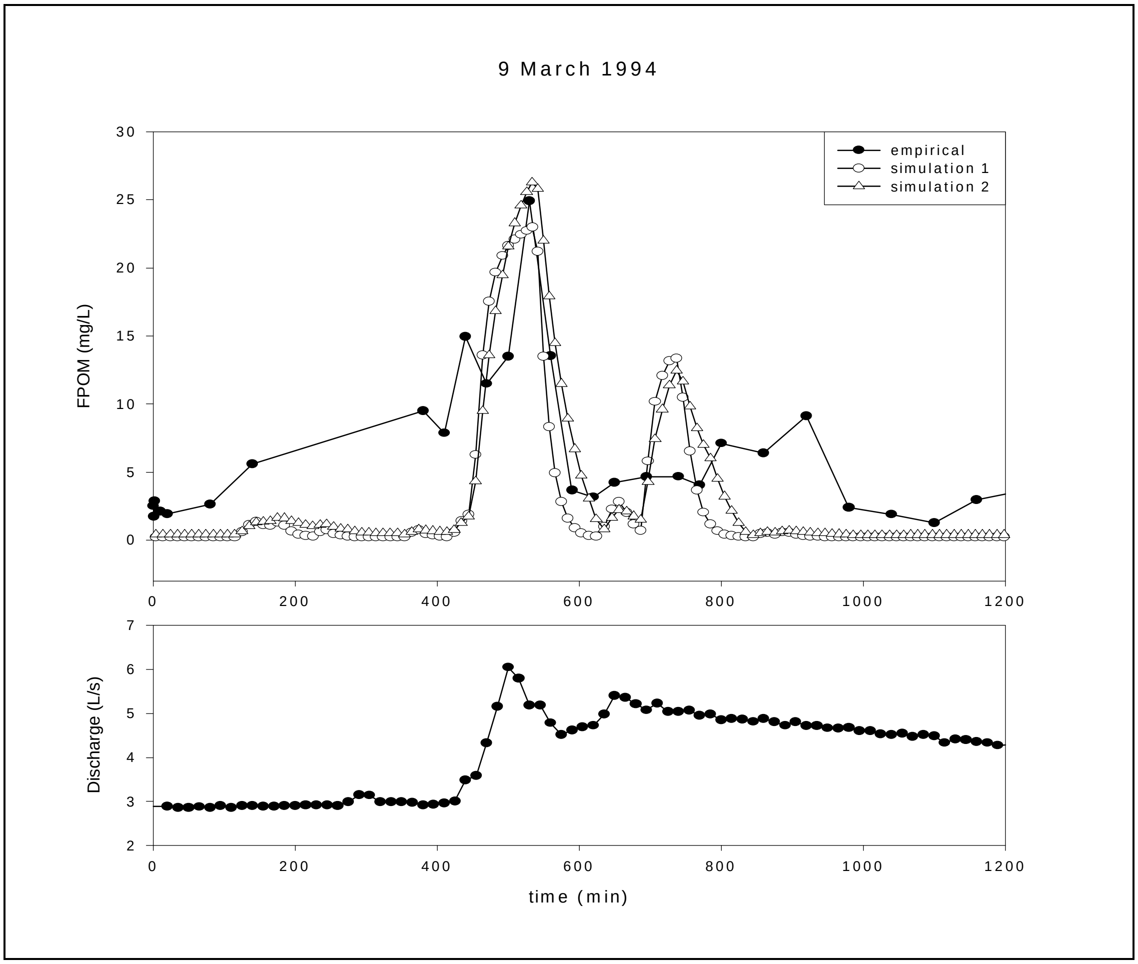

Figure 4. Simulations and empirical data for 9 March 1994. All times are expressed in minutes after an arbitrary time before the onset of the storm.

A drizzle started at approximately 2115h on 20 November 1994 and continued throughout the night as discharge more than doubled from 0.80 to 1.8 L/s and 2.24 cm of rain fell by 0800h the next morning. By 1630h, discharge had dropped close to pre-storm levels and sampling was halted. There were no November pre-exclusion samples, so I matched ΔQ from storms in Sep 86 and Jun 89. Both sets of parameters produced higher simulated concentrations than I actually measured, suggesting that FPOM was less available (Figure 5). This may have been due to seasonal differences in organic matter availability. The September storm would likely have had FPOM available from the beginning of autumn leaf drop, while FPOM export per unit discharge is higher in summer than the rest of the year (Wallace *et al*. 1991).

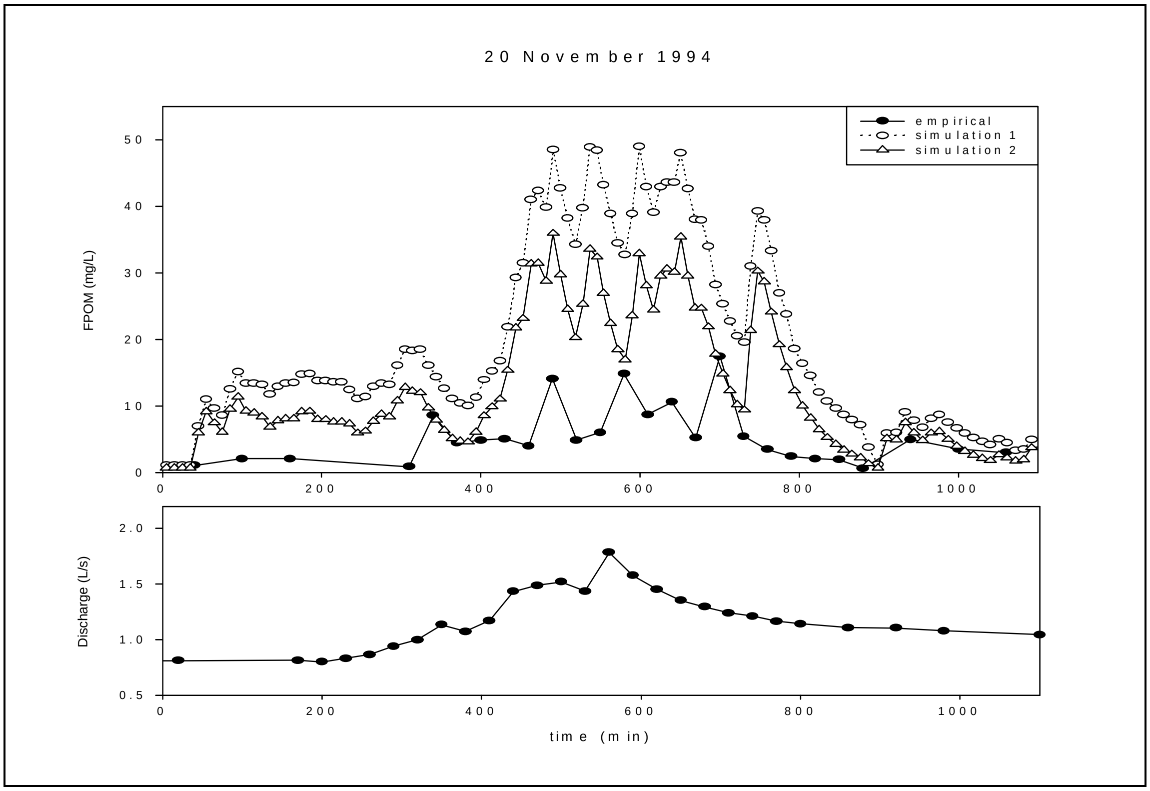

Figure 5. Simulations and empirical data for 20 November 1994.

A steady rain during the night of 27 January 1995 caused discharge to rise from 1.8 to 2.9 L/s. The first simulation for this storm matched time of year by using the Jan 89 parameters, despite Q being much higher in 1989. The simulation fit closely, but was a bit higher. Simulation 2 matched Q more closely, despite parameters being from Sep 86, however the FPOM concentrations predicted by simulation 2 were much higher than measured (Figure 6).

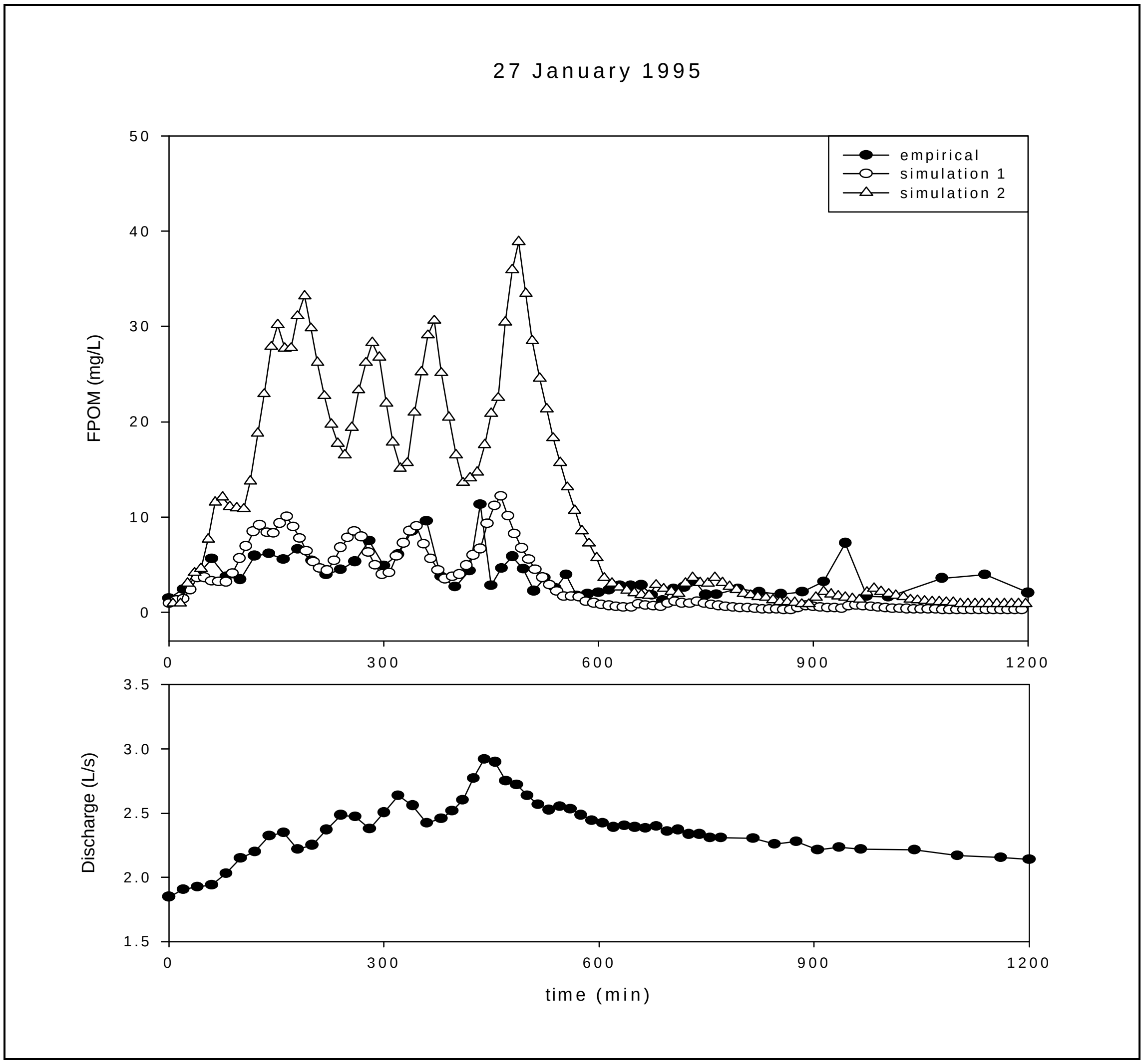

Figure 6. Simulations and empirical data for 27 January 1995.

During a brief thunderstorm on 21 June 1995, seston was sampled over a five-hour period as discharge rose from 0.65 to 0.81 L/s. I matched time of year and ΔQ with two pre-exclusion storms, Jun 89 and Jul 88. Both parameters predicted generally higher FPOM concentrations, although there were higher non-peak and lower peak values (Figure 7).

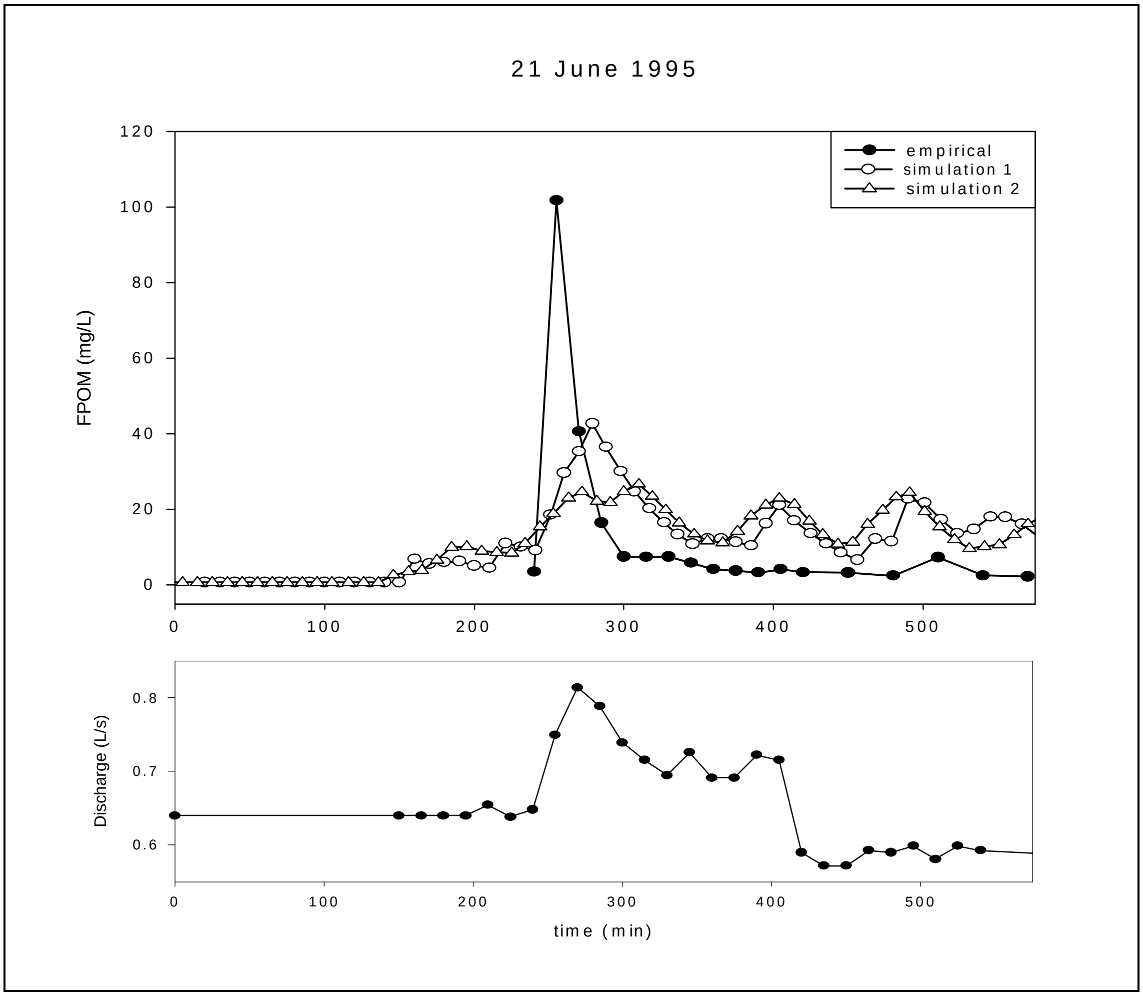

Figure 7. Simulations and empirical data for 21 June 1995.

The 26 July 1995 rainfall was very brief and gentle, with discharge only increasing from 0.41 to 0.50 L/s. I tried two simulations using the Jun 89 and Jul 88 parameters to match the time of year but could not match the discharge, as the July 95 storm was lighter than either 88 or 89. The July 88 parameters resulted in an unstable simulation. The simulation using June 89 parameters predicted higher concentrations than were measured during this storm (Figure 8), likely because the low discharge did not entrain many particles.

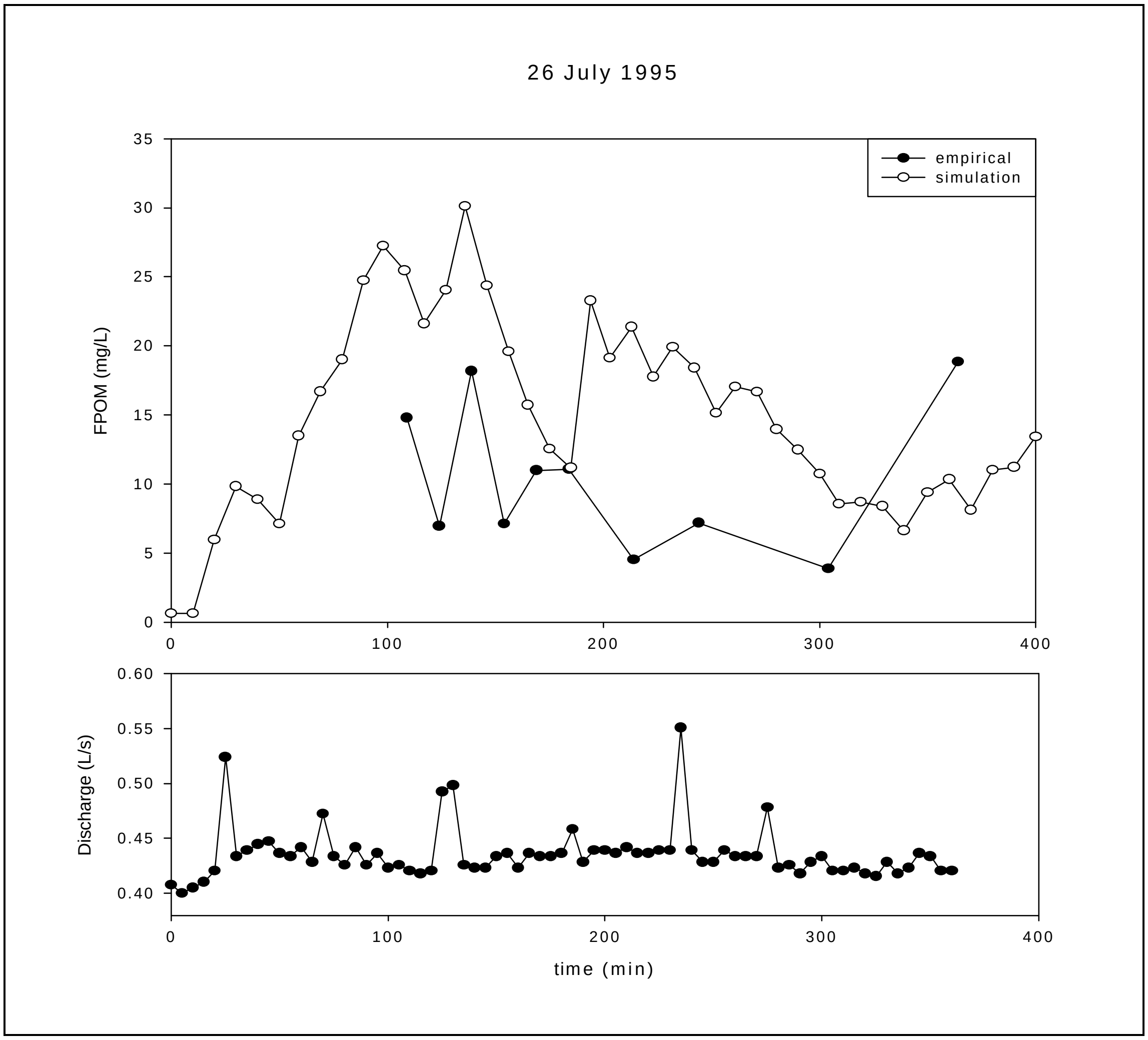

Figure 8. Simulations and empirical data for 26 July 1995.

The 7 August 1995 storm was very intense over the litter-excluded catchment, with the discharge rising from 0.49 to 23 L/s within about 15 minutes. There are no pre-exclusion parameters for storms this intense, so the two sets of parameters match time of year only. Although the June 87 storm was fairly large with discharge rising from 2 to 10 L/s, both simulations predicted much lower FPOM concentrations than were actually transported during this intense storm (Figure 9). The concentration measured during this storm remained elevated for quite some time after the discharge had dropped greatly (see also the graph of storm data for this date in Appendix I).

