Delivery of pollutants from nonpoint sources

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ABSTRACT The paper summarizes past and present research in Wisconsin, USA dealing with characterization and quantification of nonpoint source pollution loads from small experimental sub-basins. The sub-basins included urban, rural and urbanizing (construction) areas with predominantly homogeneous land use characteristics. The research reveals that: (a) In the overland flow phase the loss of runoff energy due to termination of rainfall determines the magnitude of the delivery ratio. This is typical for agricultural and urbanizing sub-basins. (b) Magnitude of the delivery ratio for urban and suburban sub-basins is related to type of drainage system with ranges from 100 percent for sewered sub-basins to 10 percent for suburban low density residential sub-basins with natural (grass swale) storm drainage. (c) As the largest amounts of pollutants from nonpoint sources are associated with the fine mineral and organic fractions of sediments they are enriched during the runoff process.

INTRODUCTION

At the 1985 National Convention of the Water Pollution Control Federation, the Honorable Lee Thomas--administrator of the US EPA--declared nonpoint pollution to be the focus of future water pollution control efforts (Anon., 1985). Recognizing that a massive federal nonpoint pollution clean-up program is not feasible, Thomas called for redirecting existing federal, state, local, and private resources to address nonpoint source problems of national priority.

All nonpoint pollution abatement programs must locate those lands, and define those land use activities that pose the most severe threat to receiving waters--so-called "hazardous lands" (Novotny & Chesters, 1981).

To define hazardous lands, information is needed on the strength of the areal pollution source and the attenuation of pollutants between the source and the receiving waterbody.

DELIVERY RATIO

The strength of the source, i.e., sediment or pollutant load, is usually determined by a hydrological sediment and/or pollutant generating equation or model such as the Universal Soil Loss Equation (Wischmeier & Smith, 1965).

Several studies beginning with Roehl in 1962 up to the most recent information presented at this symposium, have shown that upland erosion and pollutant generation estimated from either an erosion model or from extrapolation of measurements made on small plots, do not equal the sediment or pollutant yield measured in the receiving waters at the basin outlet. To account for these differences, the sediment delivery ratio factor (DR) has been introduced:

$$DR = \frac{Y}{A} \tag{1}$$

where Y = basin sediment or pollutant yield and A = upland erosion or pollution generation potential.

PROCESSES INVOLVED IN SEDIMENT AND POLLUTANT DELIVERY

Many factors and processes contribute to the fact that upland erosion and pollutant generation markedly differs from measured loads to the receiving waters. The attenuation processes (or factors) can be divided into those occurring during overland flow or those occurring during the channel (concentrated) flow phase of pollutant transport. The major overland flow factors were defined by Novotny (1980) as:

(a) Rainfall impact detaches soil particles and keeps them in suspension for the duration of the rainfall. When the energy from rainfall terminates or is reduced, the excess particles in suspension are redeposited.
(b) Overland flow energy detaches soil particles from small rills and together with some interrill contribution, the particles remain in suspension so long as overland flow persists. The sediment content of overland flow is at or near the saturated state, and the sediment carrying capacity of overland flow is directly proportional to the amount of flow. If flow is reduced during the receding portion of the hydrograph, the excess sediment is deposited.
(c) Vegetation slows down flow and filters out particles during shallow flow conditions.
(d) Infiltration filters out the particles from the overland flow.
(e) Small depressions and ponding allow particles to be deposited due to reduction of velocity.
(f) Change of the slope of overland flow due to concavity of the drainage area often flattens the slope near the drainage channel and steepens the slope uphill. The sediment and pollutant transport capacity of overland flow changes according to slope.

In the channel flow phase, flow is more concentrated and sediment carrying capacity is much larger. However, the delivery process usually refers to sediment and pollutant attenuation between the source area and the channel. Flow in the channels is not considered further in this paper.

