

INFLUENCE OF PARTICLE SORTING IN TRANSPORT OF SEDIMENT ASSOCIATED CONTAMINANTS

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ABSTRACT

Hydrologic and sediment transport models are developed to route the flow of water and sediment (by particle size classes) in alluvial stream channels. A simplified infiltration model is used to compute runoff from upland areas and flow is routed in ephemeral stream channels to account for infiltration or transmission losses in the channel alluvium. Hydraulic calculations, based on the normal flow assumption and an approximating hydrograph, are used to compute sediment transport by particle size classes. Contaminants associated with sediment particles are routed in the stream channels to predict contaminant transport by particle size classes. An empirical adjustment factor, the enrichment ratio, is shown to be a function of the particle size distribution of stream bed sediments, contaminant concentrations by particle size, differential sediment transport rates, and the magnitude of the runoff event causing transport of sediment and contaminants. This analysis and an example application in a liquid effluent-receiving area illustrate the significance of particle sorting in transport of sediment associated contaminants.

INTRODUCTION

Contaminants associated with large volume wastes may be transported from waste disposal sites with eroding soils. Soil erosion and subsequent sediment transport can be important in contaminant transport^{1,2,3} and are of particular concern in the arid and semiarid Western United States^{4,5} where much of the annual precipitation occurs during intense summer thunderstorms.⁶ Runoff from such storms can result in accelerated loss of soil from a waste disposal site⁷ and subsequent high rates of sediment transport.⁸ Minimizing risks associated with offsite transport of disposal site contaminants requires an understanding of the mechanisms controlling runoff, erosion, sediment transport, and deposition of sediment particles.

Many contaminants which are transported by runoff travel in association with transported sediment particles. Differential erosion, transportation, and deposition result in sediment particle sorting. As these processes are selective, as a function of particle characteristics, the result is that transported sediment is usually enriched in

the finer particles. Because of physiochemical processes, again as a function of particle characteristics, contaminants can be more strongly associated with the smaller sediment particles. The combined processes of particle sorting during erosion, transportation, and deposition and the differential association of contaminants by sediment particle size produce complex relationships between runoff, sediment transport, and associated contaminant transport. Because knowledge of contaminant transport is important in designing monitoring systems, in estimating contaminant inventories, and in contaminant-risk assessments, there is a need to determine the influence of particle sorting on contaminant transport rates.

This paper describes a method to predict sediment transport, by particle size classes, in alluvial streams with noncohesive sediments. Intermittent and ephemeral streams of this type are a common feature of Western landscapes and are frequently the recipient of contaminants from waste disposal sites. The contaminants are then deposited in the channel bed sediments and can be available for transport during subsequent runoff events. Based on a knowledge of contaminant concentrations in the bed sediments, procedures are developed to predict the transport rate of contaminants traveling in association with sediment particles. Runoff, sediment, and contaminant rates are integrated over a given period of runoff (the runoff hydrograph) to estimate water, sediment, and contaminant yields. The results of this routing procedure are compared with empirical methods, such as enrichment ratios,⁹ that are commonly used to predict contaminant yields. The routing method includes the influence of particle sorting and thus represents an improvement over the enrichment ratio approach.

METHODS AND PROCEDURES

Although the procedures described herein have somewhat more general applications, the emphasis is on applications in semiarid regions. Important characteristics of runoff from semiarid watersheds often include flashy, highly sediment laden flow in ephemeral stream channels. Moreover, as flow travels in normally dry, alluvial channels, water is abstracted or lost in the channel bed and banks. These abstractions or transmission losses affect runoff volumes and flow rates and thus influence the stream's ability to transport sediment.⁸

Runoff from Semiarid Watersheds

The Soil Conservation Service (SCS) method is used to estimate runoff volume for specified antecedent moisture conditions and rainfall depth. A National Engineering Handbook¹⁰ is available to aid in selecting parameters and improved estimates are available for semiarid watersheds.^{11,12,13}

Based on previous work,¹⁴ the rate of change in runoff volume with distance in a channel is approximated by a differential equation to account for transmission losses as

$$\frac{dQ}{dx} = -wc - wk Q(x) + Q_L/x \quad (1)$$

where:

- $Q(x)$ = Runoff volume (L^3),
- Q_L = Lateral inflow volume (L^3),
- c = Parameter (L),
- k = Parameter (L^{-2}),
- w = Width of the channel reach (L), and
- x = Length of the channel reach (L).