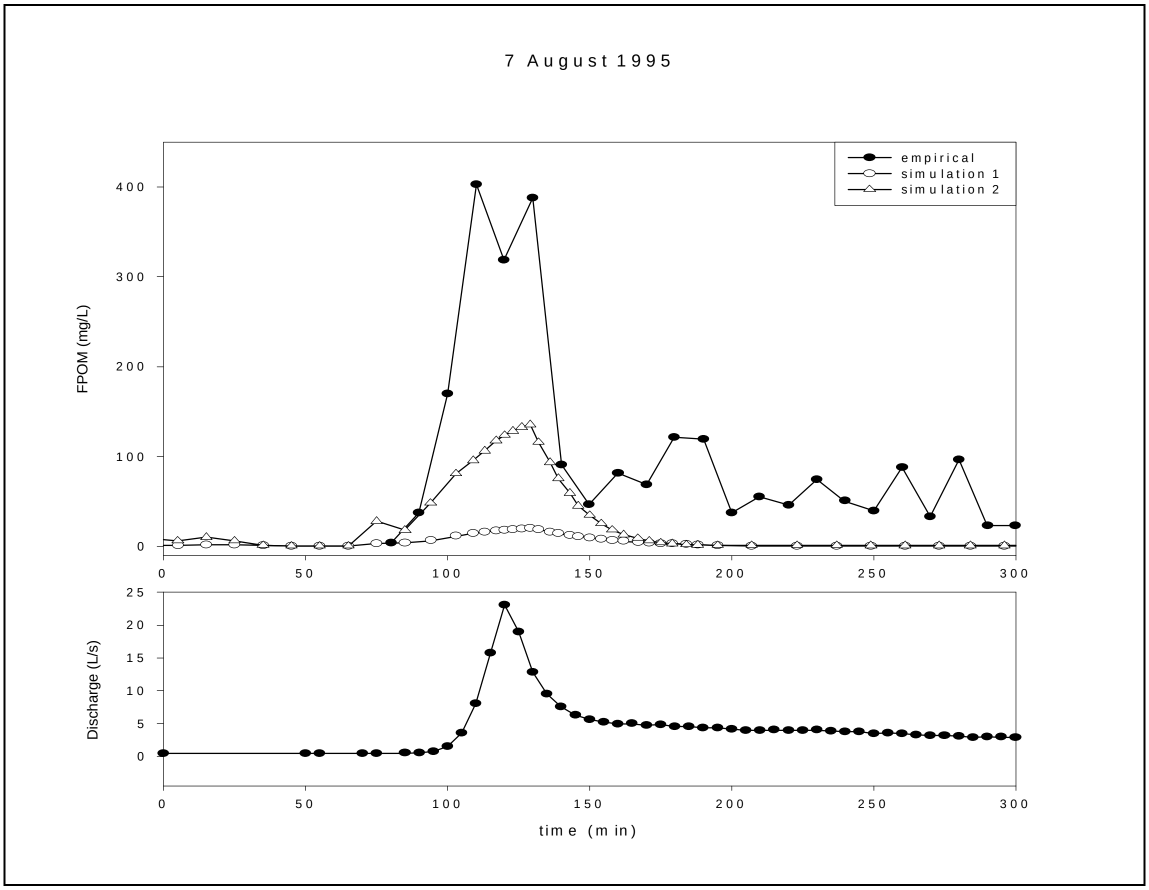

Figure 9. Simulations and empirical data for 7 August 1995.

The 11 November 1995 rain was steady and heavy for 600 min beginning approximately 300 min into the sampling period, resulting in a steep increase in discharge from 1.4 to 13 L/s. By 940 min into the sampling period, the rain had changed to snow flurries but sampling continued for several more hours as discharge gradually decreased to nearly pre-storm levels. As for the Nov 94 storm, no autumn pre-exclusion data were available to use for simulating this storm. The nearest time of year, Sep 86, had a very small change in discharge and yielded higher predicted FPOM concentrations, while the nearest Q match from Jan 89 predicted lower concentrations of FPOM (Figure 10). This was most likely due to seasonal availability of benthic FPOM being higher in September and lower in January.

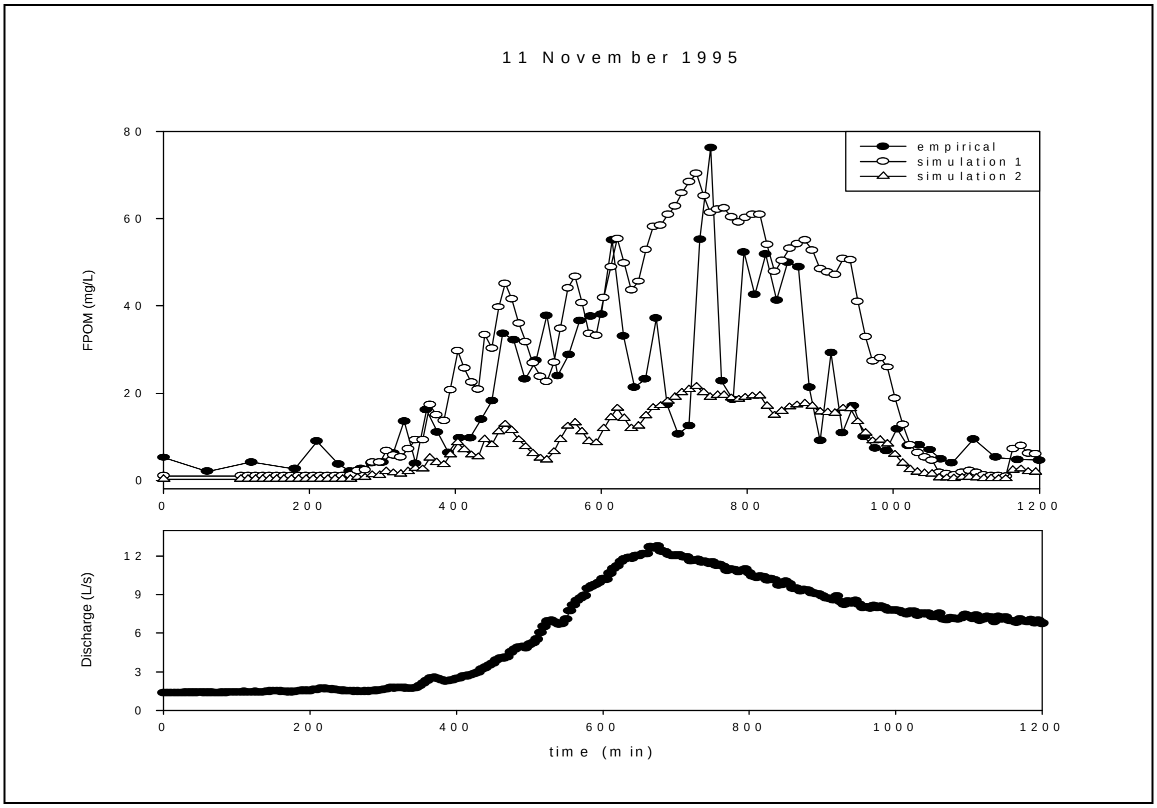

Figure 10. Simulations and empirical data for 11 November 1995.

STORMS AFTER WOOD REMOVAL:

The 2 September 1996 storm was very light, with discharge increasing only from 0.50 to 0.75 L/s. Both the time of year and increase in Q matched closely with Sep 86, though the simulation using those parameters yielded much higher concentrations of FPOM than were measured (Figure 11).

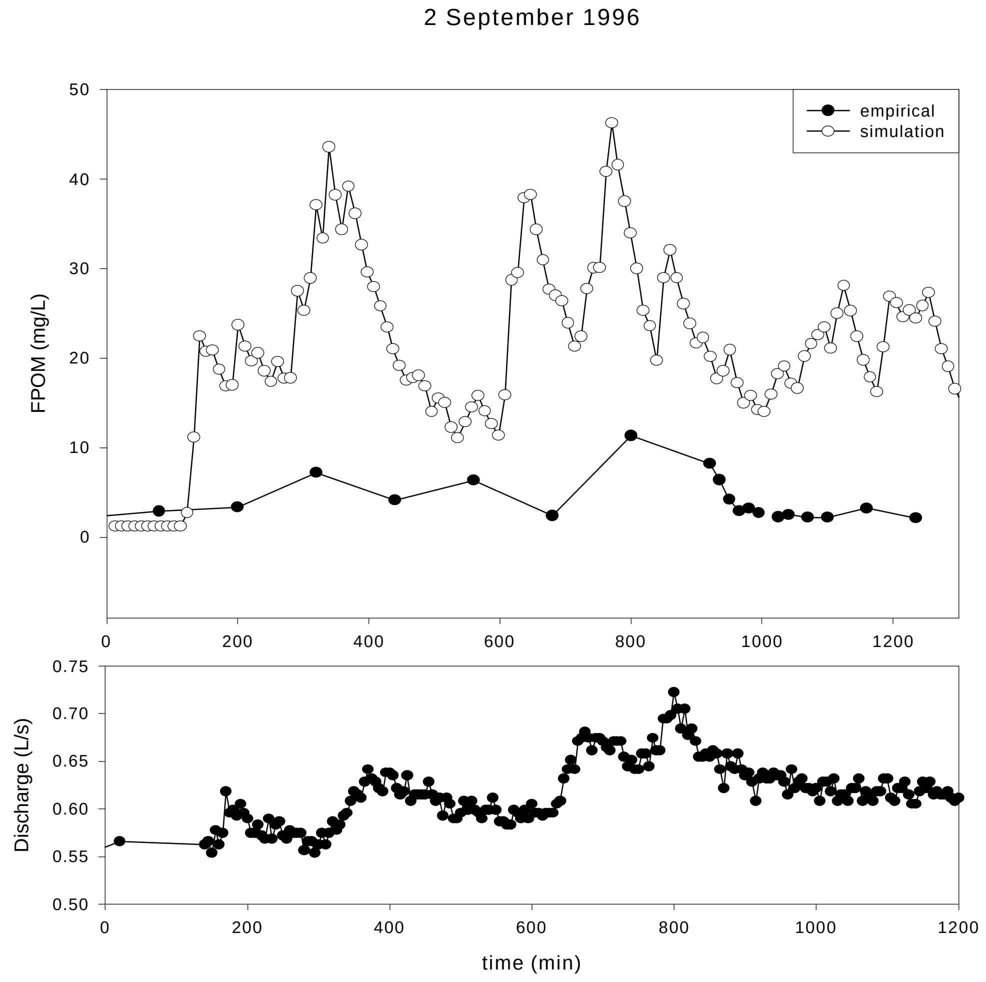

Figure 11. Simulations and empirical data for 2 September 1996.

During the 3 September 1996 storm, discharge rose from 0.50 to 2.0 L/s in two distinct peaks. Both time of year and discharge for this storm matched closely with Sep 86, but the simulation using those parameters yielded generally higher FPOM concentrations than were measured, although the two peak points were lower (Figure 12).

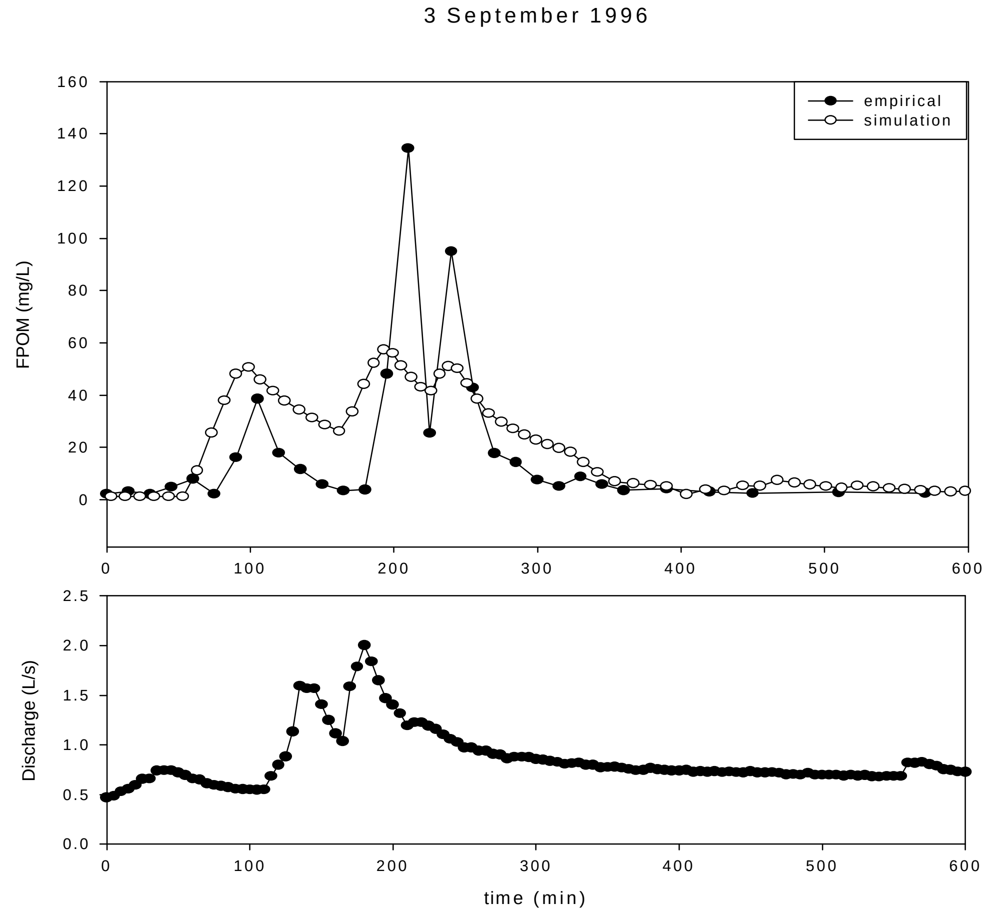

Figure 12. Simulations and empirical data for 3 September 1996.

During the 28 September 1996 storm discharge increased sharply from 2.8 to 16 L/s. When simulated, the time of year match with Sep 86 yielded lower predicted FPOM concentrations, as did the Q match using Jan 89 parameters (Figure 13). Like the November 95 storm, the particle concentration peaked after the maximum discharge was reached. The total particle concentration peaked nearly an hour later, as can clearly be seen in Appendix I on the graph of storm data for this date.

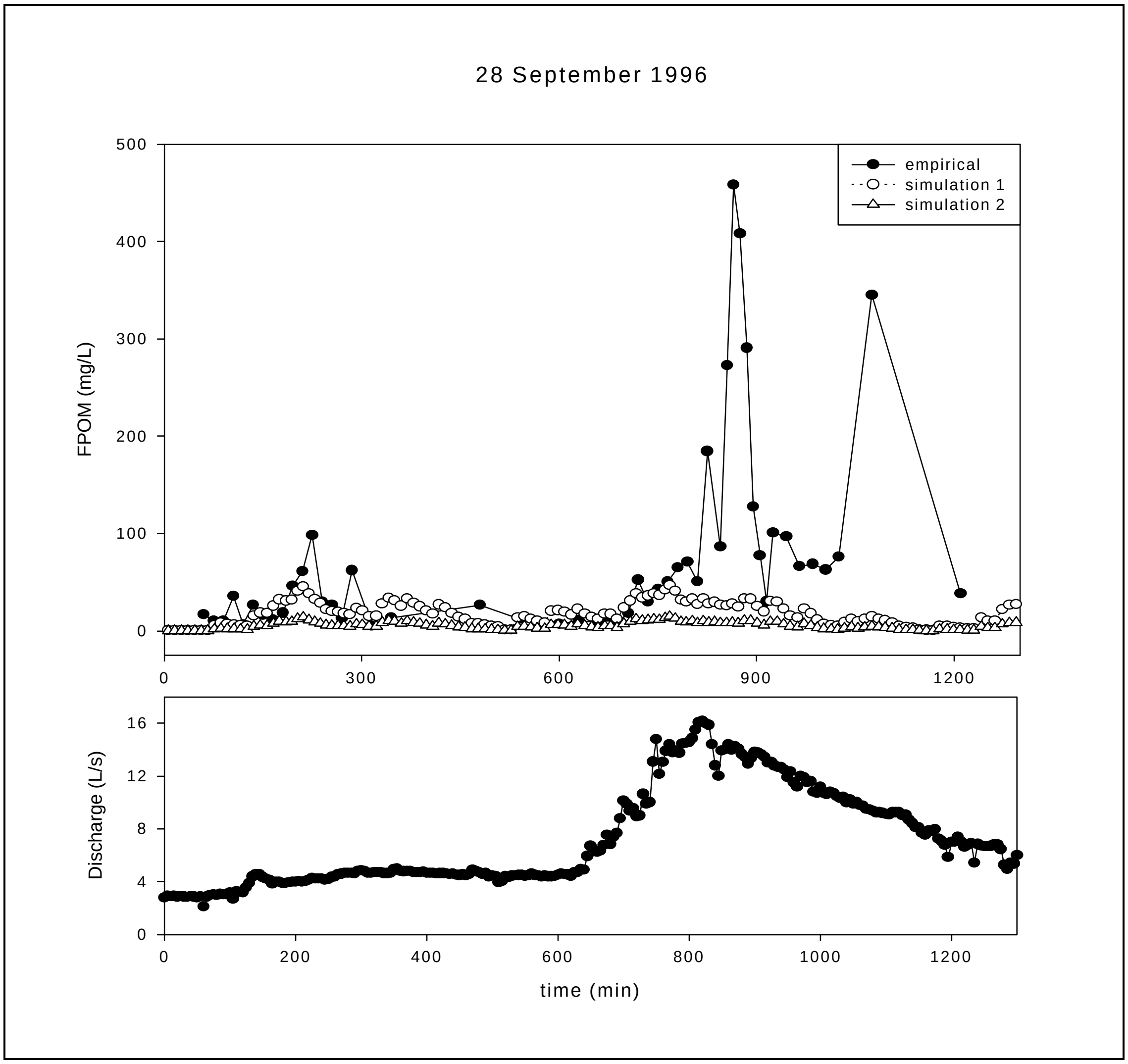

Figure 13. Simulations and empirical data for 28 September 1996.

The 7 November 1996 storm was of short duration, but discharge increased from 0.7 to 10 L/s. The time of year match with Sep 86 values yielded lower predicted FPOM concentrations, as did the Q match using Jan 89 parameters (Figure 14). Like the Nov 95 simulations, this is probably a factor of seasonal differences in FPOM availability.

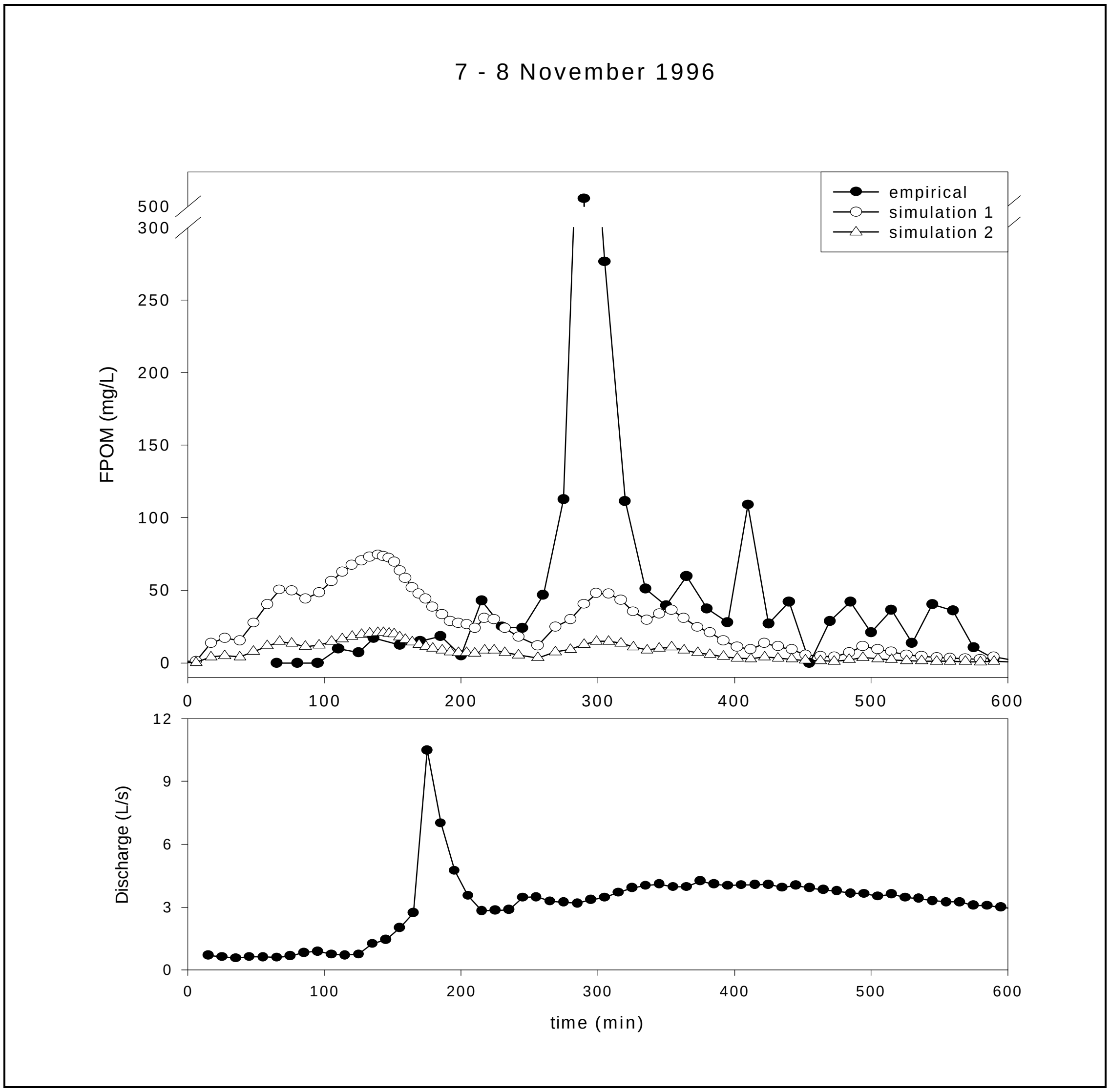

Figure 14. Simulations and empirical data for 7 November 1996.