OVERLAND FLOW EFFECT

The principal relationship between detachment, deposition, and sediment carrying capacity of overland flow was defined by Foster & Meyer (1972) as:

$$\frac{D_f}{D_c} + \frac{q_s}{T_c} = 1 \qquad (2)$$

where D_f = detachment or deposition by flow (mass/area x time), D_c = detachment capacity of flow mass/area x time), q_s = sediment load of flow (mass/width x time), and T_c = transport capacity of flow (mass/width x time).

If D_c and T_c are similarly related to a function involving shear stress and other parameters the detachment or deposition rate defined in (2) becomes:

$$D_f = \alpha(T_c - q_s) \qquad (3)$$

indicating that as long as sediment content is below the sediment carrying capacity of the overland flow, then overland flow is erosive. When sediment carrying capacity decreases below the sediment content in the receding portion of the hydrograph then excess sediment is deposited.

The sediment carrying capacity of overland flow is related to two energy inputs: (a) rainfall impacting on the surface of shallow flow significantly increases transport (Novotny, 1980; Neibling & Foster, 1983), and (b) shear stress of the overland flow is related to turbulence characteristics of the overland flow.

From the Yalin (1963) equation, the sediment carrying capacity of overland flow is proportional to water flow, q is defined by Novotny (1980) as $T_c \sim q^{\beta}$ where the coefficient β ranges from 1.2 to 1.5. The sediment concentration in the runoff C_e is then:

$$C_e \sim q^{\beta-1} \qquad (4)$$

Measured and computed concentrations of sediment from a construction site as related to rainfall and runoff energy are shown in Figure 1. The experimental sub-basin at the construction site had an area of 9.7 ha, average slope <3 percent and slope-length (overland flow distance of approximately 100 m. The sediment delivery ratio for the event was 0.43.

TRAPPING EFFICIENCY OF GRASSES AND VEGETATION

Often overland flow percolates under shallow flow conditions (grass height is greater than the depth of flow) through vegetative filters. Research at the University of Kentucky (Toller et al., 1976; Hayes et al., 1982; Barfield et al., 1984) led to the development of a preventive model for determining the trapping efficiency of grass filters:

$$\% \text{ removal} = 100 * \exp(-\ 0.00105 \frac{R_e^{0.82}}{N_f^{0.91}}) \qquad (5)$$

where $N_f = \frac{Lw}{Vy}$; $Re = \frac{VR_s}{\gamma}$; L - length of the grass filter, w = the settling velocity of the particle, V = flow velocity, y = flow depth, γ = kinematic viscosity, and R_s = the spacing hydraulic radius of grasses.

Experimental measurements and the above model indicate that 90 percent removal efficiency can be achieved during shallow flow through a grass strip of 2 m width (Novotny & Chesters, 1981; Hayes et al., 1982).

