EARTH SURFACE PROCESSES AND LANDFORMS, VOL. 12, 217–228 (1987)

(6)

#82301

COPPER DISPERSION IN EPHEMERAL STREAM SEDIMENTS

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Received 19 October 1984
Revised 16 October 1986

ABSTRACT

Sediment transport related parameters in ephemeral streams may be used to model and delineate: (1) average dispersion patterns of copper-laden sediments; (2) differences in dispersion of copper in bedload and suspended sediments; and (3) variability in the copper-sediment dispersion patterns. A model that effectively describes dispersion of copper in ephemeral stream sediments in a simple mixing model:

$$C_r = \left|\frac{C_m \cdot X_m}{X_m + X_t}\right| + \left|\frac{C_t \cdot X_t}{X_m + X_t}\right|$$

where C_r is the resultant concentration beneath the confluence of the main channel with a tributary, C_t is the concentration of metal in sediments of the tributary, C_m is the metal concentration in main channel sediments, and X_m and X_t are the basin areas or sediment yields of the main channel and tributary channel at their confluence. Variability in metal concentrations about values predicted by this model may be due to the different responses of bedload and suspended load to changes in stream hydraulics, the dynamics of bedload transport, the spatial and temporal variability rainfall within the drainage basin, and chemical mobility of the copper.

KEY WORDS Copper Ephemeral stream Heavy metals Sediment transport

NATURE OF STUDY

Hydrodynamic processes are often the primary agent dispersing heavy metals in stream sediments, particularly in streams where solution–dissolution processes are not very active. In this paper, the relationship of sediment transport parameters to heavy metal dispersion in ephemeral stream sediments in Central Arizona is examined by asking: (1) can models utilizing the sediment transport related parameters of distance, basin area, and changes in sediment yield downstream from a heavy metals source effectively simulate mainchannel dispersion patterns; and (2) how do downstream dispersion patterns differ for heavy metals carried in suspended load and bedload? Answers to these questions can aid in assessing the potential environmental impacts of sources discharging heavy metals, as well as providing clues to understanding sediment transport processes.

PREVIOUS RESEARCH

In general, researchers have noted that metal concentrations in sediments tend to decrease downstream of a heavy metals source, largely because of the dilution of contaminated by uncontaminated sediments (e.g. Lewin *et al.*, 1977; Yim, 1981). Solution processes can also play a significant role in reducing metal concentrations in sediments, particularly when tributary waters with markedly different chemistries or metal loads mix with contaminated sediments (e.g. Waslenchuck, 1977). The combination of chemical and hydrodynamic processes generally produces an overall logarithmic decay of metal concentrations in the downstream direction.

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Occasionally, hydrologic processes can serve to elevate metal levels in stream waters and sediments by resuspending polluted sediments (Williams *et al.*, 1973). Such peaks in metal concentrations tend to be short term, however, as dilution by cleaner sediments reduces metal concentrations (Jones, 1958; Müller and Förstner, 1977).

High concentrations of metals in sediments can also occur because of the tendency for heavy metals to accumulate in sediments of very fine sand size or smaller (Huff, 1971; Gibbs, 1973; Perhac, 1972). Areas where fine sediments are deposited, such as floodplains, thus can act as sinks where heavy metals accumulate (Davies and Lewin, 1974; Viviant and Massie, 1977; Wolfenden and Lewin, 1977). Channel floor hydraulics can also serve to concentrate heavy metals in bedload, with the heavy metal bearing sediments being segregated by dune transport processes (Hubbell and Glenn, 1973; Sayre and Hubbell, 1965) or simply on the basis of density and size (Brady, 1971).