DISCUSSION

My objective was to quantify the degree to which leaf litter and small wood in streams contribute to particle retention. I hypothesized that removal of leaf litter would decrease substrate stability, particularly during periods of high flow when scouring of the streambed is most likely. Storm flow would therefore export more particles from the litter-excluded reach. However, leaves are also a major source of organic particles and I expected litter exclusion to result in a decrease in organic particle generation and export.

Many studies have attempted to relate particle concentration to stream power or discharge. Naiman and Sedell (1978) did not find a significant relationship between POM concentration and stream power or type of organic input. Hill and Gardner (1987) found total seston transport to be only moderately correlated with stream discharge in two prairie storms during non-storm periods. Webster and Golladay (1984) found no relationship between stream power and seston concentration during non-storm periods in high-gradient, headwater streams in North Carolina. Additional work demonstrated a hysteretic relationship between storm discharge and particle concentration (Golladay *et al*. 1987, Webster *et al*. 1987, Golladay *et al*. 1989). This hysteretic effect, where particle concentration increases more rapidly on the rising limb of the hydrograph than the falling limb, results in a clockwise loop being produced when plotted in the time sequence of occurrence, rather than a linear plot (e.g., Whitfield and Schrier 1981, Golladay *et al*. 1987).

In this study, stream particle concentrations increased during storms, but storm concentrations were not significantly related to maximum discharge. The storm FPOM concentrations were highly variable, most likely due to differences in pre-storm stream conditions such as the rate of biological particle generation, time since previous storm, rainfall intensity, and duration of the storm (e.g. Verhoff *et al.* 1979, Bilby and Likens 1980, Golladay *et al.* 1987). When adjusted for watershed area or streambed area, the litter-excluded stream did not export significantly more particles during storms than the reference stream.

In addition to a reduction in FPOM concentrations, I expected that a higher inorganic fraction of suspended particles would be transported due to both 1) lower FPOM availability and 2) an increase in streambed instability. The litter exclusion canopy was 95.2 % efficient in excluding litter, resulting in only 0.05 kg/m^2 of organic material entering the stream compared to 1.12 kg/m^2 outside the canopy (Wallace *et al*. 1997). This reduction in leaf material entering the stream decreased the amount of surficial organic matter available for breakdown by both physical and biological processes. However, the %FPOM exported during storms did not decrease after litter exclusion, despite much lower litter inputs to the stream.

The litter inputs and subsequent particle generation were greatly decreased, but storm exports did not differ significantly from those of the reference stream, suggesting that the stream was much less retentive. The continuing export of large amounts of FPOM was probably because benthic organic material in storage and contributed by bank erosion buffered the effects of the absence of leaves. This is supported by the fact that the amount of BOM in the litter-excluded streambed decreased from 1.05 kg/m^2 to 0.52 kg/m^2 after litter exclusion (Wallace *et al*. 1997). In studying streams in the years following watershed logging, Webster *et al*. (1988) suggested that continued elevated seston concentrations beyond the first few years were due to downcutting of the stream channel. They found that the concentrations of both organic and inorganic seston were significantly higher in disturbed watersheds, but the inorganic fraction increased more. As discussed above, the inorganic fraction did not significantly increase after litter exclusion. This is contrary to what I expected, and may be another bit of evidence of a buffering effect by stored organic matter.

The suggestion that organic matter stored in the stream sediment after litter exclusion was entrained during periods of high storm flow is supported by examination of exported

FPOM plotted against total storm discharge for the reference stream and the litter-excluded stream before and after exclusion (Figure 15). Regression lines were calculated through each plot in order to compare slopes.

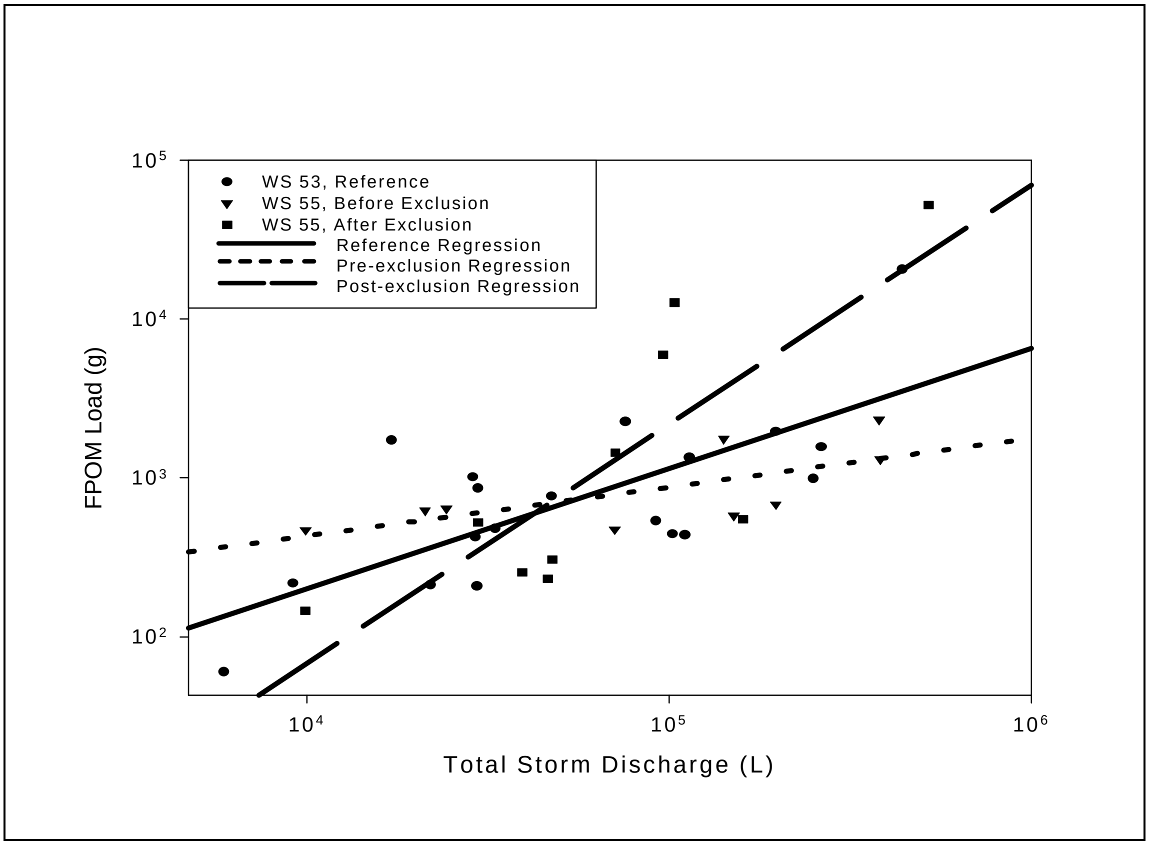

Figure 15. FPOM load exported by total storm discharge before and after litter exclusion. Regression equations for reference, pre-exclusion, and post-exclusion data sets are shown below, where y is the natural log of the amount of FPOM exported and x is the natural log of discharge:

Reference Stream: $y = 0.76x - 1.67$, $r^2 = 0.52$

Litter-excluded Stream BEFORE exclusion: $y = 0.31x + 3.24$, $r^2 = 0.47$

Litter-excluded Stream, AFTER exclusion: $y = 1.51x - 9.65$, $r^2 = 0.66$

The post-exclusion slope is significantly steeper than the pre-treatment slope (p = 0.0079, General Linear Models Procedure, SAS) and almost significantly steeper than the reference stream slope (p = 0.0559, General Linear Models Procedure, SAS). This implies that the effect of litter exclusion was to reduce FPOM retention and thereby increase entrainment as discharge increased, despite the fact that there was no new organic matter entering the stream from the riparian zone during the exclusion period. This suggests that the stability of the litter-excluded streambed was lowered compared to the reference and pre-treatment streambeds, and stability was further reduced with increased discharge.

The storms of 7 August 1995, 11 November 1995, 3 September 1996, 28 September 1996, and 8 November 1996, in which particle concentrations peaked later than discharge in the litter-excluded stream, may also indicate decreasing streambed stability. Unlike in headwater streams, peak sediment loads measured in downstream areas match or lag behind the discharge peak because the site has to "wait" for the sediment to be delivered from upstream (e.g., Verhoff *et al*. 1979, Gordon *et al*. 1992). It is possible that during these very large storms, which all had rapid, high increases in discharge, there was a delay while FPOM was scoured from the streambed. Decreased retention resulted in longer travel distances of FPOM, making transport after litter-exclusion more like transport in a higher-order stream.

It is possible that some of the organic material transported in the litter-excluded stream was washed from the exposed streambanks beneath the exclusion netting. Unfortunately, I had no way of discerning the prior location of the BOM being exported, because both benthic and the bank material initially originated from the same terrestrial sources. However, soils at Coweeta are highly permeable and infiltration rates can exceed 125 cm/hr, thus overland flow is not a common occurrence (Douglass and Swank 1975). Bretschko and Moser (1993) found that FPOM from bank runoff comprised less than 10% of the annual organic matter imported to an Austrian stream and was mainly washed into the stream during spring snowmelt.

Another possibility is that more of the FPOM being exported since litter exclusion was not leaf-derived, but wood-derived. In coniferous forests, 35% of sediment FPOM is recognizably wood-derived (Ward and Aumen 1986). There was evidence of increased rate of wood decomposition occurring in the litter-excluded stream (Tank and Webster

1998, Tank *et al*. 1998). Higher microbial decomposition of wood may contribute organic matter to the stream and partially compensate for the lack of leaf litter. Thus, the amount of FPOM transported in the litter-excluded stream, while not significantly different from the reference stream, may have been derived from different sources.

The Simulation Model

Simulated FPOM concentrations (Table 10) were usually lower than the measured concentrations when storm intensity, indicated by the rate of increase in discharge, was great. During less intense storms, the simulated FPOM concentrations were higher than what were measured in the stream. The conclusion drawn from this is that after litter exclusion, FPOM transport decreased during low-intensity storm flow. However, intense storms that greatly increased discharge turned over more bed material and entrained higher concentrations of FPOM after exclusion.

In all of the simulation equations, I attempted to use parameters that had been determined in previous studies. Reported deposition velocity, as measured in field studies, ranges from 0.00007 m/min (Cushing *et al*. 1993 for Salmon R.) to 0.01 m/min (WS 55 pollen releases, J.R.Webster, VA Tech, unpub) and the values that I used to fit the model to the experimental data are within this range. However, there is always a degree of uncertainty when making the simplifications necessary to fit mathematical equations to complex biological systems. Several issues were identified during calibration of the pre-treatment data that required some judgements to be made regarding the relative importance of certain components of the model. First, the modeled concentrations of FPOM were lower than the amounts measured before and after a storm. I believe that this is because the model did not incorporate input of FPOM during non-storm periods. At baseflow, seston transport depends on the rate of biological particle generation and the retention characteristics of the streambed (Webster *et al*. 1987). The model does not include any accrual of FPOM via biological and physical mechanisms, such as breakdown of woody debris, insect frass, etc. At stormflow, this background concentration is relatively small, so is not evident.

Secondly, the entrainment equation was derived from a small data set. As explained in the Methods section, the equation for storm concentration was obtained from regressing concentration vs. the rate of change of discharge from one storm. So the entrainment may actually be too small when the rate of change of discharge is low, although the fit is much better when the rate of change of discharge is high.

Thirdly, the pretreatment data used to calibrate the model were from a period that encompassed extreme wet and dry years. During 1986, annual precipitation was 124 cm (the long-term average is 180.1 cm), the lowest measured for the 57-year period of record at Coweeta. Precipitation in 1988 was 126.7 cm, the 3rd -driest year on record. The following two years were wetter than average, with 234.1 cm falling in 1989 and 209.4 cm in 1990. Wallace *et al*. (1991) noted that during the dry years of 1986 to 1988, even small storms produced large increases in PIM during rising hydrographs. The entrainment and deposition parameters fitted from the storms during drought years may be quite different from what they would have been during average or wet years. The data set is too small to determined the likelihood of such effects.

Lastly, my model was not sufficiently complex to account for effects of previous precipitation on the entrainment and deposition of organic particles. It is logical to assume that a prior storm could have an effect on the amount of material present and its ease of entrainment during a subsequent storm. For instance, a storm with a high discharge entrains not only particles on the surface of the streambed, but also picks up material that has accumulated outside the wetted baseflow perimeter. A small storm following shortly after could find a severely depleted pool of available material to export.

Conclusion

Sampling suspended particles during storms showed that although litter inputs and subsequent particle generation were greatly decreased (Wallace *et al.* 1997), storm exports did not differ significantly from those of the reference stream. This suggested that the effect of litter exclusion was to reduce FPOM retention so that although there was no new organic matter entering the stream from the riparian zone during the exclusion period, stored material scoured from the streambed compensated for it.

The computer simulations of post-exclusion storms were run using parameters determined from pre-exclusion storm data. The model results predicted higher FPOM concentrations for storms after litter exclusion than were measured in the stream, except during very heavy rains that greatly increased discharge. These results suggest that after litter exclusion, low-intensity storm flow exported lower concentrations of FPOM than before exclusion. However, after exclusion, intense storms that greatly increased discharge turned over more bed material and entrained higher concentrations of FPOM.

Both the field studies and the computer model indicated that the stability of the litter-excluded streambed was lower compared to the reference and pre-treatment streambeds, and stability was further reduced with increased discharge.

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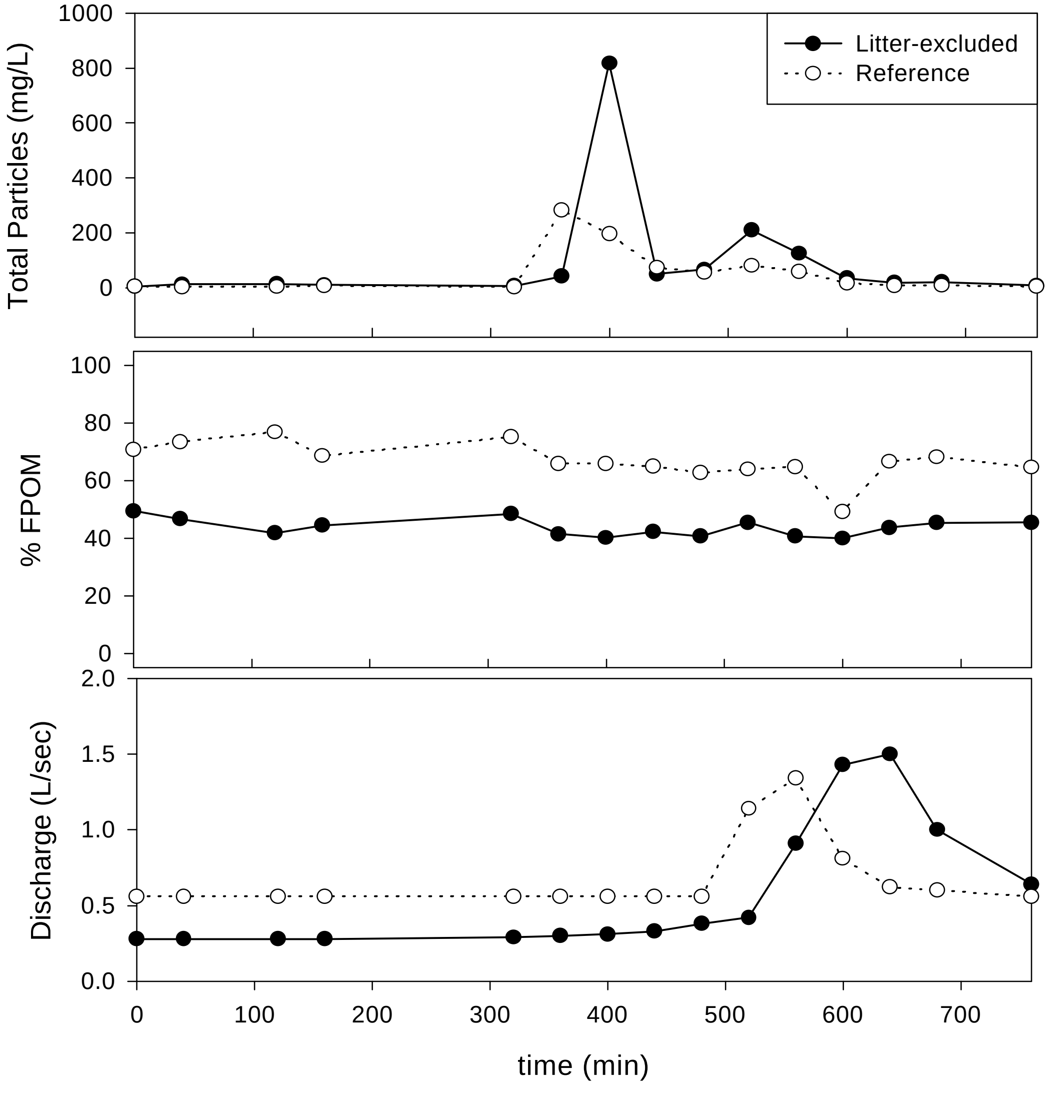
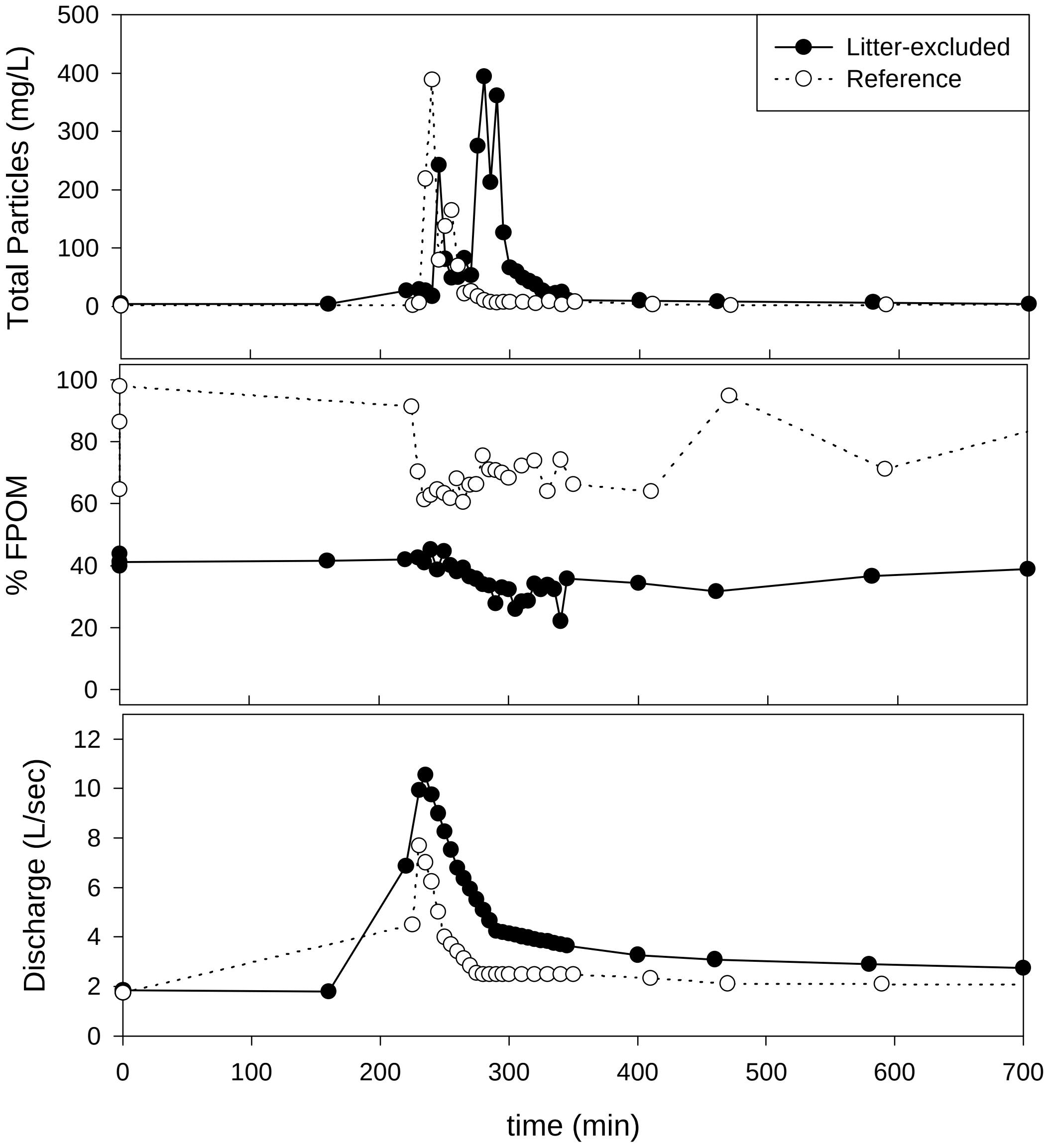
APPENDIX A. GRAPHS OF STORM DATA COLLECTED

The following figures show the total particle concentrations, %FPOM in each sample, and the discharge during each storm sampled in the litter-excluded and reference streams.