The combined effect of overland flow deposition and infiltration and

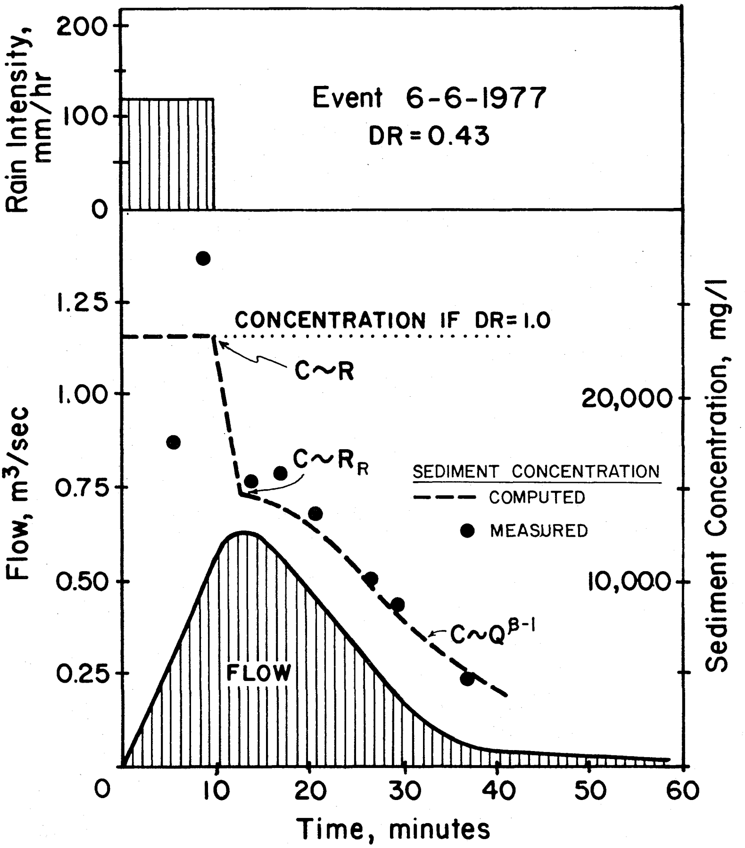

FIG. 1 Hydrograph and sediment concentrations for a sub-basin in the Germantown area of the Menomonee River basin on 6 June 1977.

vegetative filtering in agricultural basins may result in surprisingly low delivery ratios. Frequently, as much as 80 percent of the sediment produced by sheet and rill erosion is redeposited without leaving the field (Piest et al., 1975).

EFFECT OF DRAINAGE ON SEDIMENT AND POLLUTANT DELIVERY

From 1975 to 1980, a number of small experimental sub-basins were monitored in the Menomonee River basin located in Metropolitan Milwaukee (Novotny et al., 1979). A hydrological model, calibrated and verified by field measurements from very small, uniform sub-basins within the basin was used to estimate upland loadings of sediment and phosphorus. hydrology (water yields) and sediment yields were calibrated and subsequently simulated.

The simulation showed that the DR for sediment ranged from 0.01 for pervious portions of the basin for developed lands in unsewered areas to 1.0 for urban land in completely storm sewered sub-basins. Thus the DR was largely dependent on the degree of storm sewering in the sub-basins. Table 1 shows the ranged of estimated DR values.

TABLE 1 Estimated sediment DR from pervious areas for various land uses in sub-basins of the Menomonee River (Wisconsin) experimental basin (Novotny et al., 1979)*

Sub-basin type	*Impervious area (%)*	*Degree of storm sewering (%)*	*Sediment DR*
Agricultural	<5	0	0.01 - 0.3
Developing construction	<5	20-50	0.2 - 0.5
Low density residential, unsewered	<20	0	<0.1
Parks	<10	0	<0.03
Medium density residential, partially sewered	30 - 50	<50	0.3 - 0.7
Medium density residential, sewered	30 - 50	>50	0.7 - 1.0
Commercial high density residential, sewered	>50	80 - 100	1.0

**Delivery ratio of sediment from impervious connected areas - 1.0.*

RELATION BETWEEN DR AND ENRICHMENT OF POLLUTANTS IN RUNOFF

Deposition is important in nonpoint pollution analyses because it changes the qualitative properties of sediments. Firstly, detachment of the sediment and pollutants from the parent soil is selective for dissolved pollutants and for the fine particle fractions of the soil. In soils, most pollutants are adsorbed by the clay and organic fractions because of their high surface area leading to the formation of strong adsorption bonds. When rainwater reaches the surface horizon of the soil, some pollutants are desorbed and go into solution; another portion remains adsorbed and moves with the soil particles. Thus pollutants contained in runoff sediments may be present in higher concentrations than in the parent soil. This difference is termed the enrichment ratio (ER):

$$ER = \frac{C_r}{C_s} \qquad (6)$$

where C_r = the pollutant content of the runoff per gram of sediment, and C_s is the pollutant content of the parent soil per gram.