The parameters c and k are functions of the effective hydraulic conductivity of the channel alluvium and the mean duration of flow in the channel reach. The solution to Eq. (1) is $Q(x)$, the runoff volume at the end of a channel reach of length x and width w . Each channel reach can receive upstream input from an upland area or from one or two upstream tributary channels and uniform lateral inflow along its length. The channel network is constructed of any number of channel reaches, each described by Eq. (1). Through the use of the mean flow duration and the double-triangle hydrograph approximation, peak discharge of the outflow hydrograph is estimated as

$$Q_p = C Q / \bar{D} \quad (2)$$

where

- Q_p = Peak discharge (L^3/T),
- Q = Runoff volume (L^3),
- \bar{D} = Mean flow duration (T), and
- C = Peak discharge coefficient.

The coefficient C is a function of the hydrograph shape assumed, which in turn is a function of the drainage basin characteristics.¹⁵

Mean duration of flow in Eq. (2) is estimated using drainage basin characteristics.¹⁵ Given a volume of runoff from Eq. (1) and a flow duration as in Eq. (2), hydrograph shape and peak discharge are estimated using a double-triangle hydrograph approximation.^{16,17} If the approximating double-triangle hydrograph is

broken into N intervals for the period [0,D], where D is the flow duration, and normal flow is assumed within each of the N time intervals, the result is the piecewise normal approximation. By changing the piecewise approximating hydrograph in the downstream direction the result is an approximation to the spatial variability. By assuming normal flow within each time interval, but changing the flow rate between intervals to approximate the hydrograph, the result is an approximation to the unsteady flow. Moreover, the assumption of normal flow allows calculation of depth, hydraulic radius, and velocity, throughout the hydrograph, to be used in the sediment transport equations.

Sediment Transport in Alluvial Channels

Following Einstein¹⁸ and others, a distinction is made between bed load and suspended load. If we assume that sediment transport rate is proportional to the water flow rate, then this distinction is somewhat arbitrary. This is because particles that travel as bed load at one flow rate may be suspended at another. The relationship between mode of transport and flow rate is a dynamically complex one and represents a continuous rather than distinct transition.

Nevertheless, it is reasonable to assume that the "larger" particles travel as bed load and that the "smaller" particles more easily enter suspension. Moreover, it is computationally convenient to assume a sharp distinction based on particle size. Therefore, we arbitrarily assume that all sediment larger than 0.062 mm in diameter is transported as bed load and that finer material is transported as suspended load. Separate transport equations were derived for bed load transport and suspended load transport based on this assumption.

Using a modification of the DuBoys-Straub formula¹⁹ transport capacity for bed load-sized particles is computed as

$$g_{sb}(d_i) = \alpha f_{is}(d_i) T [T - T_c(d_i)] \quad (3)$$

where

$g_{sb}(d_i)$ = Transport capacity per unit width for particles of size d_i (M/T-L),

α = A weighting factor to ensure that the sum of the individual transport capacities equals the total transport capacity computed using the median particle size,

f_i = Proportion of particles in size class i ,

d_i = Diameter of particles in size class i ,

$B_s(d_i)$ = Sediment transport coefficient ($L^3/M-T$),

T = Shear stress (F/L^2), and

$T_c(d_i)$ = Critical shear stress for particles in size class i (F/L^2).

Values of B_s and T_c were determined by Straub²⁰ in English units and presented in metric units by Zeller.²¹ The total bed load transport capacity is then found by summing the results from Eq. (3) over all the size fractions.

Bagnold^{22,23} proposed a sediment transport model based on the concept of stream power as

$$i_s = P \frac{e_s u_s}{v_s} (1 - e_b) \quad (4)$$

where

i_s = Suspended sediment transport rate per unit width (M/T-L).

P = TV = Available stream power per unit area of the bed (F/T-L),

e_s = Suspended load efficiency factor,

e_b = Bed load efficiency factor,

u_s = Transport velocity of suspended load (L/T), and

v_s = Settling velocity of the particles (L/T).

Now, if u_s is assumed equal to the mean velocity of the fluid, V , then Eq. (4) is of the form

$$g_{sus} = KTV^2 \quad (5)$$

where the coefficient k includes the efficiency parameters, the settling velocity for the representative particles, and the proportion of particles smaller than 0.062 mm in the channel bed material. The total load is then computed as the sum of the bed load, from Eq. (3), and the suspended load from Eq. (5). The shear stress in Eqs. (3-5) can also be estimated as the grain shear¹⁹ (as opposed to total shear) with corresponding parameter values adjusted for the lower shear stress.