11 September 1986

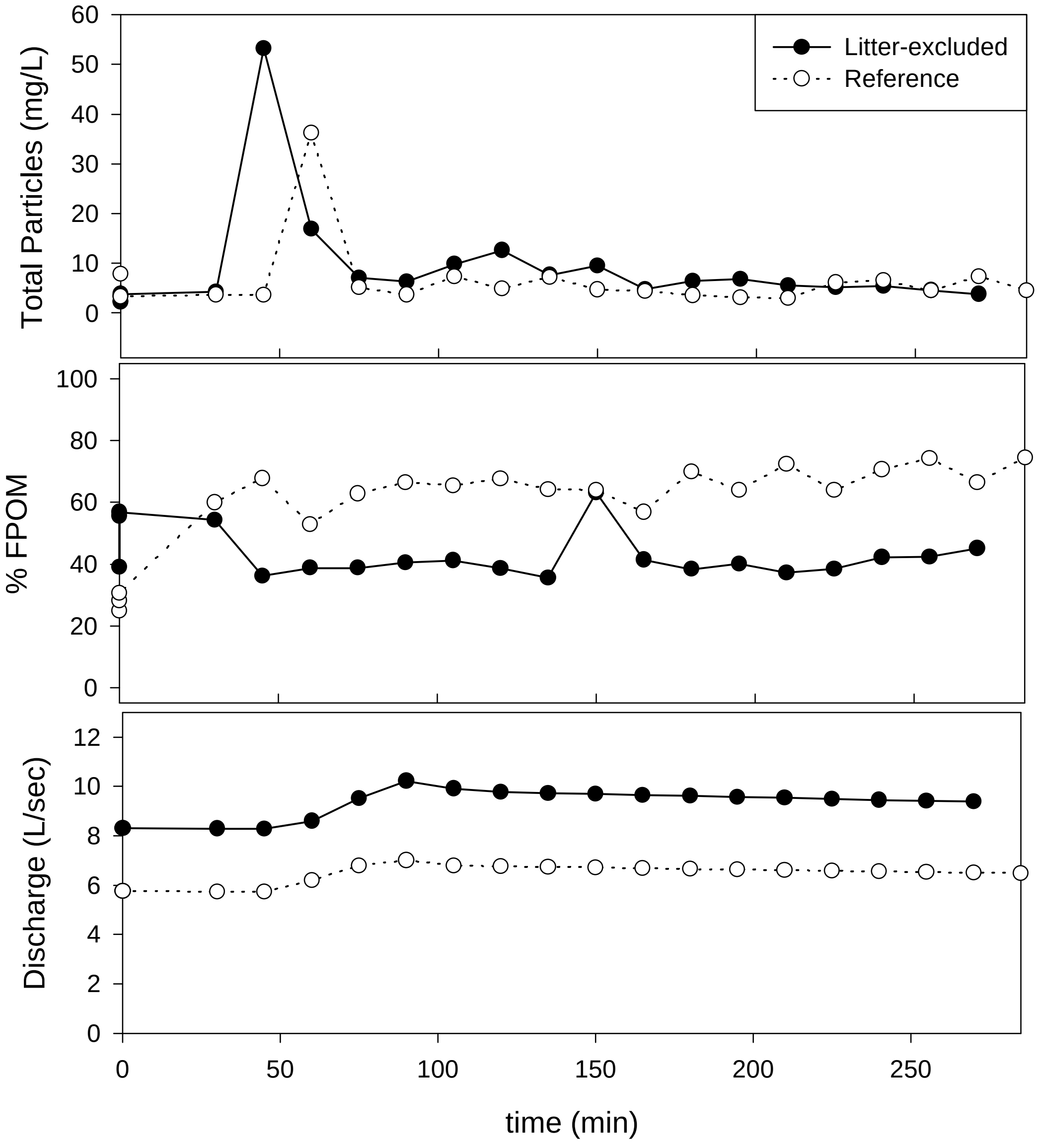


12 June 1987



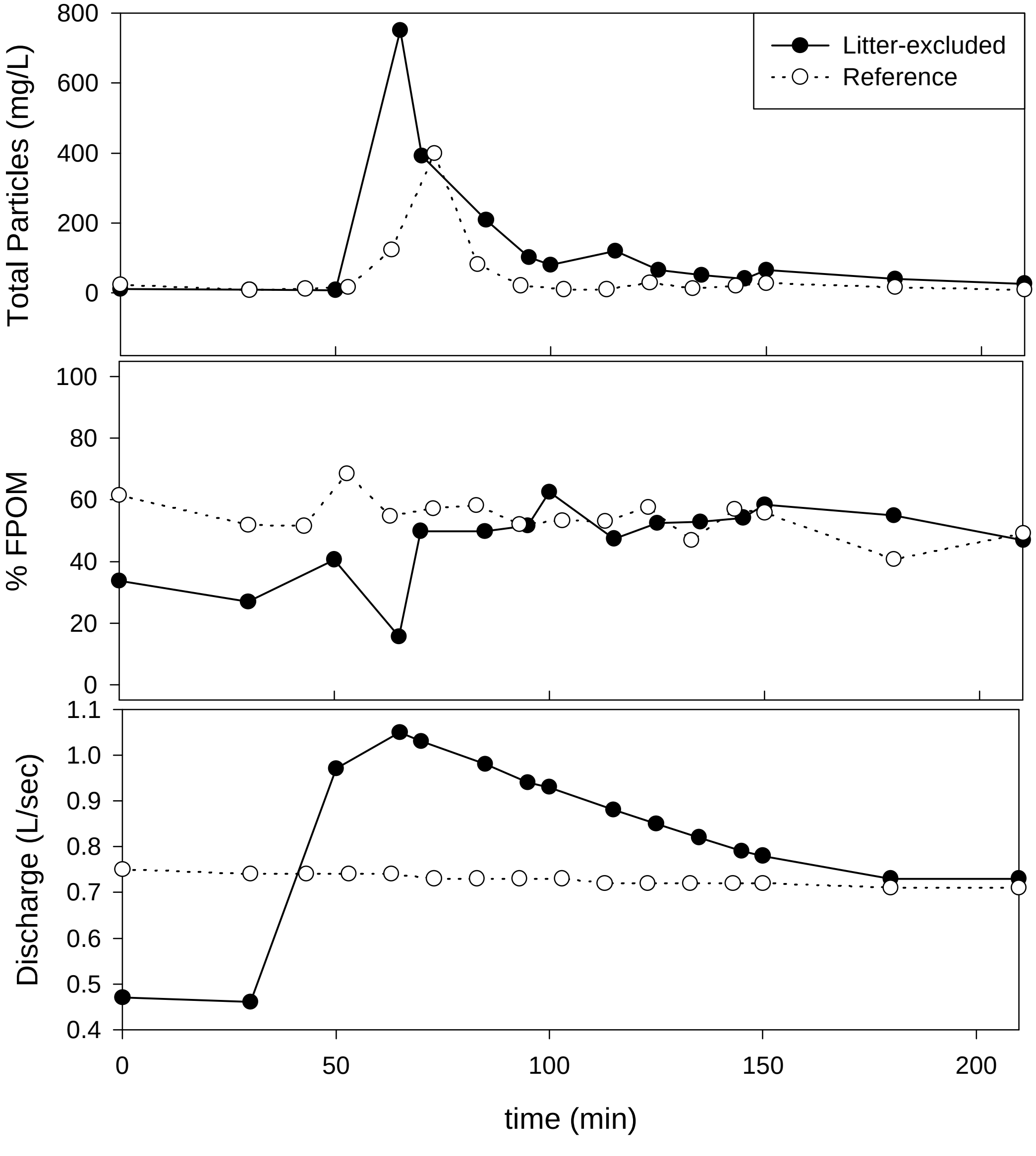
Litter-excluded
Reference
Total Particles (mg/L)
0
100
200
300
400
500
% FPOM
0
20
40
60
80
100
Discharge (L/sec)
0
2
4
6
8
10
12
0
100
200
300
400
500
600
700
time (min)

3 March 1988



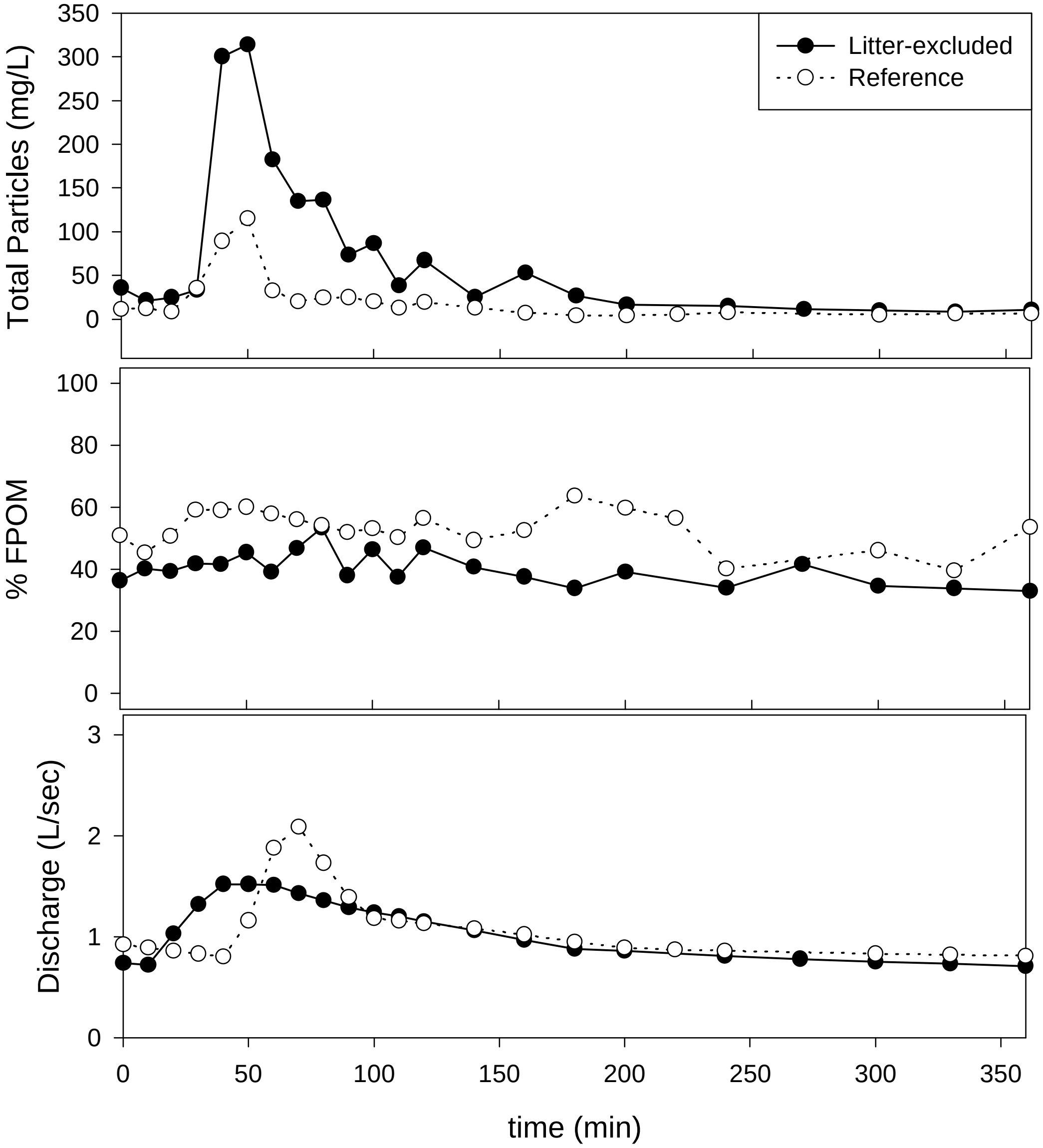
Litter-excluded
Reference
Total Particles (mg/L)
0
10
20
30
40
50
60
% FPOM
0
20
40
60
80
100
Discharge (L/sec)
0
2
4
6
8
10
12
0
50
100
150
200
250
time (min)

13 July 1988

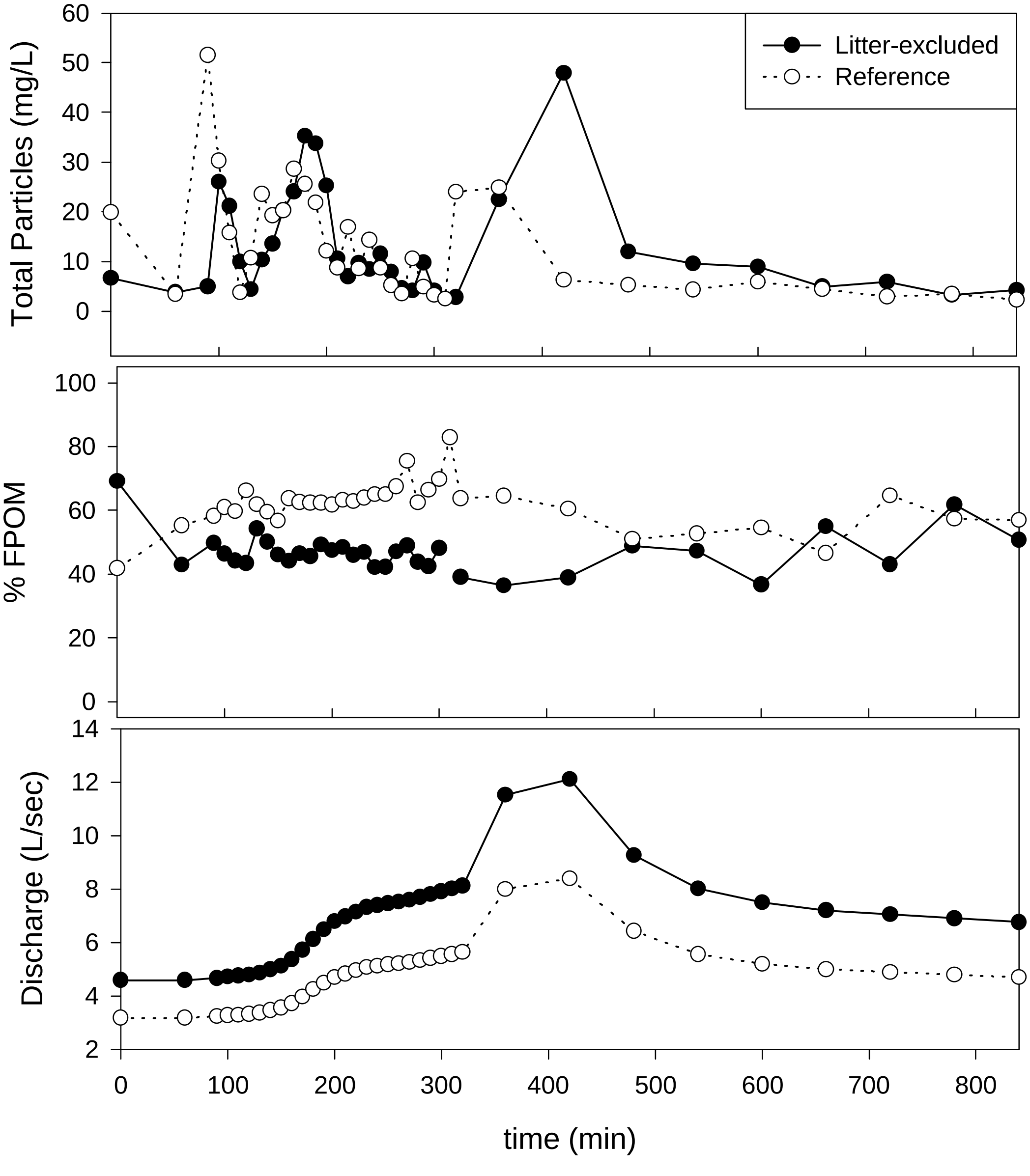


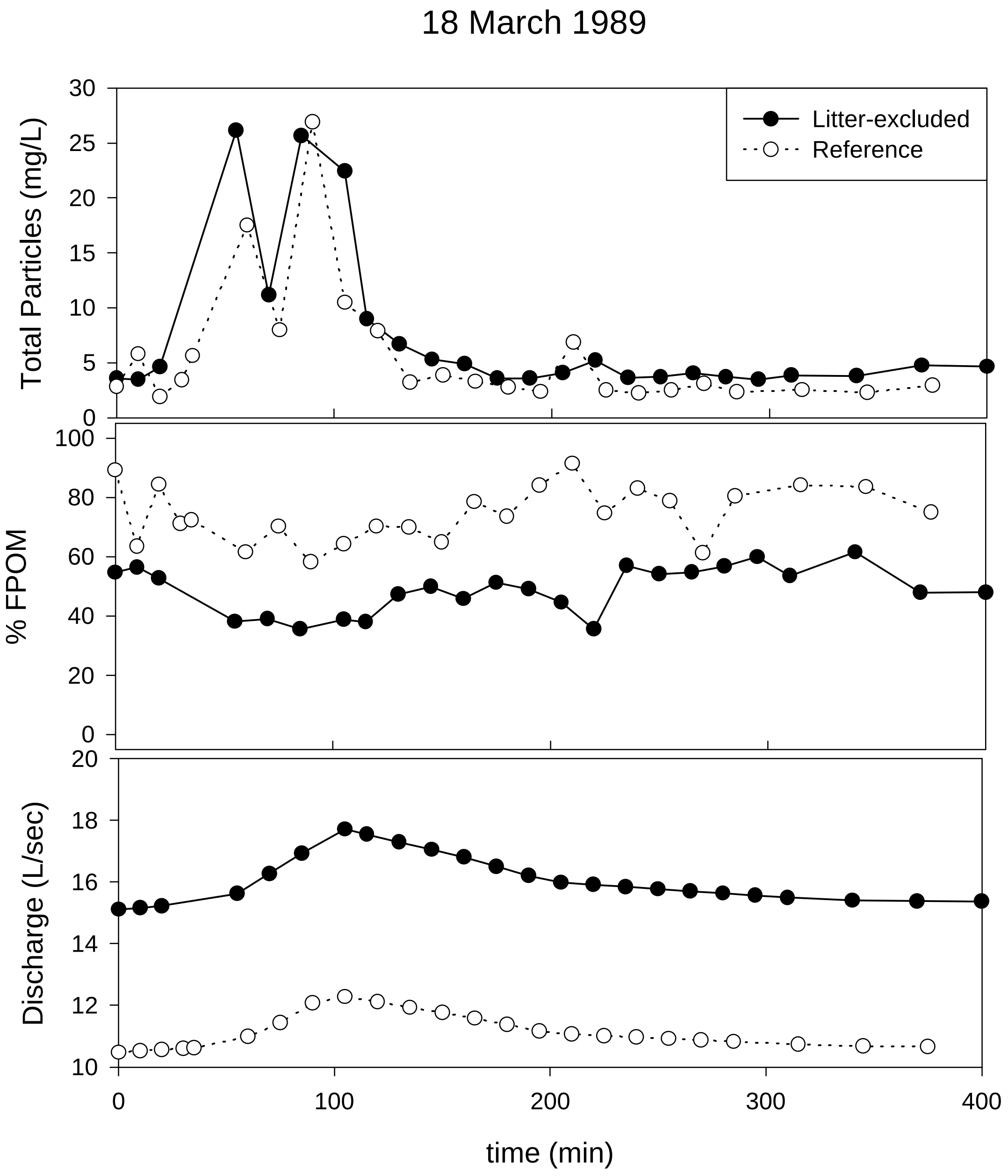
Litter-excluded
Reference
Total Particles (mg/L)
800
600
400
200
0
% FPOM
100
80
60
40
20
0
Discharge (L/sec)
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0
50
100
150
200
time (min)