Studies modelling the dispersion by hydrodynamic processes of heavy metals in main channel sediments are sparse. Glover (1964) developed diffusion models for dissolved solids and extremely fine suspended sediments that can be used to predict downstream, vertical and lateral sediment concentrations resulting from both instantaneous and continuous releases of contaminated material. Sayre and Hubbell (1965) developed a model based on probability theory for bedload transport over a 300 m reach, with dispersion time and distance as independent variables. Both models simulate in-stream, short-term diffusion, but do not take into account broader scale and longer-term factors such as dilution from tributaries and heavy metal sinks. Wolfenden and Lewin (1978) proposed a more general regression model that correlated the logarithm of heavy metal concentrations in sediments to downstream distance. This regression model provided good descriptive results for copper, lead, zinc and cadmium dispersion patterns in the River Twymyn, Wales, with the correlation constants varying from one metal to the next.

STUDY AREA

The study area was Queen Creek, an ephemeral stream in Central Arizona (Figure 1) with copper tailings in its headwaters. Queen Creek drains an area of mixed volcanic and sedimentary rocks, which are interspersed with units of quartzite and schist (Short *et al.*, 1942; Wilson and Moore, 1959). In the eastern portion of the study area is the town of Superior with its copper tailing piles (Figure 2). At the lower end of the study area and 18 km downstream of Superior is Whitlow Ranch Dam, which was constructed in 1959.

The climate of the region is semiarid, with an annual precipitation that rarely exceeds 51 cm (Sellers and Hill, 1974). The majority of this rainfall comes from local, intense summer thunderstorms, with a second seasonal maximum occurring in the winter when Pacific cyclones produce widespread and generally more gentle precipitation. Mean temperatures range from 15·8°C in January to 36·2°C in July. Vegetation varies from Upper Sonoran Desert Scrub community near Whitlow Ranch Dam at 640 m to pinyon–juniper forest in the higher peaks at 1700 m.

Superior, with a population of 4600 in 1980, is the only town in the study basin. Copper mining is the major industry of the area, although there is also some perlite mining, cattle ranching, and local commerce. The first mining that produced tailings in Superior occurred in 1881, when six concentrators were constructed along Silver King Wash (Chappel, 1973). In 1913 a 150 ton concentrator mill was put in at Superior, signalling the beginning of major tailing piles. Since that time, copper production has continued in Superior up to the present, with occasional stoppages due to depressed copper prices and demand. In recent years the tailings have been used as back fill in mine shafts and the tailing piles have begun to decrease in size.

STUDY METHODS

Sampling of heavy metals was limited to copper because of its relative freedom from chemical interference (Nakagawa, 1975) and known presence in large quantities in the upper reaches of Queen Creek. The sediment size ranges tested for copper content were medium to fine sands (0·60 to 0·18 mm), which travel primarily in suspension (e.g. Bagnold, 1966, pp. 30–33).