Computation of Sediment Transport and Yield

Typical applications of the sediment transport component of the model include predicting sediment discharge rates for steady flow and predicting sediment yields using the piecewise normal hydrograph approximation. The sediment transport model was fitted to data representing 27 observations at the Niobrara River in Nebraska, USA.²⁴ These data represent nearly steady-state conditions and were used to estimate parameters in the sediment transport equations.

The sediment yield model, based on the piecewise normal approximation and parameters estimated using the Niobrara data, was used to predict sediment yields

for 47 runoff events from five small watersheds in southern and southeastern Arizona. These small (1.6 to 4.0 ha) watersheds are described in detail by Lane et al.²⁵ Predicted and observed sediment yields for these watersheds are shown in Fig. 1. Although there is a great deal of variability in the data and prediction errors for any particular runoff event can be large, the model explained the trend in the observed sediment yield data.

Computation of Contaminant Transport and Yield

Eroded and transported soil is usually richer in many of the particle transported contaminants than is the original soil in the watershed or channel system. The enrichment results in part from differential transport wherein the finer particles are more readily transported. In the absence of detailed information on differential

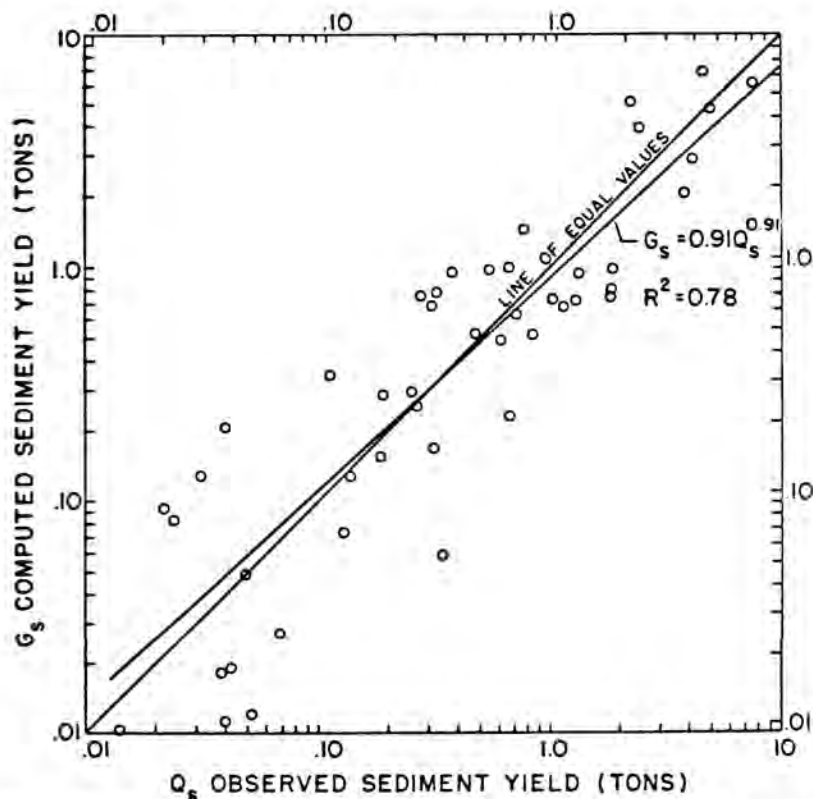


Fig. 1. Observed and computed sediment yield for five small watersheds in Arizona.

transport rates for the sediment particles, it is common to use an enrichment ratio.⁹ In this approach, the transport rate for a particle-associated contaminant is estimated as

$$Q_c = C_s \cdot O_s \cdot E_R \quad (6)$$

where

Q_c = Discharge rate of contaminant (M/T),

C_s = Concentration of contaminant in the soil,

Q_s = Sediment discharge rate (M/T), and

ER = Enrichment ratio.

Obviously, the enrichment ratio is a function of the particle-size distributions of the original soil, the transported sediment, and their relationship.