21 July 1988

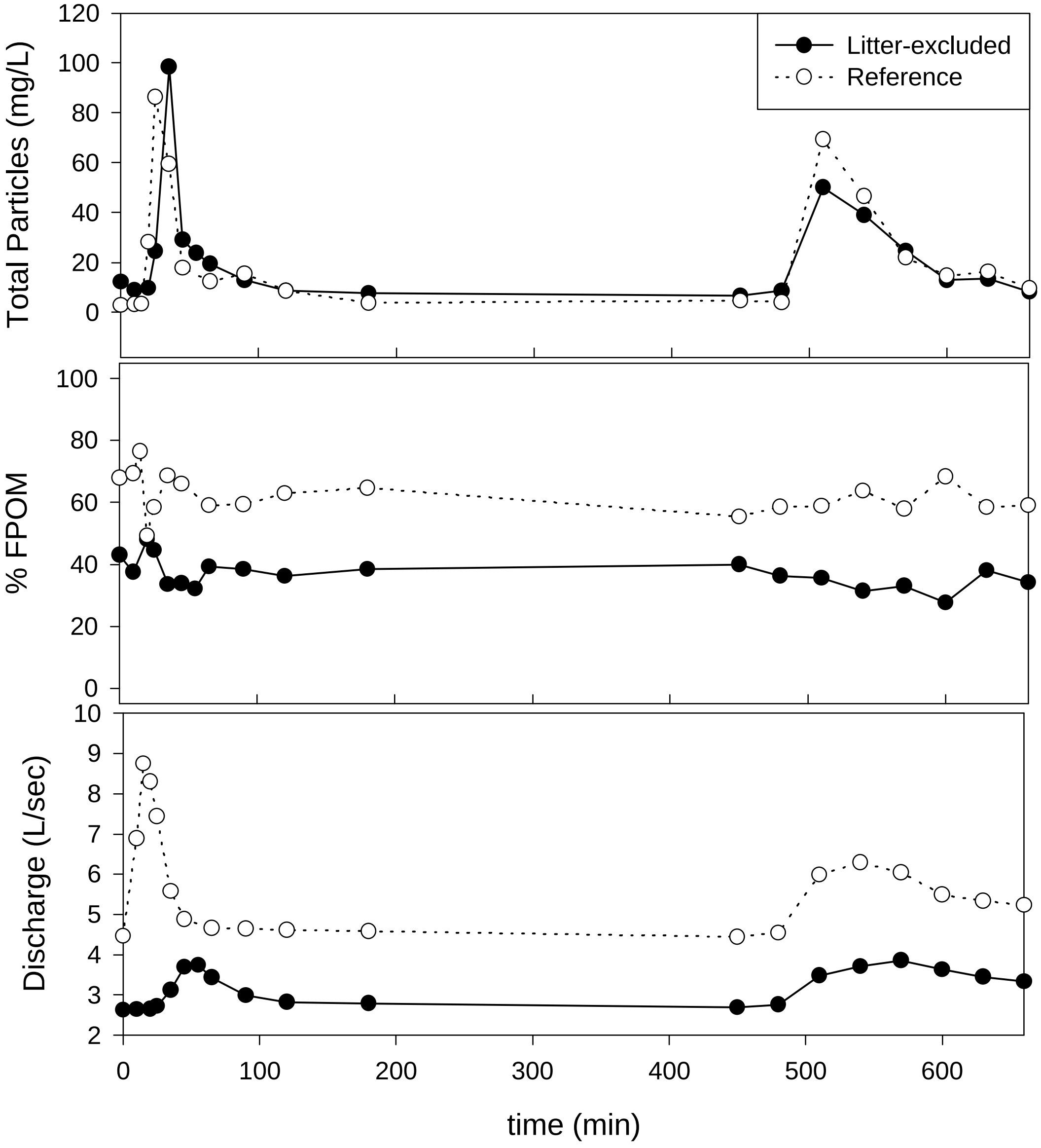

Total Particles (mg/L)
350
300
250
200
150
100
50
0
● Litter-excluded
○ Reference
% FPOM
100
80
60
40
20
0
Discharge (L/sec)
3
2
1
0
0
50
100
150
200
250
300
350
time (min)

6 January 1989

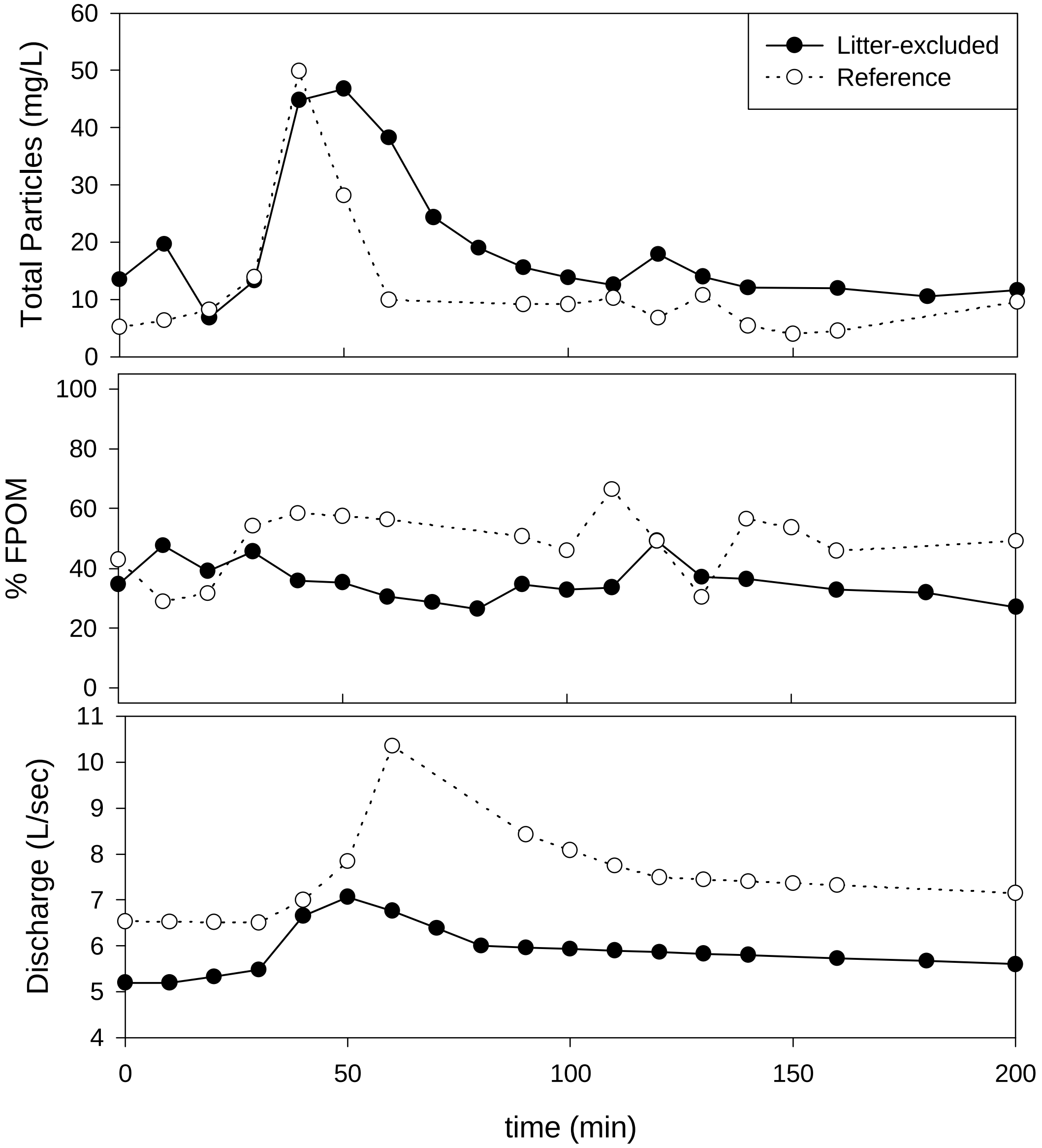



18 March 1989
Total Particles (mg/L)
0
5
10
15
20
25
30
Litter-excluded
Reference
% FPOM
0
20
40
60
80
100
Discharge (L/sec)
10
12
14
16
18
20
0
100
200
300
400
time (min)

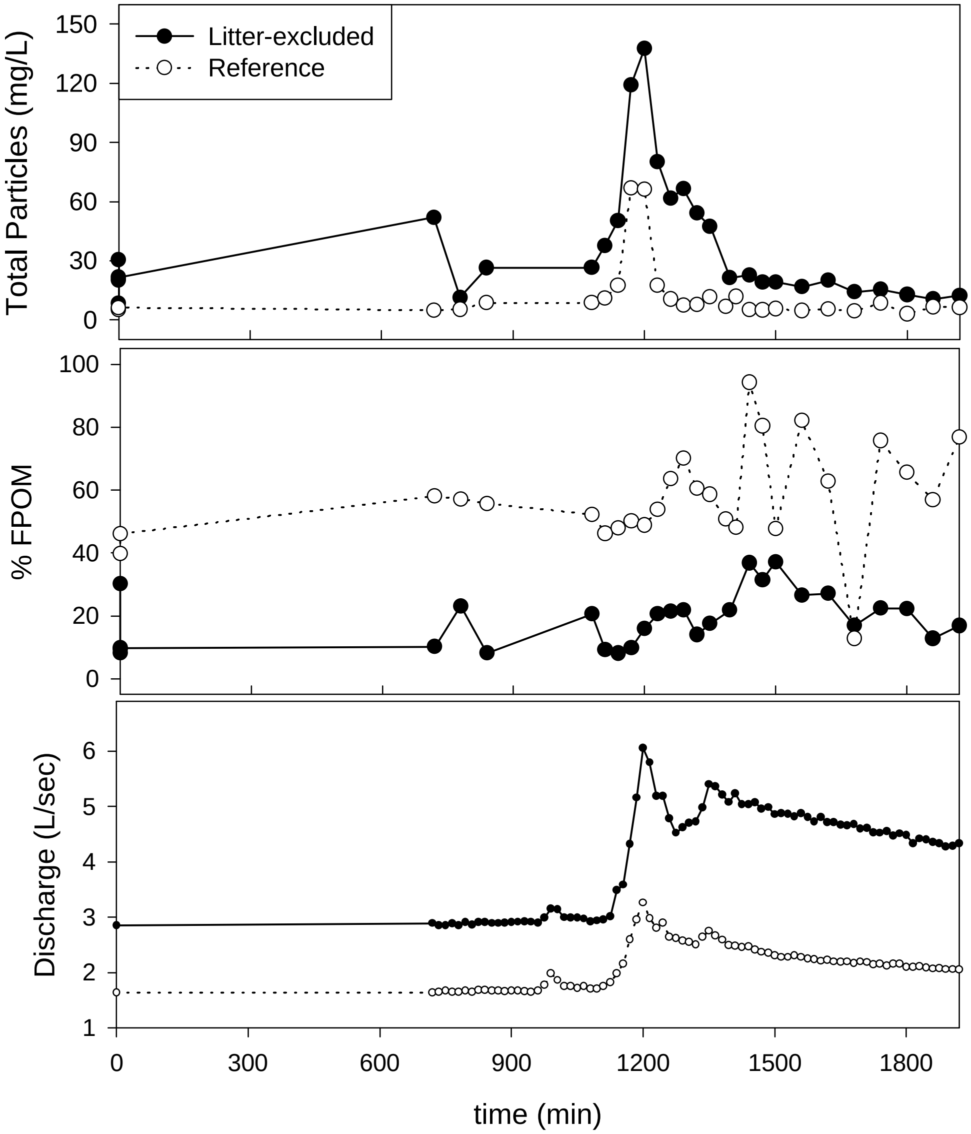
12 June 1989


Total Particles (mg/L)
120
100
80
60
40
20
0
Litter-excluded
Reference
% FPOM
100
80
60
40
20
0
Discharge (L/sec)
10
9
8
7
6
5
4
3
2
0
100
200
300
400
500
600
time (min)

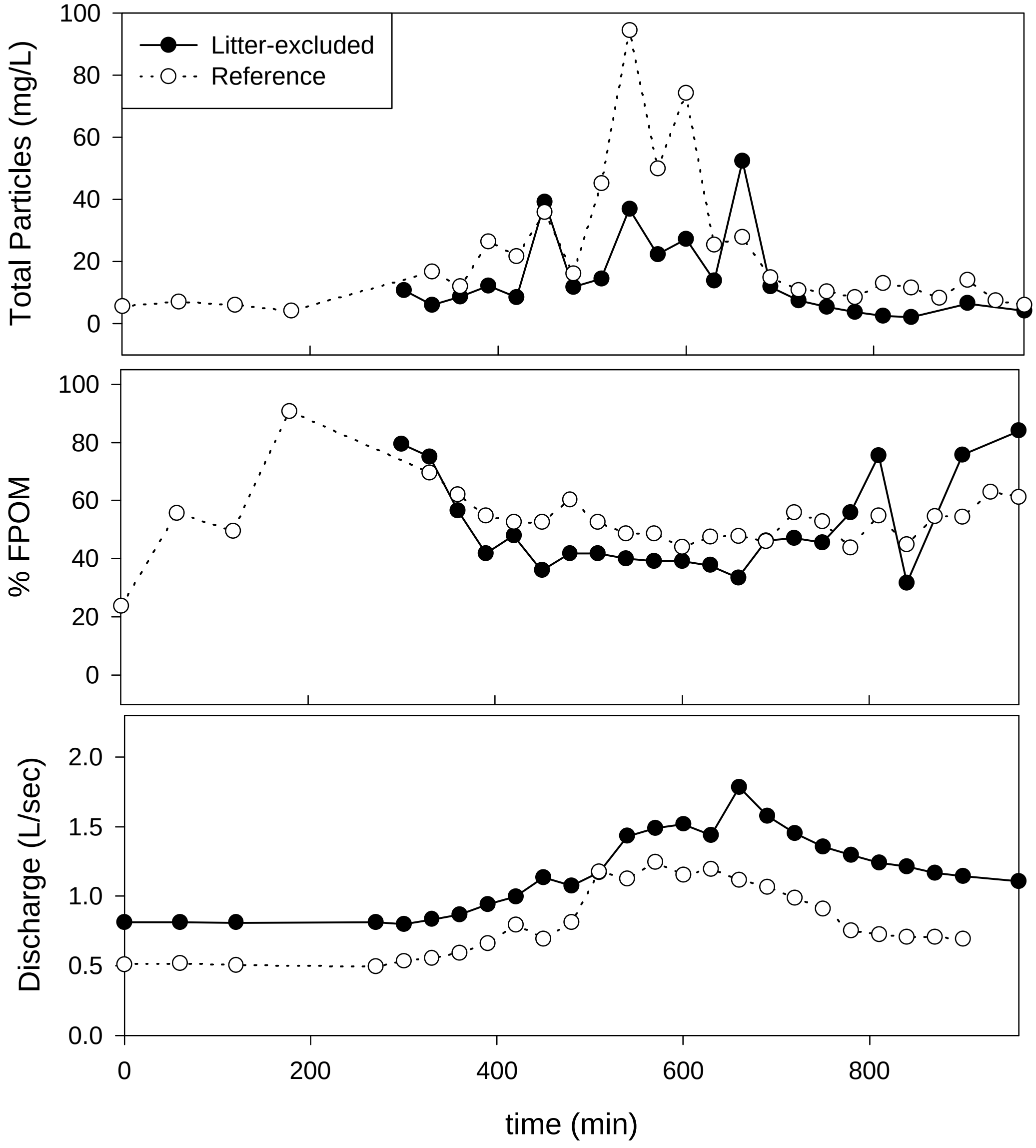
1 August 1989



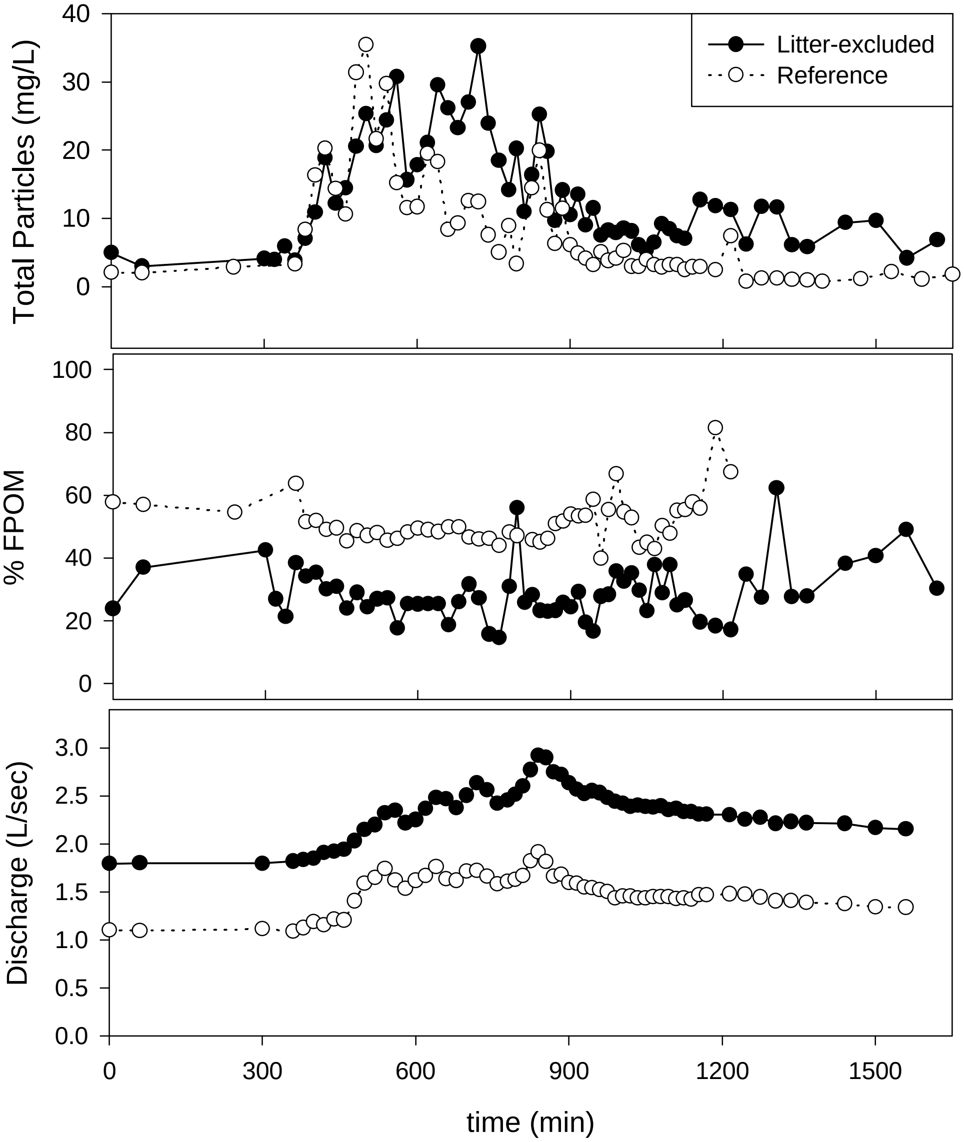
9 March 1994


Total Particles (mg/L)
150
120
90
60
30
0
Litter-excluded
Reference
% FPOM
100
80
60
40
20
0
Discharge (L/sec)
6
5
4
3
2
1
0
300
600
900
1200
1500
1800
time (min)