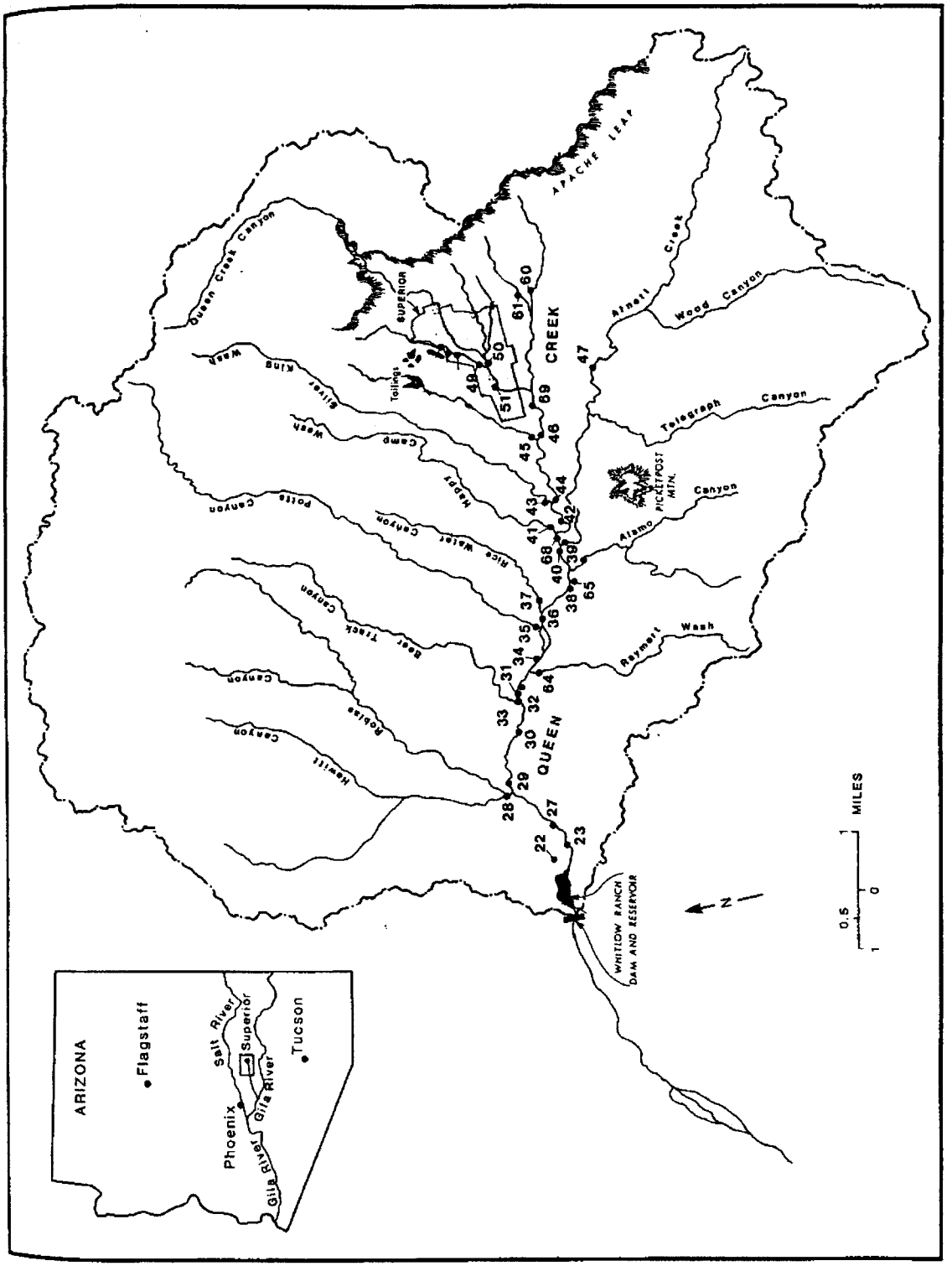

Figure 1. The study area, Queen Creek, Arizona

Figure 2. Tailings piles in Superior. Queen Creek flows to the right of the tailings pond

To examine dispersion patterns and test models, I collected sediment samples from the main channel of Queen Creek above and below its confluence with significant tributaries and from the major tributaries above their confluence with Queen Creek (Figure 1). Significant tributaries were defined as those tributaries which were larger than five square kilometres in size or which drained an area of mining activity or urban development. The tributary samples were assumed to be indicative of the average copper concentrations which the tributary drainage basins were contributing to Queen Creek. As is discussed later, this assumption is sometimes incorrect, particularly in larger drainage basins.

The samples were collected by compositing sediment from six locations within a three-metre radius in the centre of the dry stream bed, thus providing an average concentration for that portion of the channel. Samples were collected to a depth of 10 cm, with the top centimetre of the sediment being scraped away to avoid collecting recently deposited air-borne dust contaminants. Sampling near the channel edge was avoided in order to prevent collecting bank sediments rather than recently transported alluvial material. Testing for copper content followed the hot nitric acid technique for atomic absorption analysis of sediments outlined by Ward *et al.* (1969).