An alternative procedure is to write an equation for each size fraction in the soil and, by computing selective transport rates, the total transport rate could be computed by summation over the various size fractions. That is, write

$$Q_c(d_i) = C_s(d_i)Q_s(d_i) \quad (7)$$

and

$$Q_c = \sum_{i=1}^N Q_c(d_i) \quad (8)$$

where

$Q_c(d_i)$ = Discharge rate of contaminant associated with particles of size d_i (M/T),

$C_s(d_i)$ = Concentration of contaminant in the soil associated with particles of size d_i ,

$Q_s(d_i)$ = Transport rate of particles of size d_i (M/T),

Q_c = Total discharge rate of contaminant (M/T),

d_i = Representative diameter of particles in size class i , (L),

i = Index for size classes, and

N = Number of size classes in the sediment mixture.

The important difference between Eqs. (6) and (8) is that the relative proportions of the various particle sizes (f_i , d_i) vary from site to site, the concentrations of contaminants by size fraction can vary over an order of magnitude in going from silt-clay to sand and gravel, and the sediment discharge rates by size fraction [$Q_s(d_i)$] vary with discharge rates, channel slopes, channel widths, and other factors as discussed earlier.

The concentration, C_s , in Eq. (6), can be interpreted as a mean concentration over all particles sizes. That is, write

$$C_s = \sum_{i=1}^N f_i C_s(d_i) \quad (9)$$

where f_i is the proportion of sediment in size class i with a representative diameter of d_i . Also, the total sediment discharge rate can be written as

$$Q_s = \sum_{i=1}^N Q_s(d_i) \quad (10)$$

so Eq. (6) becomes

$$Q_c = ER \sum_{i=1}^N f_i C_s(d_i) \sum_{i=1}^N Q_s(d_i) \quad (11)$$

Equation (8) can be written as

$$Q_c = \sum_{i=1}^N C_s(d_i) Q_s(d_i) \quad (12)$$

Equating Eqs. (12) and (11) and solving for ER, the result from summing over the N size fractions is

$$ER = \frac{\sum_{i=1}^N C_s(d_i) Q_s(d_i)}{\sum_{i=1}^N f_i C_s(d_i) \sum_{i=1}^N Q_s(d_i)} \quad (13)$$

Thus, enrichment ratio ER is defined by Eq. (13) where the numerator is like a sum of cross products, and the denominator is like a cross product of sums. Therefore, ER is not a constant, but is a variable which is a function of the soil concentrations, $C_s(d_i)$, the particle size distribution, f_i , and the sediment transport rates, $Q_s(d_i)$. Thus, ER is expected to vary from soil to soil and from runoff event to runoff event for the

same soil. Therefore, we chose to use Eq. (8) rather than the enrichment ratio approach to compute particle contaminant transport.

For any particular time or any interval on the piecewise normal approximating hydrograph, the total contaminant transport rate is given by Eq. (8). By integrating over the entire hydrograph, the result is a total contaminant yield for the storm event.

EXAMPLE APPLICATION

Mortandad Canyon is the site of an incised or canyon drainage system in the Pajarito Plateau. The alluvium in the intermittent stream was formed from volcanic rocks of the Bandelier Tuff. The stream has received treated radioactive wastes in effluent since 1963. These wastes, although treated, contain small amounts of plutonium which then deposit in the channel bed and banks as the effluent infiltrates into the channel. Stormwater runoff in the canyon is rare and usually follows periods of intense thunderstorm rainfall. Streamflow also occurs in response to snowmelt as a result of winter storms. However, runoff resulting from summer storms is of particular importance in the transport of sediment and sediment-associated plutonium.

Background material and site descriptions for Mortandad Canyon and other areas near Los Alamos, New Mexico are provided by Nyhan et al.²⁶ The distribution of plutonium in sediments by size fraction and by distance below the effluent outfall were determined.²⁷ From these data it was found that higher concentrations of plutonium are associated with the smaller size fractions and that concentrations decrease almost exponentially with distance below the outfall.

Hydrologic data were collected for a storm in 1974⁴ and used to compute sediment transport rates using Eqs. (3) and (4) and plutonium discharge rates using Eqs. (7) and (8). The computed plutonium transport data were then compared with observed data based on samples taken during the runoff. For five sampling times where the runoff rates and sediment concentrations were known, the relation between computed activity flux, y , and observed activity flux, x , in pCi/sec was

$$y = 5320 + 0.66 x \quad (14)$$

with $R^2 = 0.92$. By way of comparison, if observed rather than computed sediment discharge rates are used to compute plutonium flux the relation between computed, y , and observed activity flux, x , in pCi/sec is

$$y = 2750 + 0.90 x \quad (15)$$

with $R^2 = 0.94$. The mean observed activity flux was 24,600 pCi/sec, the mean computed activity flux using the model was 21,600 pCi/sec, and the mean computed activity flux using observed sediment transport data was 24,900 pCi/sec. Therefore, although Eq. (14) suggests the activity flux computed using the model described

herein underpredicted the observed activity flux, given the small sample size, the predictions [Eq. (14)] were comparable with the observations and with computations based on observed sediment concentration [Eq. (15)].