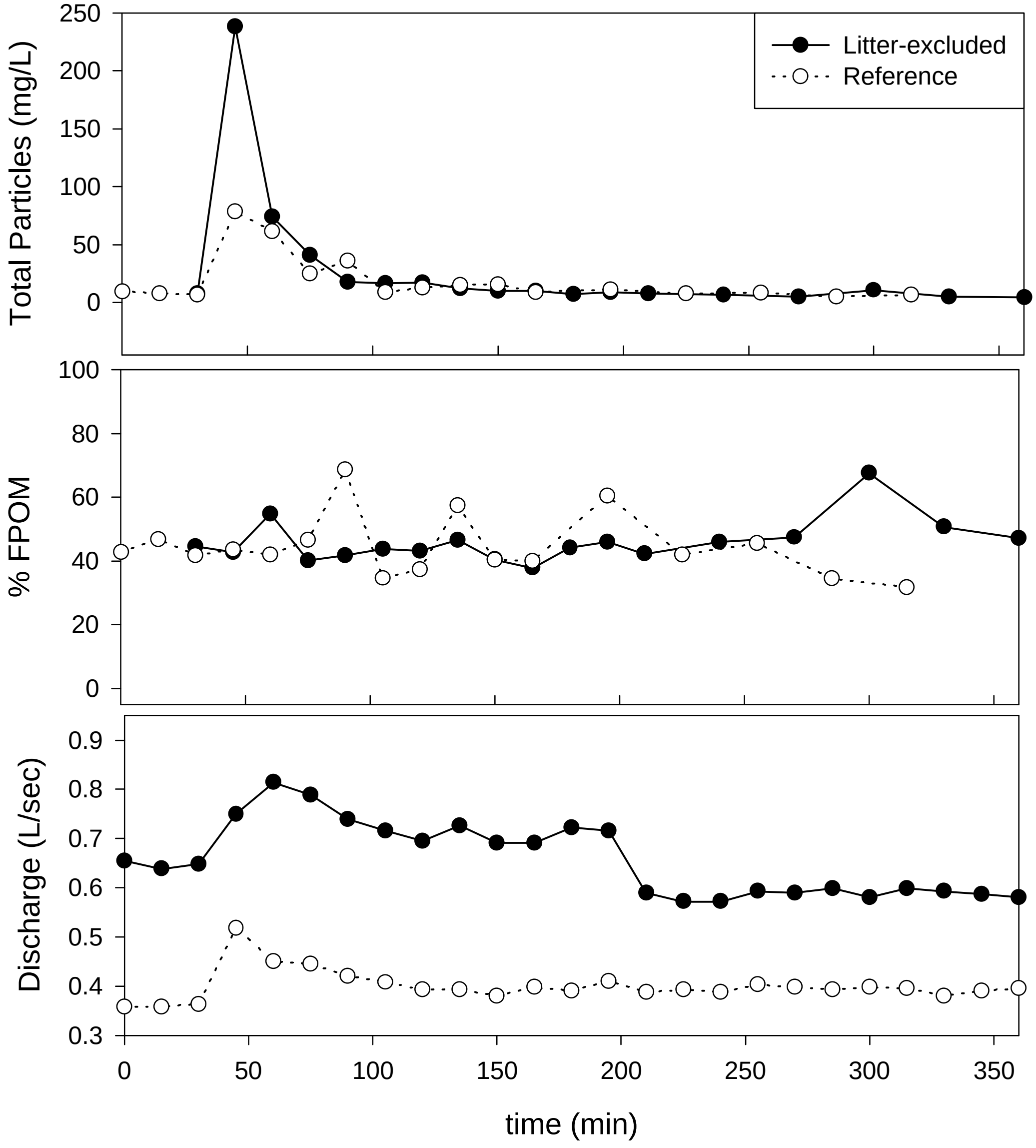
20 November 1994



27 January 1995

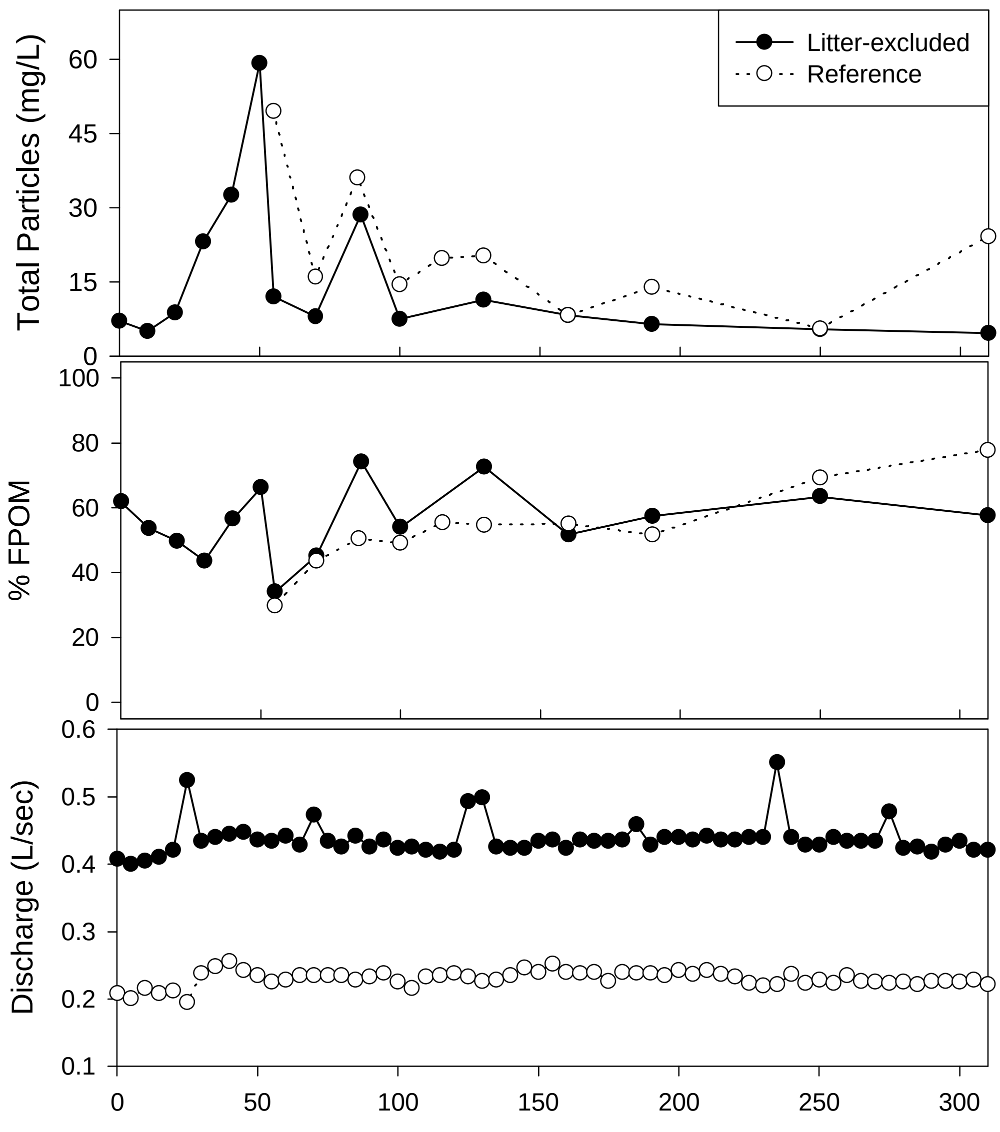


21 June 1995

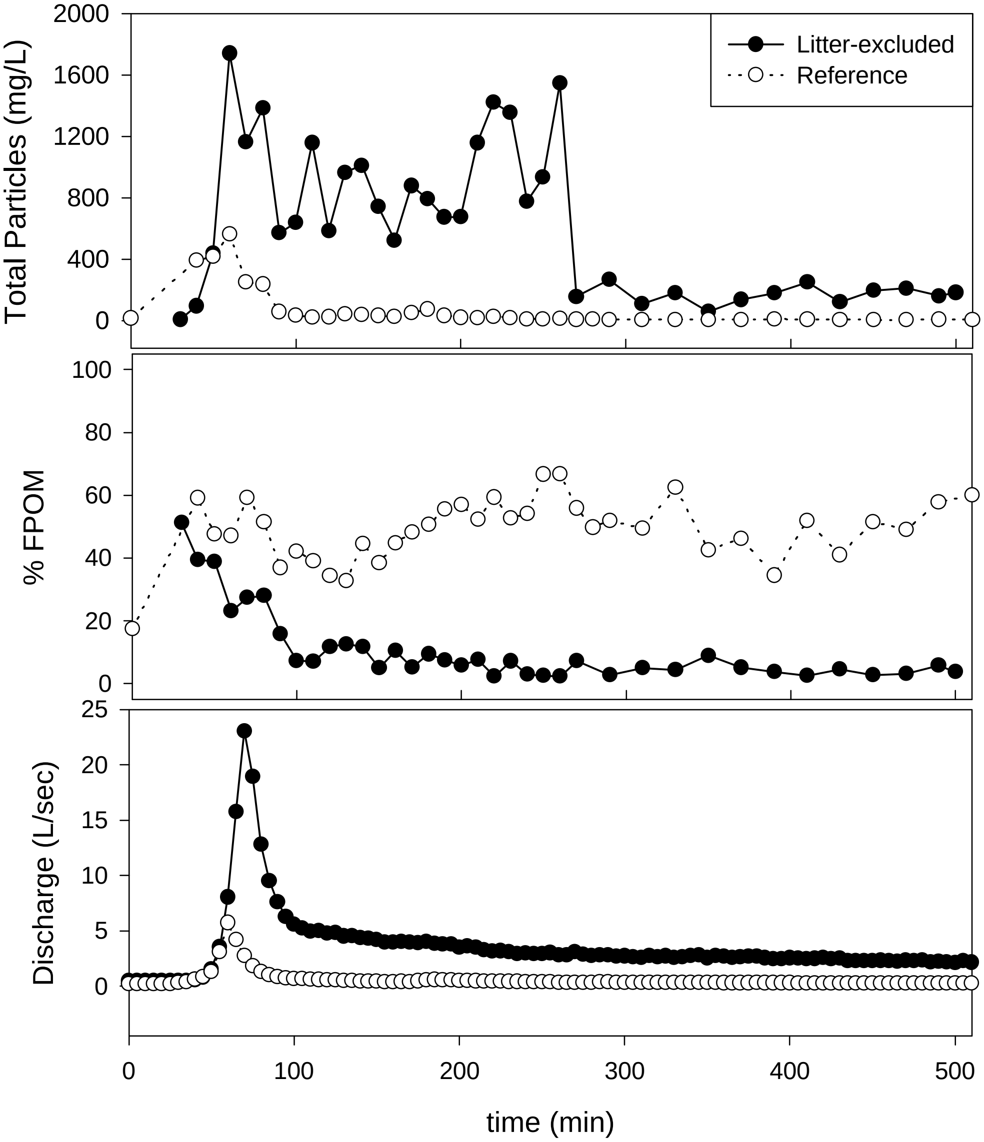


Total Particles (mg/L)
250
200
150
100
50
0
Litter-excluded
Reference
% FPOM
100
80
60
40
20
0
Discharge (L/sec)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0
50
100
150
200
250
300
350
time (min)

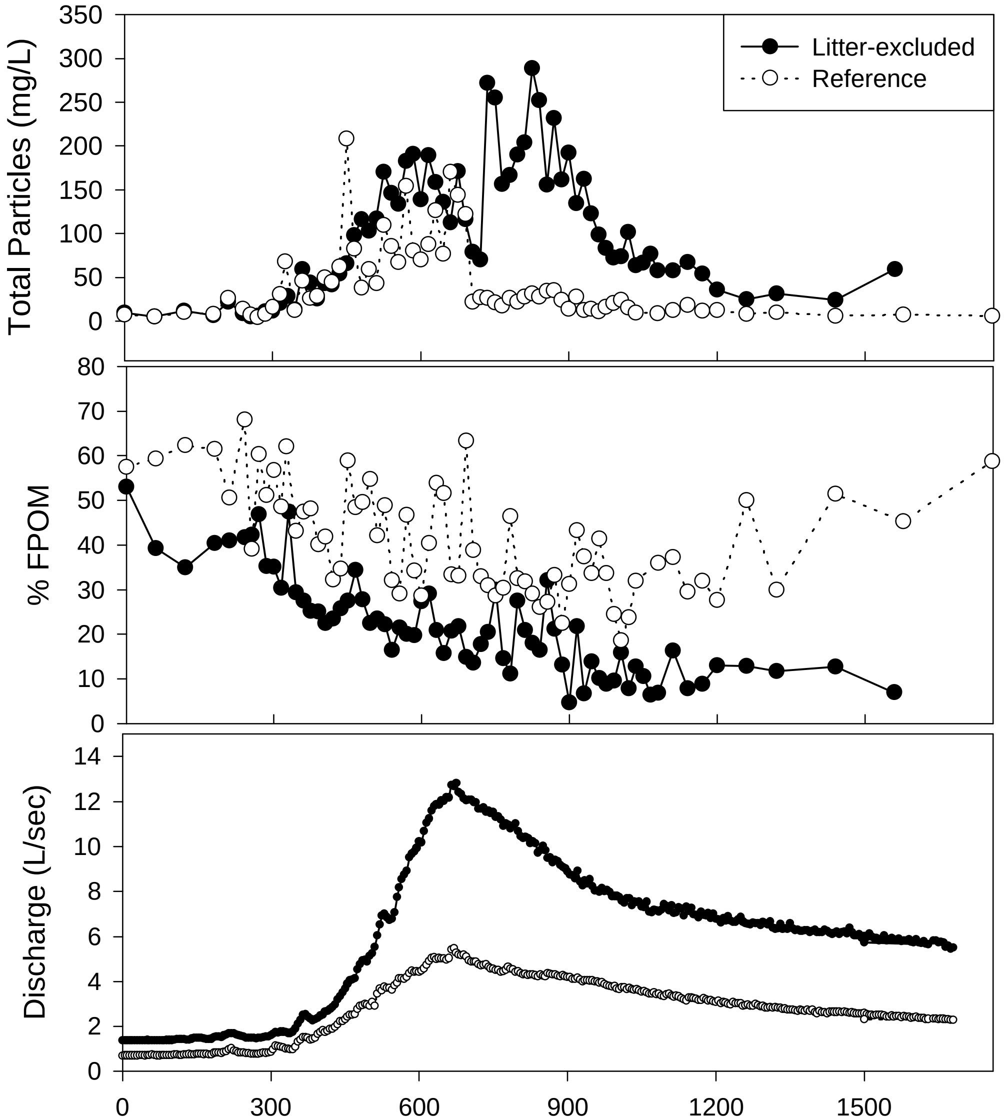
26 July 1995


Total Particles (mg/L)
0
15
30
45
60
Litter-excluded
Reference
% FPOM
0
20
40
60
80
100
Discharge (L/sec)
0.1
0.2
0.3
0.4
0.5
0.6
0
50
100
150
200
250
300
time (min)