Stream distances and drainage basin areas were measured from 1:24,000 U.S. Geological Survey topographic maps. The basin areas also served as surrogate measures of sediment discharge through use of a sediment yield equation developed for the Bureau of Reclamation (Strand, 1975):

$$Q_s = 12077(A)^{-0.229} \tag{1}$$

where Q_s is the sediment yield in cubic metres per square kilometre per year and A is the drainage basin area in square kilometres. This equation was chosen because it was developed from data on rivers in the American Southwest, including the Aqua Fria River, which is 110 km from Queen Creek and is at approximately the same elevation.

DATA

Copper concentrations in the channel sediments ranged from 35 to 2300 ppm for the clays to very fine sands (less than 0·18 mm) and from 15 to 1865 ppm for the very fine to medium sands (0·18 to 0·60 mm, Table I). Also

Table I. Copper concentrations and stream basin data for Queen Creek, Arizona

Sample number	Concentrations in 0·18 to 0·60 mm sediments (ppm)	< 0·18 mm sediments (ppm)	Basin area (km^2)	Sediment yield* (hectare–m/yr)	Downstream† distance (km)
22	16	45	0·4	0·07	Unnamed tributary
23	41	120	363	13·4	16·5
27	30	110	359	13·3	15·8
28	17	55	80	4·2	Hewitt Wash
29	85	140	275	10·8	14·2
30	55	135	270	10·7	12·6
31	90	195	253	10·1	11·7
32	85	105	253	10·1	11·7
33	20	55	12·6	1·00	Bear Tank Wash
34	65	140	243	9·8	10·5
35	50	55	47	2·7	Potts Canyon
36	125	165	196	8·3	9·5
37	85	155	4·9	0·49	Rice Water Wash
38	70	195	185	7·9	8·1
39	18	40	81	4·2	Arnett Creek
40	75	195	165	7·3	6·9
41	125	190	11·5	0·93	Happy Camp Wash
42	50	130	73	3·9	6·0
43	55	115	16·6	1·24	Silver King Wash
44	480	445	56	3·1	5·2
45	245	355	4·8	0·47	Unnamed Wash
46	335	480	48	2·8	3·0
47	16	27	57	3·2	Arnett Creek
48	95	120	6·9	0·63	Donkey–Belmont–Pacific–Washes
49	1865	2300	2·3	0·28	Tailings Tributary
50	160	400	32	2·1	Queen Creek, upstream of Site 49
51	290	795	35	2·2	0·6
60	125	145	4·0	0·41	Beaumont–Pacific Canyon
61	175	350	1·3	0·17	Donkey Canyon
64	16	50	9·5	0·8	Raymert Wash
65	15	35	1·5	0·20	Unnamed Wash
67	20	51	16·1	0·12	Alamo Wash
68	80	135	84	4·3	6·6

* Sediment yield calculated with the Strand (1975) equation.
† Distance downstream in Queen Creek is measured from site 49, where the tailings tributary enters Queen Creek.

listed in Table I are the downstream distance of each sample site from the tailings tributary mouth (site 49), the drainage basin area and the theoretical sediment yield at each sample location.

In general, copper concentrations decreased in the downstream direction (Figure 3). Two notable exceptions were an increase at sites 44 and 46 for the 0·18 to 0·60 mm sediments and downstream of Happy Camp Wash for both size fractions.

MODELS

Regression analysis

The semi-log regression approach utilized by Wolfenden and Lewin (1978) yields the equation:

$$\log C = b_1 D + a_1 \tag{2}$$

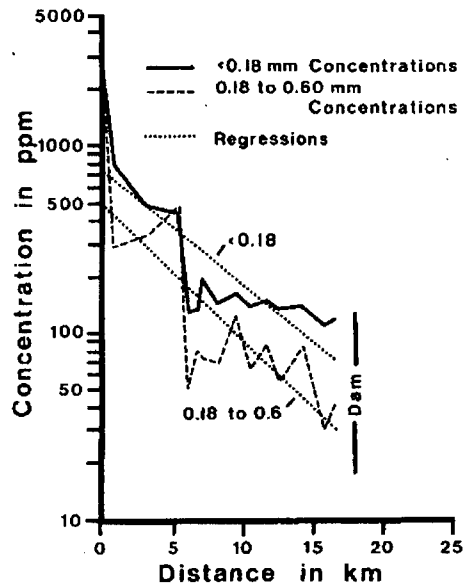

Figure 3. Metal dispersion patterns: semilog regression

where C is the concentration in ppm, D is distance downstream from the heavy metal source, and b_1 and a_1 are constants. In Queen Creek, this regression equation yields correlation coefficients of 0·63 for the 0·18 to 0·60 mm and 0·66 for the less than 0·18 mm fractions (Table II), notably lower than those calculated by Wolfenden and Lewin for a perennial stream in Wales. This relatively poor fit (Figure 3) suggests that a further transformation to the log–log regression classically used in fluvial geomorphology (e.g. Leopold and Miller, 1956) would be more effective. A linear regression of this type takes the form:

$$\log C = b_2 \log X + a_2 \tag{3}$$

where X is downstream distance, or some other parameter related to sediment mixing processes such as basin area or sediment yield. A comparison of Figures 3 and 4 and the correlation coefficients in Table II clearly show

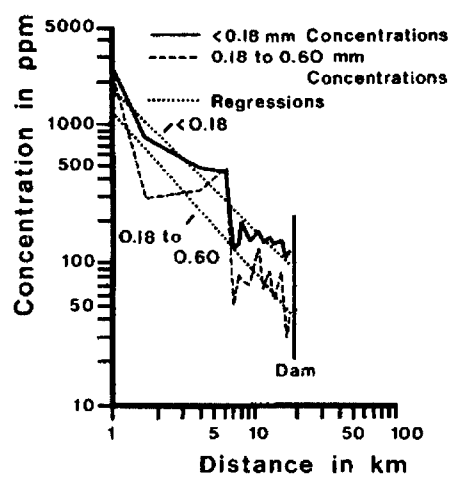

Figure 4. Metal dispersion patterns: log–log regression—distance vs. concentration

Table II. Statistics for dispersion models*†

Dispersion model	Sediment fraction (mm)	N	a	b	r^2	$Sx \cdot y$
Semilog regression	0·18–0·60	15	2·86	−0·07	0·63	0·30
	< 0·18	15	2·86	−0·06	0·66	0·23
Log–log regression:	0·18–0·60	15	3·06	−1·14	0·74	0·25
distance vs. concentration	< 0·18	15	3·22	−0·99	0·88	0·13
Log–log regression:	0·18–0·60	15	3·58	−0·74	0·79	0·22
area vs. concentration	< 0·18	15	3·59	−0·61	0·85	0·15
Log–log regression:	0·18–0·60	15	2·77	−0·97	0·79	0·23
sediment yield vs. concentration	< 0·18	15	2·93	−0·80	0·85	0·15
‡mixing model,	0·18–0·60	14	−53	1·44	0·59	89
concentrations sampled: area = x	< 0·18	14	−61	1·25	0·73	109
‡mixing model, concentrations	0·18–0·60	14	−16	1·05	0·61	88
sampled: sed. yield = x	< 0·18	14	−18	1·04	0·78	97

* N is the sample size.
a is the y intercept.
b is the slope of the regression line.
r^2 isthe coefficient of determination.
$Sx \cdot y$ is the standard error of the estimate.
† All correlations are significant at the 0·01 level.
‡ Regressions for the mixing models are calculated for predicted (x) versus observed (y) concentrations.

that the log–log regression more accurately depicts patterns of metal dispersion in Queen Creek than does the semilog approach. The regression equations in which basin area or sediment yield are the independent variables yield very similar results to the downstream distance-based equations (Table II, Figures 5 and 6), indicating that copper concentrations probably do decrease as a function of parameters related to sediment yield.