SIGNIFICANCE OF PARTICLE SORTING

As discussed earlier, total sediment transport, transport by particle size fractions, and total sediment yield are influenced by runoff characteristics and the size distribution of sediment in the stream bed. These factors in turn influence statistics such as enrichment ratios used to compute contaminant transport. Flood frequency analysis, the analysis of flood events of various magnitudes and their probability or frequency of occurrence, can be used to illustrate the influence of particle sorting on contaminant transport. This is done by simulating floods of various magnitudes, computing the associated sediment yield by particle size fractions, and computing contaminant transport associated with the sediment particles. By comparing contaminant yields computed using an enrichment ratio, Eq. (6), with contaminant yields computed using particle size fractions, Eqs. (7) and (8) or Eq. (12), it is possible to estimate the influence of particle sorting on contaminant yields for floods of various magnitudes.

The relationship between particle size and plutonium concentration for stream bed sediments near the outfall in Mortandad Canyon are shown in Fig. 2. Notice that plutonium concentrations are an order of magnitude greater for the silt-clay sized particles than for the gravel sized particles. Although the concentrations are high in the silt-clay size range, the particles make up only 1-2% of the total mass of sediment. Over 90% of the sediment is in the sand size range.

The runoff and sediment yield models were used to compute sediment yield for floods of various sizes in Mortandad Canyon. The enrichment ratio approach, Eq. (6) and the mean concentration from Fig. 2, was used to compute plutonium yields. Next, the particle size approach, Eq. (12) and the concentration-particle size distribution from Fig. 2, was used to compute plutonium yields. The results are summarized in Fig. 3. The horizontal axis in Fig. 3 shows the peak sediment discharge rate for various sized storms. For example, the 2 year flood has a 50% chance of occurring in any one year, the 10 year flood is expected to occur once in 10 years or has a 10% chance of occurring in any one year, and so on.

The vertical axis in Fig. 3 shows the percent error resulting from use of the enrichment ratio with an enrichment ratio of 1.0 and the mean plutonium concentration in the stream bed sediment as opposed to using sediment transport by size fractions and the distribution of plutonium concentrations by particle size fractions. For example, for storms of approximately the size of the 2 year flood, contaminant yield computed using the enrichment ratio approach is just over half (50% error) the yield using the particle size approach. This is because the enrichment ratio approach is based on the mean concentration in the bed sediments, Eq. (9), while the transported sediments are enriched in the finer particles. Of course, use of an enrichment ratio of 2.0 would eliminate the error for the 2 year flood. However, a value of 2.0 would underestimate contaminant yields for smaller storms and