The ER refers to the difference in particle size distribution and adsorbed pollutant content of washload particles and the soils from which the sediment originated (Novotny & Chesters, 1981). Enrichment of sediments by clays is a two-step process, namely, enrichment during particle pickup and enrichment due to redeposition of coarser particles during overland and channel flows. Thus as DR decreases with increasing basin area, the enrichment of the washload by clays and other fine fractions increases (Fig. 2). During the delivery process, the texture of the sediment is changed and eventually is enriched by fine fractions. For a delivery ratio of DR, an amount equivalent to (1-DR) is redeposited during transport. The redeposition process is selective,

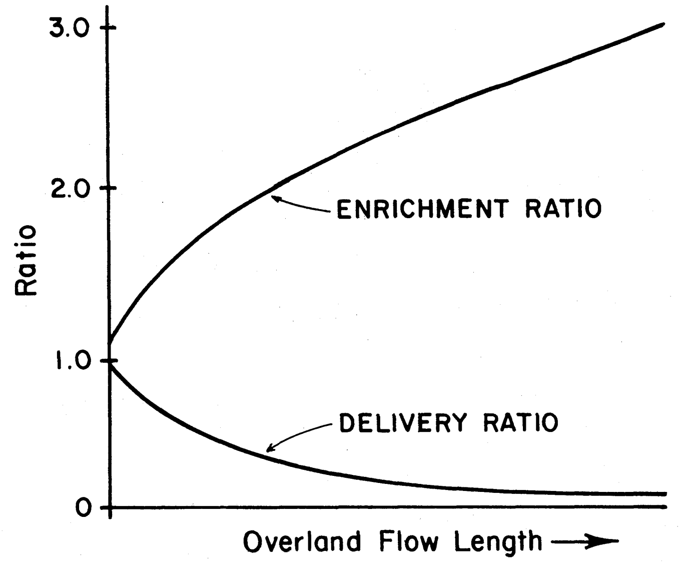

FIG. 2 Relation between sediment delivery and enrichment of sediments with fine particles.

i.e., according to the shear stress and flow turbulence, sand fractions are redeposited first followed by silt, and only when the flow slows to a very small velocity are clays deposited. Deposition of clays is enhanced if the clay particles move in the form of aggregates. Ease of dispersibility of aggregates varies among soils and a technique for determining an index of clay dispersion has been proposed by Dong <u>et al</u>., (1983a).

TABLE 2 Enrichment of suspended sediment by clay and associated pollutants

*Constituent**	*Soil*	*Suspended sediment*	*ER*
Clay	*27*	*91*	*3.4*
Total P	*810*	*1,700*	*2.1*
Pb	*19*	*39*	*2.0*
Cd	*0.30*	*0.31*	*1.0*
Zn	*69*	*280*	*4.0*
Cu	*25*	*45*	*1.8*
Al	*22,000*	*49,000*	*2.2*
Fe	*21,000*	*46,000*	*2.2*
Mn	*700*	*730*	*1.0*
Cr	*29*	*56*	*1.9*
Ni	*17*	*45*	*2.6*

**Clay is in % and P and metals are in μg g^{-1}.*

Novotny & Chesters (1981) have presented mathematical and graphical techniques of estimating clay enrichment of eroded soils and washloads. The variables needed are particle size distribution of the basin soils and DR of the sediment.

Particle size distribution and composition of soils and sediments from the 350 km^2 Menomonee River basin, Wisconsin, USA were investigated by Dong et al., (1983b, 1984). Data from a 21 km^2 predominantly agricultural (74 percent) sub-basin located in the upper reaches of the river provide a direct determination of sediment enrichment by clays and pollutants (Table 2). Average particle size distribution of soils in this sub-basin is 27 percent clay, 49 percent silt, and 24 percent sand. Suspended sediment samples collected near the drainage outlet of the sub-basin during runoff events show a particle size distribution of 91 percent clay, nine percent silt, and negligible sand.

Significant enrichment of clay particles occurred in the suspended sediment; about a three-fold increase over that of the surrounding soils. This clay enrichment results in two- to four-fold increases in concentrations of phosphorus and several metals in the sediment over those of the parent soil. Several organic chemicals such as pesticides have strong affinity to soil organic carbon. Since organic carbon is concentrated in the clay fractions it is likely that pesticides with high K_{oc} (amount of pollutant adsorbed per gram of organic carbon contained in soil or sediment) are enriched in the sediment.

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