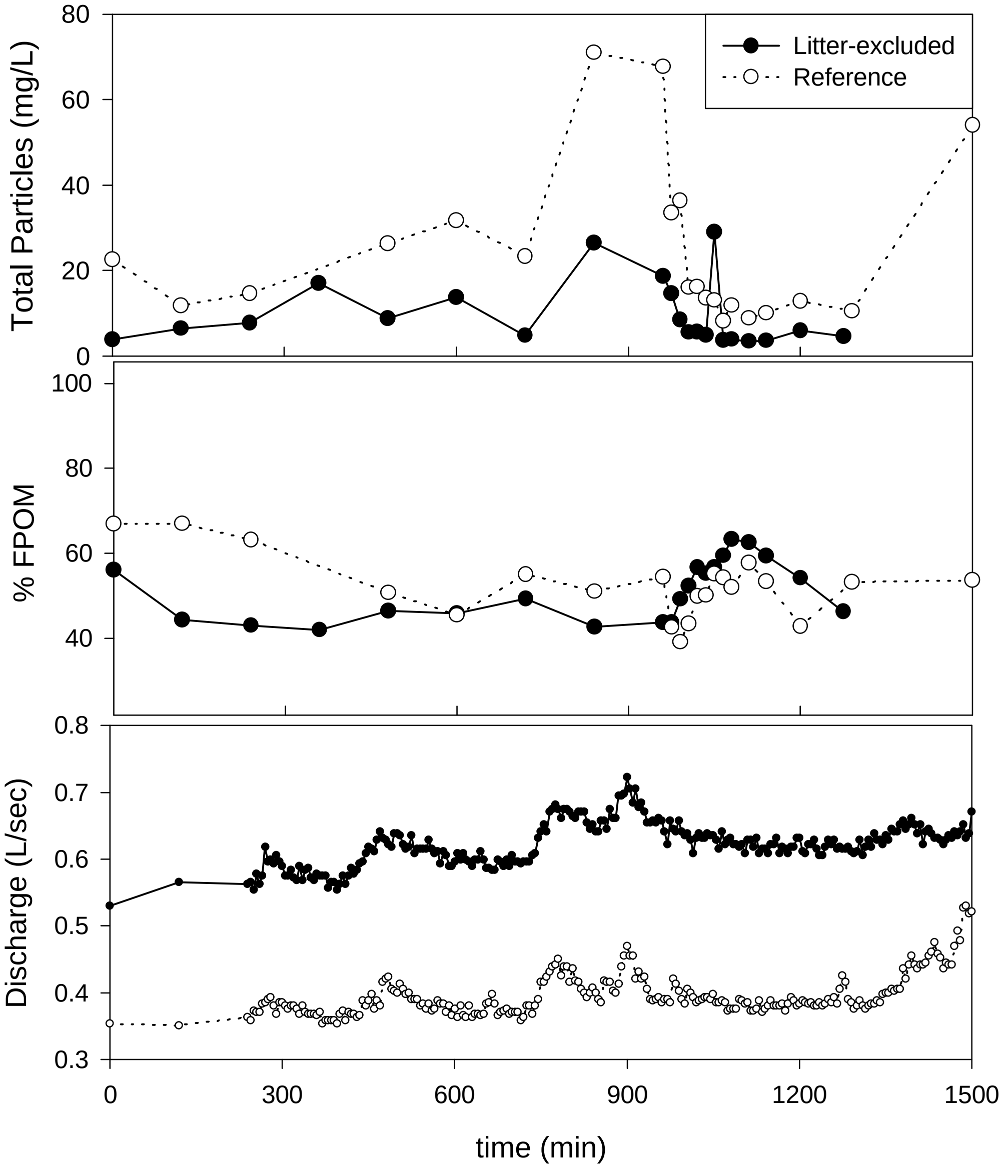
7 August 1995



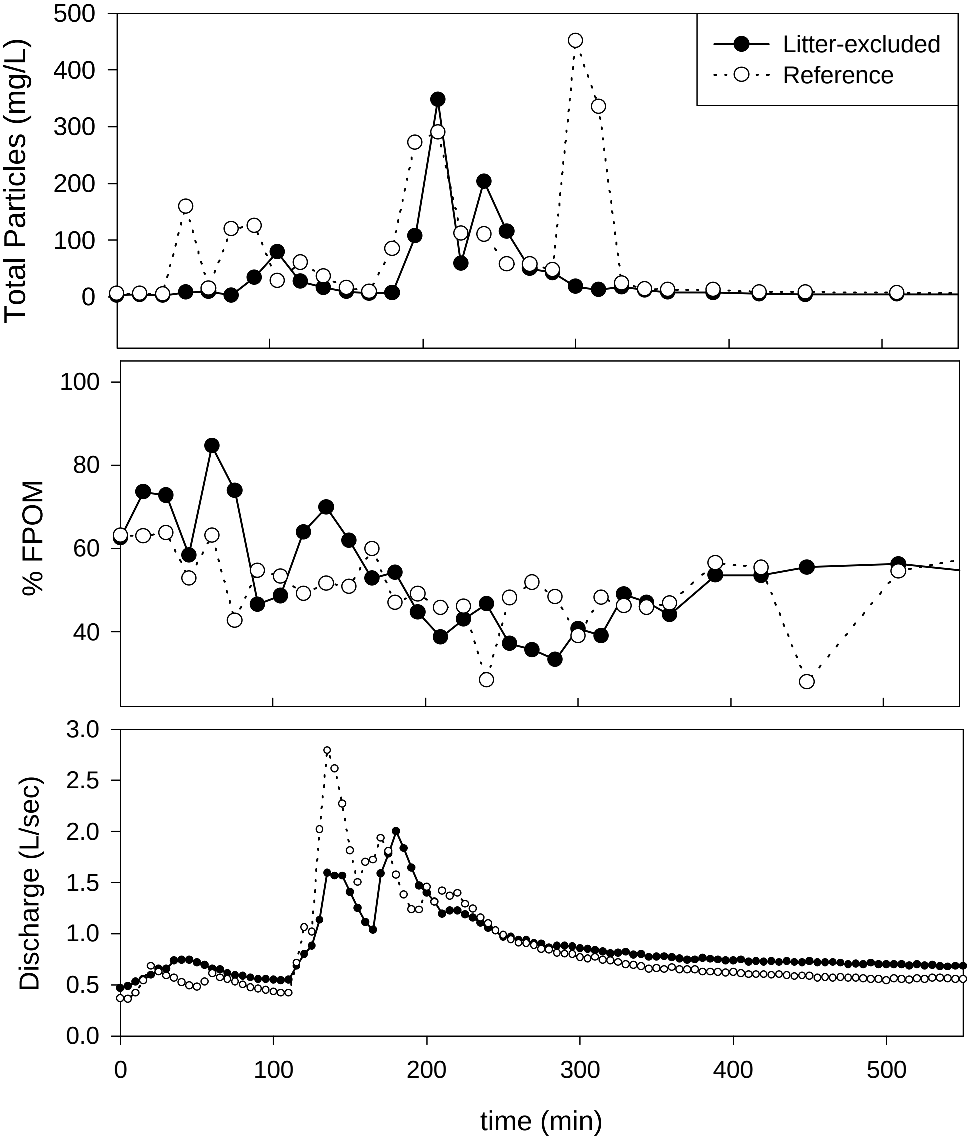
11 November 1995



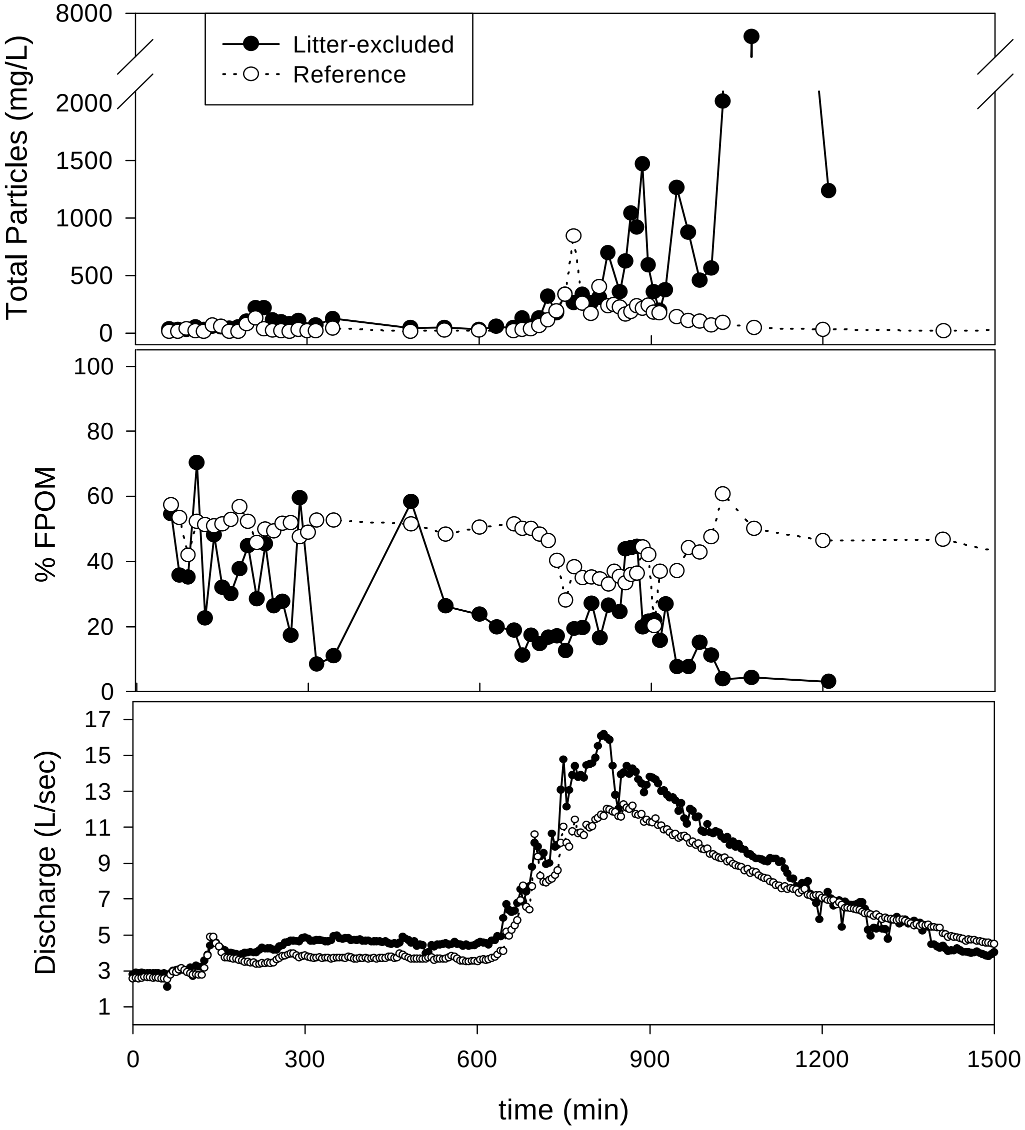
2 September 1996



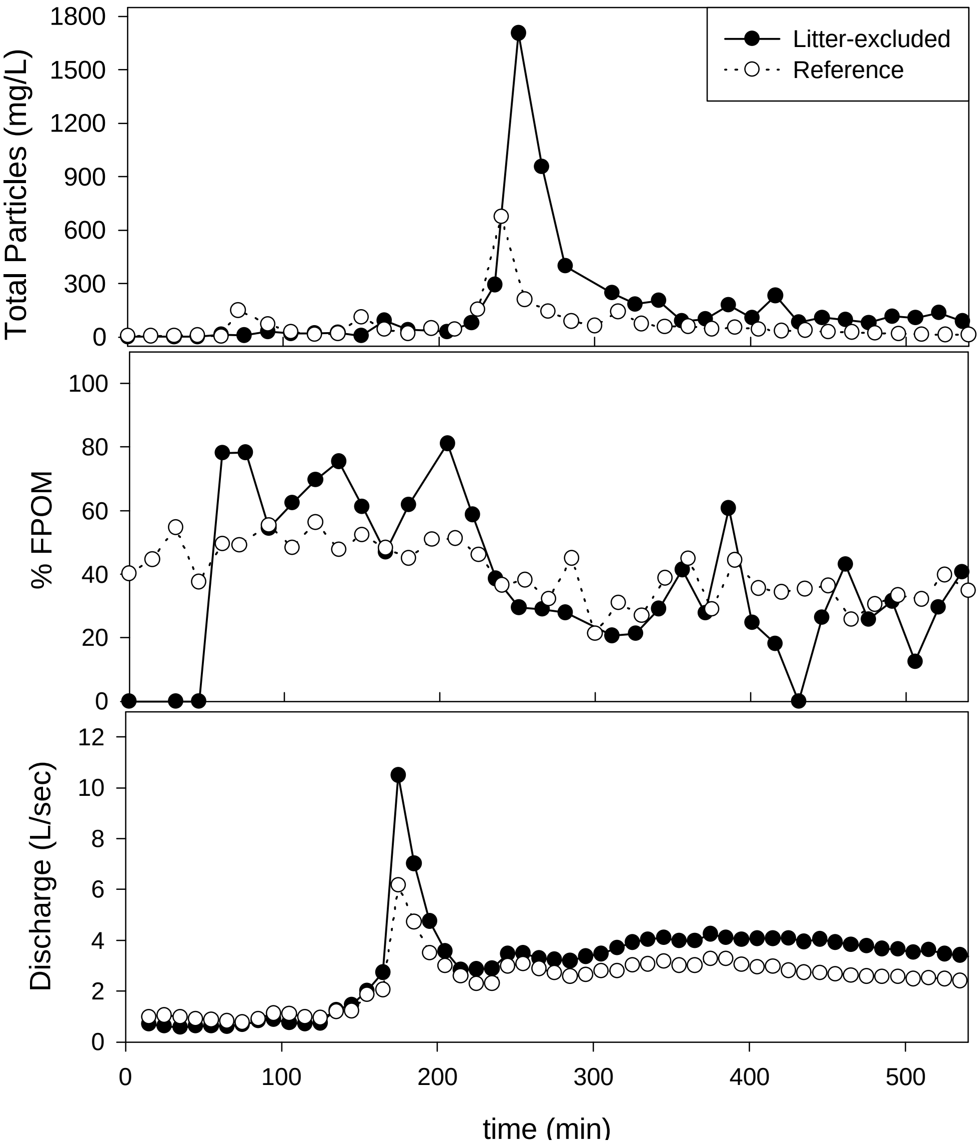
3 September 1996



28 September 1996



7-8 November 1996



APPENDIX B. COMPUTER PROGRAM

```
C        WS 55 MODEL  22 August, 1996      JC ADAMS
C        MODIFIED FROM SIMPLE SESTON MODEL & MODBALL, A.K.A. HGSS
C        MODEL (WEBSTER, UNPUB).
C
C        UNITS -- THE UNITS USED IN THE DIFFERENTIAL EQUATIONS ARE
C        G, M, AND MIN, (BUT NOTE G/M3 = MG/L)
C
C        MAIN PROGRAM VARIABLES:    S(1) DISTANCE  (X IS ALSO
DISTANCE)
C                                                               (M FROM HEADWATERS)
C                                                      S(2) FPOM CONC IN WATER COLUMN
C                                                               (G/M3 = MG/L)
C
C        JJD                DAY COUNTER
C        JJR                RUN COUNTER
C        JDATE              JULIAN DATE -- NO LEAP YEAR
C        TIME               TIME SINCE START IN MINUTES
C        DT                 INTERVAL BETWEEN RUNS DOWNSTREAM (MIN)
C        DTR                INTEGRATION INTERVAL (MIN)
C        EOS                END OF STREAM (M), DISTANCE OF SIMULATION
C        TRUN               TIME SINCE THE START OF A RUN (MIN)
C        IOUT               NUMBER OF ITERATIONS PER OUTPUT
C        ICOUNT             COUNTS ITERATIONS BETWEEN OUTPUTS
C
C        GEOMORPH VARIABLES: G         GRADIENT (M/M)
C                                      BFW    BANKFULL WIDTH (M)
C                                      WIDTH           WETTED WIDTH (M)
C                                      ROUGH           MANNINGS ROUGHNESS COEF
C                                      DEPTH           MEAN DEPTH (M)
C                                      V               VELOCITY AT THAT TIME AND
C                                                      POINT (M/MINUTE)
C                                      A               CROSS SECTION AREA (M2)
C
C        FLOW VARIABLES:
C                           Q                 FLOW AT THAT TIME AND PLACE (L/S)
C                           DQDX              RATE OF CHANGE OF FLOW WITH
C                                             DISTANCE DERIVATIVE OF EQN
C                           DQDT              RATE OF CHANGE OF FLOW AT WEIR WITH
C                                             TIME,  CHANGE SINCE LAST RUN (L/S/HR),
C                                             DQDT IS ZERO EXCEPT DURING STORMS
C
```

```
C        IOFLAG SITE, 1=1M, 2=10M, 3=25M, 4=50M,  5=85M, 6=115M, 7=150M,
C                               8=175M (EOS)
C
      IMPLICIT REAL (K,L,M,N)
      DIMENSION S(2)
C   OPEN INPUT AND OUTPUT FILES
      OPEN (5,FILE='C:\MODEL\Q8nov96.PRN')
      OPEN (6,FILE='CON')
      OPEN (7,FILE='C:\MODEL\SESMODWK.PRN')
      OPEN (4,FILE='C:\MODEL\TIMECONC.PRN')
C
      JDATE=8
C   READ IN FLOW DATA
      CALL FLOWIN
C
C   ISTART IS A FLAG TO IDENTIFY THE INITIALIZATION CALL TO BENTH
      ISTART = 0
C   ISTRT2 IS A FLAG TO IDENTIFY THE FIRST RUN DOWNSTREAM
      ISTRT2 = 0
C
C   SET TIMER CONTROL VARIABLES. THESE ARE IN MIN.
      DT=10
      DTR=.01
C
C***THIS LOOP CONTROLS TIME BETWEEN DOWNSTREAM RUNS***
C   RUNS,(R), ARE AT 10 MIN INTERVALS
C
      DO 99 JJR=1,156
C
C   INITIALIZE OR UPDATE BENTHIC COMPARTMENTS
      CALL BENTH(ISTART,JJR,DT,JDATE)
C
C    SET INITIAL CONDITIONS FOR THE RUN DOWN THE STREAM
      S(1)=0.
      S(2)=0.8
      X=S(1)
      EOS=175
      TRUN=0.
      TIME=FLOAT(JJR-1)*10.
      IOFLAG=1
C
      CALL FLOWW (JJR,QWEIR,DQDT)
      CALL FLOWX (X,QWEIR,DQDT)
      CALL GMORPH (X,QWEIR)
```

```
C
C   **************  RUN LOOP STARTS HERE  **********************
3      CONTINUE
C
C   CHECK FOR OUTPUT
C
      IF(IOFLAG.GT.1)GO TO 4
      CALL OUTT(ISTRT2,TIME,S,EOS)
      IOFLAG=2
      GO TO10
 4    IF(IOFLAG.GT.2)GO TO 5
      IF(S(1).LT.10)GO TO 10
      CALL OUTT(ISTRT2,TIME,S,EOS)
      IOFLAG=3
      GO TO 10
 5    IF(IOFLAG.GT.3)GO TO 6
      IF(S(1).LT.25)GO TO 10
      CALL OUTT(ISTRT2,TIME,S,EOS)
      IOFLAG=4
      GO TO 10
 6    IF(IOFLAG.GT.4)GO TO 7
      IF(S(1).LT.50)GO TO 10
      CALL OUTT(ISTRT2,TIME,S,EOS)
      IOFLAG=5
      GO TO 10
 7    IF(IOFLAG.GT.5)GO TO 8
      IF(S(1).LT.85)GO TO 10
      CALL OUTT(ISTRT2,TIME,S,EOS)
      IOFLAG=6
      GO TO 10
 8    IF(IOFLAG.GT.6)GO TO 9
      IF(S(1).LT.115)GO TO 10
      CALL OUTT(ISTRT2,TIME,S,EOS)
      IOFLAG=7
      GO TO 10
 9    IF(IOFLAG.GT.7)GO TO 10
      IF(S(1).LT.150)GO TO 10
      CALL OUTT(ISTRT2,TIME,S,EOS)
      IOFLAG=8
 10   CONTINUE
C
C   CHECK FOR END OF RUN
      IF(S(1).GE.EOS)GO TO 97
C
```

```
      CALL RKS (TIME,S,DTR,JDATE)
      TRUN=TRUN+DTR
      TIME=TIME+DTR
CC
C   END OF INTEGRATION LOOP
      GO TO 3
C
C  *************  END OF RUN  **********************
C
97   CONTINUE
C   PRINT OUTPUT (OF TRANSPORT) AT END OF RUN
      CALL OUTT(ISTRT2,TIME,S,EOS)
      ISTRT2=1
C
C   END OF SIMULATION TIME
99    CONTINUE
C
C  UPDATE BENTHIC COMPARTMENTS FOR THE LAST INTERVAL.
      CALL BENTH(ISTART,JJR,DT,JDATE)
      STOP
      END
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      SUBROUTINE DFQS(SD,S,TIME,JDATE)
C
C   THIS SUBROUTINE CONTAINS THE DIFFERENTIAL EQUATIONS FOR
C      DISTANCE AND THE WATER COLUMN CONCENTRATIONS
C      UNITS ARE DAYS AND METERS FOR THE DQS
      IMPLICIT REAL (K,L,M,N)
      COMMON /GMOR/G,BFW,WIDTH,DEPTH,ROUGH,V,A
      COMMON /LFLM/LFF,LFS,LFW,LMF,LMS,LMW
      COMMON /FLOW/Q,DQDX,DQDTP
      COMMON /BENTHO/BFPOM
      COMMON /KS/KDEPFP
      COMMON /ENTS/ENTFP
C
      DIMENSION S(2), SD(2)
      DIMENSION BFPOM(10,3)
C
      X=S(1)
C
C  DETERMINE WHICH BENTHIC BOX WE ARE IN
      IF(X.LT.10.)I=1
```

```
      IF(X.GE.10.AND.X.LT.20.)I=2
      IF(X.GE.20.AND.X.LT.35)I=3
      IF(X.GE.35.AND.X.LT.50.)I=4
      IF(X.GE.50.AND.X.LT.70)I=5
      IF(X.GE.70.AND.X.LT.90.)I=6
      IF(X.GE.90.AND.X.LT.110)I=7
      IF(X.GE.110.AND.X.LT.130.)I=8
      IF(X.GE.130.AND.X.LT.150.)I=9
      IF(X.GE.150.)I=10
      IDIST=I
C
C   FIND FLOW AT WEIR FOR THIS TIME (QWEIR, L/S)
C    AND INCREASE IN FLOW OVER THE PAST HOUR (DQDT, L/S/HR)
      JJT=IFIX(TIME/10)+1
      CALL FLOWW (JJT,QWEIR,DQDT)
C
C   FIND FLOW PARAMETERS FOR DISTANCE DOWNSTREAM, X
C     THESE PARAMETERS GO INTO A COMMON AREA /FLOW/ TO SET DQDTP
      CALL FLOWX(X,QWEIR,DQDT)
C
C   FIND GEOMORPHIC PARAMETERS FOR THE DATE AND PLACE
C     THESE PARAMETERS GO INTO A COMMON AREA /GMOR/
      CALL GMORPH(X,QWEIR)

C   DEPOSITION AND ENTRAINMENT
      CALL ENTDEP (S,IDIST)
C
C *************** DIFFERENTIAL EQUATIONS ***********************
C
C   S(1) IS DISTANCE, VELOCITY IS THE DERIVATIVE OF DISTANCE
      SD(1)=V
C
C  S(2) IS TFPOM -- FPOM CONCENTRATION IN THE WATER COLUMN
C      .O6 CONVERTS L/S TO M3/MIN AND L/S/M TO M3/MIN/M
C      DIVIDING BENTHIC BY DEPTH CONVERTS TO CONCENTRATION
      SD(2)=ENTFP-(KDEPFP*S(2))
     $      -(S(2)*DQDX*.06/A)
C
      RETURN
      END
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      SUBROUTINE ENTDEP (S,IDIST)
```

```
C
C    CALCULATES ENTRAINMENT AND DEPOSITION RATES
C
C    ALL EXCHANGES BETWEEN TRANSPORTED AND BENTHIC
C        COMPARTMENTS ARE CALCULATED IN THIS SUBROUTINE.  DURING
C        EACH RUN DOWNSTREAM, INSTANTANEOUS RATES ARE
C        CALCULATED AND USED ASSUMING BENTHIC COMPARTMENTS ARE
C        CONSTANT.  BETWEEN RUNS BENTHIC COMPARTMENTS ARE
C        UPDATED USING AVERAGE EXCHANGE RATES OVER THE DISTANCE
C        OF THE BENTHIC COMPARTMENT.
C
C         KDEPFP         FPOM DEPOSITION
C
C         ENTFP          FPOM ENTRAINMENT   (MG/L/MIN)
C
C         ERFP           FPOM ENTRAINMENT RATE  (PER MIN)
C
      IMPLICIT REAL (K,L,M,N)
      DIMENSION S(2)
      DIMENSION BFPOM(10,3)
      COMMON /GMOR/ G,BFW,WIDTH,DEPTH,ROUGH,V,A
      COMMON /FLOW/ Q,DQDX,DQDTP
      COMMON /BENTHO/ BFPOM
      COMMON /KS/KDEPFP
      COMMON /ENTS/ENTFP
C
C ***************** DEPOSITION *************************************
C
C  VD IS DOWNWARD VELOCITY (DEPOSITION VELOCITY, M/min)
C
      VDFP=0.0001
C  TT IS THE AVERAGE PARTICLE TRAVEL TIME (MIN)
      TTFP=(DEPTH/2)/VDFP
C
C  KDEP IS THE DEPOSITION RATE = 1/TT (PER MIN)
      KDEPFP= 1/TTFP
C
C *************** ENTRAINMENT ************************************
C
C  SET ENTRAINMENT RATES (PER MIN)
C  ERFP IS ARBITRARY NUMBER CHOSEN BY MANUAL INTERATION TO GET
BEST FIT TO PRETREATMENT DATA
      ERFP=0.00165
C
```

```
C  THIS EQN IS BASED ON WS 55 STORM DATA FROM 86-89,(WEBSTER,unpub)
C   THE MAXIMUM POSSIBLE IS SET AT 400, ~HIGHEST RECORDED CONC.
C
      MXCONC=(12.79*DQDTP)+3.88
      IF(MXCONC.GT.400.)MXCONC=400.
C
C  PARTITION MXCONC INTO COMPONENTS
      MCNCFP=.94*MXCONC
C
C2    CONTINUE
C  IF CURRENT CONCENTRATIONS ARE GE THAN MAX CONCS, ENT=0
C   OTHERWISE ENTRAINMENT IS THE ENT RATE TIMES THE DEFICIT
C   (MAX-ACTUAL) IF THERE IS ENOUGH AVAILABLE ON THE BOTTOM.
C    BE SURE ENTRAINMENT AT THIS RATE OVER THE NEXT 10 MINS WON'T
C     MORE THAN DEPLETE STORAGE
C    IF IT WOULD, THEN THE ENTRAINMENT RATE IS JUST WHAT IT TAKES
C     TO DEPLETE STORAGE OVER THE NEXT 10 MINUTES.
C
      ENTFP=(MCNCFP-S(2))*ERFP
      IF(S(2).GT.MCNCFP) ENTFP=0.
      IF((ENTFP*10.).GT.(BFPOM(IDIST,1)/DEPTH))
     $ENTFP=(BFPOM(IDIST,1)/DEPTH)*0.1
C
      I=IDIST
C
C  ***ACCUMULATE INPUTS AND OUTPUTS ***************************
C
      BFPOM(I,2)=BFPOM(I,2)+(KDEPFP*S(2)*DEPTH)
     $            -(ENTFP*DEPTH)
      BFPOM(I,3)=BFPOM(I,3)+1.
C
      RETURN
      END
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      SUBROUTINE BENTH (ISTART,JJR,DT,JDATE)
C          INITIALIZES OR UPDATES THE BENTHIC COMPARTMENTS
C
C       BENTHIC COMPARTMENTS    BFPOM   BENTHIC FPOM (G/M2)
C
C          EACH BENTHIC COMPARTMENT IS SUBDIVIDED INTO 10
C           COMPARTMENTS ALONG THE LENGTH OF THE STREAM.  DIVISION
C           POINTS ARE:  0, 10, 20, 35, 50, 70, 90, 110, 130, 150, AND 175
```

```
C
C           BFPOM(X,1) IS STANDING CROP,
C           BFPOM(X,2) IS THE TOTAL NET (DEP-ENT)
C                     INPUT DURING THE PERIOD,
C           AND BFPOM(X,3) IS THE NUMBER OF INPUTS.
C
C     OTHER           BIO    BENTHIC INPUT - OUTPUT
C                     DB     DERIVIATIVE OF BENTHIC COMPARTMENT
C
      IMPLICIT REAL (K,L,M,N)
      DIMENSION BFPOM(10,3)
      COMMON /GMOR/ G,BFW,WIDTH,DEPTH,ROUGH,V,A
      COMMON /LFLM/LFF,LFS,LFW,LMF,LMS,LMW
      COMMON /FLOW/ Q,DQDX,DQDT
      COMMON /BENTHO/ BFPOM
C
C  SKIP THIS SECTION EXCEPT ON THE FIRST CALL TO THIS SUBROUTINE
      IF(ISTART.GT.0)GO TO 1
C
C  SET FREQUENCY OF BENTHIC OUTPUT
C   1 FOR DEBUGGING
      IOUTB=1
      ICOUNT=IOUTB
C
C SET INITIAL CONDITIONS FOR BENTHIC FPOM ( G/M2) from most recent BOM
C         samples taken from WS 55 prior to storm date.
      BFPOM(1,1)=390.0
      BFPOM(2,1)=390.0
      BFPOM(3,1)=390.0
      BFPOM(4,1)=390.0
      BFPOM(5,1)=390.0
      BFPOM(6,1)=390.0
      BFPOM(7,1)=390.0
      BFPOM(8,1)=390.0
      BFPOM(9,1)=390.0
      BFPOM(10,1)=390.0
C
      ISTART=1
      GO TO 98
C
1     CONTINUE
C
C  UPDATE BENTHIC COMPARTMENTS USING EULER
C  BENTHIC FPOM
```

```
      DO 7 I=1,10
C
      CALL WTEMP (JDATE,TEMP)
C
C  NO RESPIRATION
      KFPOMR=0.
C
C  ********* EULER SOLUTION OF DIFFERENTIAL EQUATIONS *********
C
      IF(BFPOM(I,3).LE.0.)THEN
       BIO=0.
       ELSE
       BIO=BFPOM(I,2)/BFPOM(I,3)
       ENDIF
      DB=BIO-(KFPOMR*BFPOM(I,1))
      BFPOM(I,1)=BFPOM(I,1)+DB*DT
C
C
7      CONTINUE
98      CONTINUE
C
C  SET INPUT AND OUTPUT BOXES TO ZERO TO START THE NEXT
C       INTERVAL
      DO 3 I=1,10
      DO 3 J=2,3
3      BFPOM(I,J)=0.
C
C   OUTPUT BENTHIC COMPARTMENTS
      IF(ICOUNT.GE.IOUTB.OR.JJR.GE.120)THEN
        CALL OUTB(JJR)
        ICOUNT=1
        ELSE
        ICOUNT=ICOUNT+1
        ENDIF
      RETURN
      END
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      SUBROUTINE OUTB(JJR)