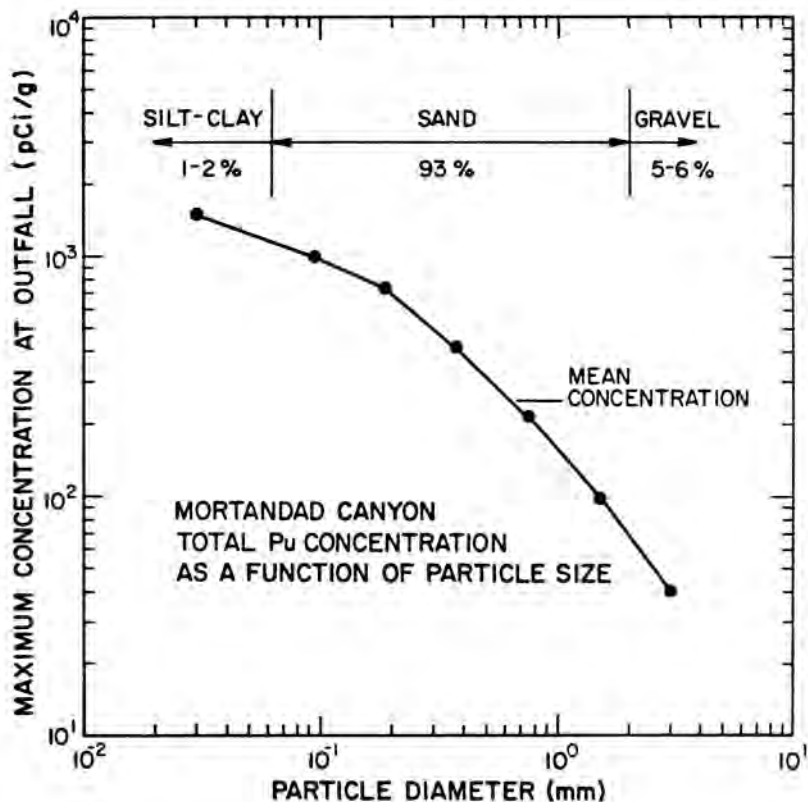


Fig. 2. Distribution of sediment sizes and associated plutonium concentrations for stream bed sediments in Mortandad Canyon.

overestimate contaminant yields for larger storms (Fig. 3). Thus, Fig. 3 illustrates the fact that enrichment ratios are expected to vary with storm size. Moreover, the particle size approach described herein can be used to estimate the variability of enrichment ratios with storm size. In the absence of a relationship of the type shown in Fig. 3, the enrichment ratio is an empirical adjustment factor which varies in an unknown manner with particle size distributions and storm size.

DISCUSSION AND CONCLUSION

Procedures described in this paper have direct application in predicting runoff and sediment yield from semiarid watersheds. Given estimates of runoff rates and amounts together with sediment yield by particle size classes, it is possible to estimate contaminant transport rates as a function of sediment transport rates and

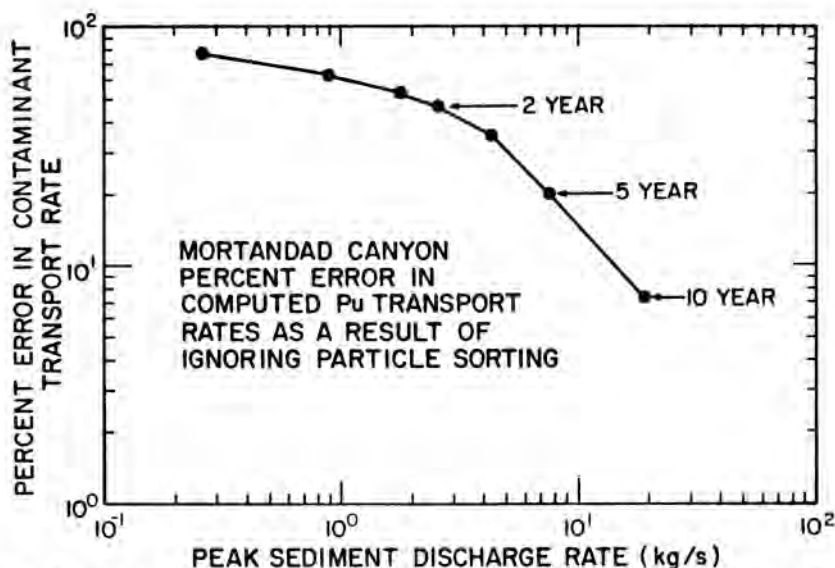


Fig. 3. Relative error in computed plutonium yields as a result of ignoring particle sorting for various sized storms.

contaminant concentrations in the channel alluvium. However, the procedure requires a knowledge of contaminant concentrations by sediment particle size classes. This information and the longitudinal distribution of contaminants in the channel system are used to compute contaminant transport rates, and through the hydrograph approximation method, contaminant yields on a storm by storm basis. Flood frequency analysis can be used to estimate the magnitude and probability of runoff, sediment, and contaminant yield events. This information in turn can be used in risk assessments and in designing monitoring schemes for contaminant movement. The flood frequency approach provides a mechanism of summarizing a watershed-channel system's response to climatic features and as such provides a means of projecting into the future.

Hydrologic processes such as infiltration, runoff, and hydrograph characteristics from the upland areas provide the driving force and transport mechanism for delivery of runoff, sediment, and contaminants to the channel system. Transmission losses and alluvial channel hydraulics in turn influence the transport of sediment and contaminants in the channel system. Procedures have been developed to model these processes on semiarid watersheds with alluvial channel systems and to determine the influence of particle sorting on the transport of sediment associated contaminants. Inasmuch as contaminant transport is related to these hydrologic processes, and the hydrologic processes can be modeled under the conditions described herein, contaminant transport is predictable.

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