C
C  THIS SUBROUTINE WRITES BENTHIC RESULTS
C  BDIST IS THE MIDPOINT OF EACH COMPARTMENT (M)
      IMPLICIT REAL (K,L,M,N)
```

```
      DIMENSION BFPOM(10,3)
      DIMENSION BDIST(10)
      COMMON /BENTHO/ BFPOM
      DATA BDIST/5,15,27.5,42.5,60,80,100,120,140,162.5/
C
C   WRITE COLUMN HEADINGS FOR BENTHIC OUTPUT
      TIME=FLOAT(JJR-1)*10
      WRITE(6,962)
      WRITE(6,964)
      WRITE(6,965)
      WRITE(7,962) TIME
      WRITE(7,964)
      WRITE(7,965)
962   FORMAT(/,' DIST   BFPOM    TIME SINCE START (MIN)',F6.1)
964   FORMAT('  (m)   (g/m2)')
965   FORMAT(' ------------------------------------------------')
C
C   WRITE OUTPUT
      DO 97 I=1,10
      WRITE(6,966)BDIST(I),BFPOM(I,1)
      WRITE(7,966)BDIST(I),BFPOM(I,1)
97    CONTINUE
966   FORMAT(' ',F7.1,5F8.2,2F9.3,F8.2)
C   CALCULATE MEAN BFPOM
      SUM=0.
      DO 98 I=1,10
98    SUM=SUM+BFPOM(I,1)
      MEAN=SUM/10.
      WRITE(6,967)MEAN
      WRITE(7,967)MEAN
967   FORMAT(' MEAN BFPOM(g/m2) = ',F10.2)
C
      RETURN
      END
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      SUBROUTINE OUTT(ISTRT2,TIME,S,EOS)
C   THIS SUBROUTINE PRINTS THE SIMULATION RESULTS FOR TRANSPORT
      IMPLICIT REAL (K,L,M,N)
      COMMON /GMOR/ G,BFW,WIDTH,DEPTH,ROUGH,V,A
      COMMON /FLOW/ Q,DQDX,DQDTP
      COMMON /BENTHO/ BFPOM
      COMMON /KS/KDEPFP
```

```
      COMMON /ENTS/ ENTFP
C
      DIMENSION BFPOM(10,3)
      DIMENSION S(2)
      X=S(1)
      LOAD=S(2)*Q
C
C  INITIALISE LOAD ACCUMULATOR
      IF (ISTRT2.GT.0) GO TO 6
      SUMS2=0.
      SUMFLO=0.
      MS2=0.
C
6     CONTINUE
C  WRITE HEADINGS FOR TRANSPORT OUTPUT IF BEGINNING OF RUN
C  ******** FORMATS AND WRITES FOR NORMAL OUTPUT *************
      IF(X.GT.1) GO TO 7
      WRITE(6,1453)
      WRITE(6,1454)
      WRITE(6,1455)
      WRITE(7,1452)
      WRITE(7,1454)
      WRITE(7,1455)
C
1452   FORMAT(/,' TIME        DIST      FPOM       FLOW     DQDTP ')
1453   FORMAT(' TIME        DIST      FPOM       FLOW     DQDTP ')
1454   FORMAT(' (MIN)       (M)      (MG/L)      (L/S)    (%/HR) ')
1455   FORMAT(' ------------------------------------------------')
C
7     CONTINUE
      WRITE(6,4)TIME,S(1),S(2),Q, DQDTP
      WRITE(7,4)TIME,S(1),S(2),Q, DQDTP
4     FORMAT(",F7.0,3X,F5.0,F10.3,2X,F8.2,2X,F10.3)
C  IF WE REACH END OF STREAM, ACCUMULATE FLOW AND
CONCENTRATION
      IF (S(1).LT.EOS) GO TO 5
C
      SUMS2=SUMS2+(S(2)*Q)
      SUMFLO=SUMFLO+Q
C
C  CALCULATE STORM MEANS
3     MS2=SUMS2/SUMFLO
      IF (ISTRT2.GT.0) GO TO 22
      CLOAD=0.
```

```
      LOADI=SUMS2
      GO TO 21
C  MULT BY 60 TO CONVERT SEC TO MIN, DIV BY 1000 TO CONVERT MG
C      TO G;
C   MULT BY 10 BECAUSE IT'S 10 MINS BETWEEN RUNS (=0.6)
22    CLOAD=(SUMS2-LOADI)*0.6
21    CONTINUE
C
      WRITE(6,14) MS2,CLOAD
      WRITE(7,14) MS2,CLOAD
14    FORMAT(' MEAN CONC (MG/L)=' ,F10.3,' CUM LOAD(G)=',F12.3)
C
C  PRINT TIME AND CONCENTRATION AT 175 METERS TO SEPARATE FILE
      WRITE(4,15) TIME,S(2)
15    FORMAT(F10.0,3X,F10.3)
C
5     CONTINUE
      RETURN
      END
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      SUBROUTINE FLOWIN
C  THIS SUBROUTINE USED TO ENTER INITIAL FLOW DATA
      DIMENSION FLOW10(500),DQDT10(500)
      COMMON/QW/FLOW10, DQDT10
C      QWEIR=1.10
      DO 3, J=1,156
      READ(5,2)FLOW10(J),DQDT10(J)
2     FORMAT(2F10.0)
3     CONTINUE
1     RETURN
      END
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      SUBROUTINE FLOWW (J,QWEIR,DQDT)
C   THIS SUBROUTINE DETERMINES THE APPROPRIATE FLOW AND RATE OF
C      CHANGE OF FLOW FOR THIS TIME AT THE WEIR
      DIMENSION FLOW10(500),DQDT10(500)
      COMMON/QW/FLOW10, DQDT10
      QWEIR=FLOW10(J)
      DQDT=DQDT10(J)
      RETURN
```

```
      END
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      SUBROUTINE FLOWX (X,QWEIR,DQDT)
C   THIS SUBROUTINE CALCULATES FLOW PARAMETERS FOR THE
C       PARTICULAR TIME AND PLACE
      IMPLICIT REAL (K,L,M,N)
      COMMON /GMOR/ G,BFW,WIDTH,DEPTH,ROUGH,V,A
      COMMON /FLOW/ Q,DQDX,DQDTP
C
C   FIND MEAN FLOW FOR THE PARTICULAR PLACE (Q, L/S)
C    THIS EQUATION COMES FROM AREA OF WATERSHED (19% OF WEIR
C    FLOW@SPRING)
C    DQDX IS THE DERIVATIVE OF THIS EQN
C  DQDT IS THE % INCREASE IN FLOW PER INTERVAL EXPRESSED IN
C     HOURS
C
      Q=(0.19*QWEIR)*EXP(0.0094899*X)
      DQDX=0.0094899*Q
      DQDTP=(DQDT/QWEIR)*100.
C
      RETURN
      END
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      SUBROUTINE GMORPH (X,QWEIR)
C   THIS SUBROUTINE CALCULATES GEOMORPHIC PARAMETERS FOR THE
C     PARTICULAR TIME AND PLACE
      IMPLICIT REAL (K,L,M,N)
      COMMON /GMOR/ G,BFW,WIDTH,DEPTH,ROUGH,V,A
      COMMON /FLOW/ Q,DQDX,DQDTP
C
C   GRADIENT (G, M/M)  NOTE: GRADIENT EQN GIVES A NEGATIVE #, BUT
C    A POSITIVE # IS NEEDED IN THE DEPTH EQN, SO THE SIGN IS CHANGED:
      G=(0.000292)*(852.80)*EXP(-0.000292*X)
C
      CALL BANKFL (X, BFW)
C   BANKFULL WIDTH (BFW, M), DATA FROM 1994 SURVEY  ((MEAN))
C      BFW=3.04
C
C   MANNINGS ROUGHNESS COEFFICIENT (ROUGH) FROM 1991 CHLORIDE
C       RELEASES AS USED IN MODBALL PROGRAM
```

```
      ROUGH=2.0784*EXP(-0.000534*X)
C
C   DETERMINE WETTED WIDTH (WIDTH), AS PERCENTAGE OF BFW
C    DETERMINED BY MEASUREMENTS MADE DURING 19145 CHLORIDE
C    RELEASES, AND SETTING QMAX AT BFW AS THE FLOOD MAGNITUDE
C    THAT OCCURS IN 2 YRS OUT OF 3 (ALLAN, 19145).  VALUE OF 25 L/sec
C    SELECTED FROM 1985-91 MAX DAILY DISCHARGE DATA PROVIDED BY
C    WALLACE (UNPUBLISHED), AND Y IS LN-TRANSFORMED AND FIT TO A
C     1ST-ORDER EQUATION.
      WIDTH=BFW*(0.400*EXP(0.036936*QWEIR))
      IF (WIDTH.GT.BFW)WIDTH=BFW
C
C  WE NOW HAVE TWO UNKNOWNS (DEPTH AND VELOCITY), AND TWO
C     EQUATIONS (MANNING AND FLOW CONTINUITY).  SOLVING, WE GET:
C     CALCULATE DEPTH FROM MANNING EQUATION, Q CONVERTED TO
C     M3/SEC   NOTE: IN MANNING EQN, Q IS M3/S AND WIDTH AND DEPTH
C     ARE M
C
      DEPTH=((((Q/1000.)*ROUGH)/((WIDTH)*G**.5))**.6)
      A=WIDTH*DEPTH
C
C  CALCULATE VELOCITY FROM FLOW CONTINUITY, Q CONVERTED TO
C     M3/MIN
      V=(Q*.06)/A
      RETURN
      END
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      SUBROUTINE BANKFL (X, BFW)
C
C  THIS SUBROUTINE CALCULATES BANKFULL WIDTH AT EACH DISTANCE
C     X BY LINEAR INTERPOLATION BETWEEN SURVEY DATA (JUNE 1994,
C     UNPUB)
C
      IMPLICIT REAL (K,L,M,N)
      DIMENSION WIDTH(36),METER(36)
C
      DATA WIDTH /2.14,2.75,3.36,2.03,3.52,5.,4.43,3.54,3.85,3.55,2.85,
     &2.46,2.44,3.42,3.62,2.86,2.71,3.5,3.1,3.44,2.26,4.5,1.74,1.98,
     &2.68,2.33,3.97,2.33,3.13,2.68,3.62,4.145,2.7,2.59,2.6,2.6/
C
      DATA METER /0,5,10,15,20,25,30,35,40,45,50,55,60,65,70,75,80,85,
     &90,145,100,105,110,115,120,125,130,135,140,150,155,160,165,170,
```

```
     &175,176/
C
      DO 52 I=1,35
52    IF (METER(I).GT.X) GO TO 22
22    HFA = (X-METER(I-1))/(METER(I)-METER(I-1))
C THE ABOVE LINE CALCULATES FRACTION OF DISTANCE X OVER REACH
      BFW = (HFA*(WIDTH(I) - WIDTH(I-1))) + WIDTH(I-1)
C
      RETURN
      END
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      SUBROUTINE RKS(TIME,S,DTR,JDATE)
C
C  THIS SUBROUTINE DOES STANDARD RUNGE-KUTTA INTEGRATION
C
      IMPLICIT REAL (K,L,M,N)
      DIMENSION S(2),SD(2),SP(2),SQ(2),SR(2),SPD(2),SQD(2),SRD(2)
      DTR2=DTR/2
      CALL DFQS(SD,S,TIME,JDATE)
      DO 1 I=1,2
1     SP(I)=S(I)+DTR2*SD(I)
      T2=TIME+DTR2
      TT=TIME+DTR
      CALL DFQS(SPD,SP,T2,JDATE)
      DO 2 I=1,2
2     SQ(I)=S(I)+DTR2*SPD(I)
      CALL DFQS(SQD,SQ,T2,JDATE)
      DO 3 I=1,2
3     SR(I)=S(I)+DTR*SQD(I)
      CALL DFQS(SRD,SR,TT,JDATE)
      DO 4 I=1,2
4     S(I)=S(I)+(DTR/6.)*(SD(I)+2.*SPD(I)+2.*SQD(I)+SRD(I))
      RETURN
      END
```

CURRICULUM VITAE

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Birthdate and Place: 27 May 1962 in Greensburg, Pennsylvania, USA.

Education

1998	Master of Science, Virginia Polytechnic Institute & State University, Blacksburg, Virginia. M.Sc.thesis topic: The role of leaf litter in the retention of fine particles in an Appalachian headwater stream.
1993	Bachelor of Science in Biology *(cum laude)*, Arizona State University, Tempe, Arizona .
1991	Associate of Arts (with high distinction), Mesa Community College, Mesa, Arizona.

Employment

March 1997 - present	Ecologist: The Rellney Group, 749 Port Road, Woodville, SA, Australia. Duties include: determining wastewater treatment requirements for wineries, designing artificial wetlands for wastewater treatment, selecting and supervising the installation of wetland plants, and monitoring wetland performance.
Nov 1996 - Dec 1996	Administrative Assistant: GEC Marconi Systems Pty. Ltd. Innovation House, The Levels, SA, Australia. Duties included: Word processing, filing, and creating presentation materials.

Jan - Aug 1996	Graduate Research Assistant: Dr. J.R. Webster, Department of Biology, Virginia Polytechnic Institute & State University, Blacksburg, VA, USA. Duties included: Stream morphometry and mapping, benthic organic matter surveying, conducting studies of hydrologic retention time, data analyses, writing computer simulation programs, and supervising undergraduate employees.
1994 - 95	Graduate Teaching Assistant: Department of Biology, Virginia Polytechnic Institute & State University, Blacksburg, VA, USA. Duties included: Teaching General Biology and Freshwater Ecology laboratories.
1992 - 94	Research Assistant: Desert Stream Ecology Lab, Department of Zoology, Arizona State University, Tempe, Arizona, USA. Duties included: Water chemistry analyses, aquatic macroinvertebrate sampling and identification, algal sampling and analysis of biomass, stream morphometry and mapping, gas analyses using gas chromatography, sediment organic matter analyses, and data entry.
1985 - 90	Medical Office Assistant: Desert Oncology Clinic, Mesa, Arizona, USA. Duties included: clinical laboratory procedures, data entry, scheduling, accounts receivables, and personnel training.

Related Coursework

Aquatic Entomology
Aquatic Vascular Plants
Biometry
Conservation Biology
Ecosystems Analysis
Hazard Evaluation of Toxic Chemicals
Lake Ecology
Limnology
Microbiology
Nonparametric Statistics
Phycology
Population & Community Ecology
Topics in Freshwater Ecology

Teaching Experience

Guest Lecturer:

Ecosystem Nutrient Cycling, College of Pharmacy, Biomedical Sciences & Environmental Toxicology, University of South Australia.

Design Considerations in Domestic Wastewater Recycling, Department of Architecture, University of Adelaide.

Laboratory Teaching Assistant:

General Biology

Principles of Biology

Freshwater Ecology

Professional Associations

Member, Australian Water and Wastewater Association

Member, Ecological Society of Australia

Division Secretary, Environment Institute of Australia

Member, North American Benthological Society

Honors/Awards

Jessie M. Bierman Scholarship for June-August 1993 to attend University of Montana's Flathead Lake Biological Station for summer field courses.

Regent's Scholarship for 1991-1993 to study at Arizona State University.

Published Abstracts and Presentations

Adams, J.C., J.R.Webster, J.B.Wallace, and S.L.Eggert. Storm transport of fine particulates in a litter-excluded Appalachian headwater stream. Paper presented at the North American Benthological Society 44th Annual Meeting. June 1996, Kalispell, Montana,USA.

Publications

Adams, J.C. 1997. The role of the Irrigation Management Plan (IMP) in schemes using reclaimed water. IN: N. Palmer (ed.) Toward the Coming of Age of the SA Water Industry, Proceedings from the 1997 AWWA South Australian Regional Conference. Australian Water & Waste Water Association, Adelaide. Pp. 125-132.

Manuscript Reviewer

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Other Qualifications

PADI Open Water Diver Certification

Senior First Aid Certification, St. John's Ambulance of Australia

References

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