Mixing models

If metal concentrations are a function of sediment mixing, then as tributaries enter the main channel, heavy metal concentrations should be diluted or increased to a certain extent, depending on the quantity of sediments mixing and their heavy metal contents. A weighted mean average is thus a simple technique for mathematically

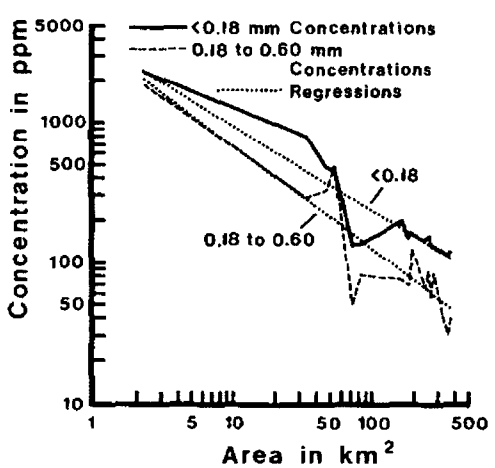

Figure 5. Metal dispersion patterns: log–log regression—area vs. concentration

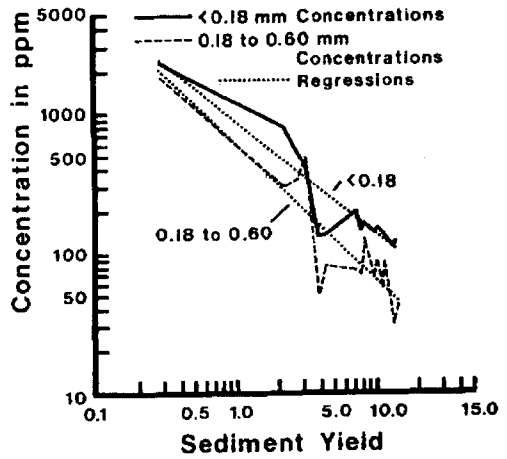

Figure 6. Metal dispersion patterns: log–log regression—sediment yield (10,000 m^3/yr) vs. concentration

'mixing' the sediments at the confluence of two basins which have different sediment yields and metal concentrations. An equation of this type takes the form:

$$C_r = \left|\frac{C_t \cdot X_t}{X_t + X_m}\right| + \left|\frac{C_m \cdot X_m}{X_t + X_m}\right| \tag{4}$$

where C_r is the resultant metal concentration below the confluence, C_m is the concentration in the main channel above the confluence, C_t is the concentration in the tributary, and X_m and X_t are the basin areas or sediment yields of the main channel and tributary channel at their confluence. Theoretical concentrations calculated using both basin area and sediment yield as independent variables in this model are compared to actual concentrations in Figures 7 and 8. Correlation constants and regression coefficients for predicted versus observed values are listed in Table II. The regression slope values for this model are very close to 1·0, indicating a close correspondence of predicted and observed values.

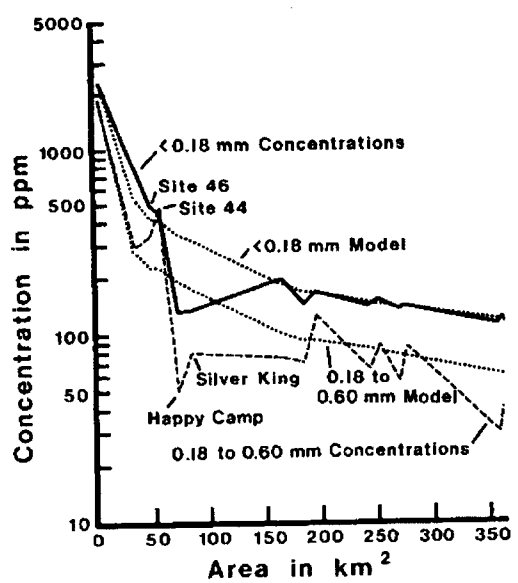

Figure 7. Metal dispersion patterns: mixing model—area vs. concentration

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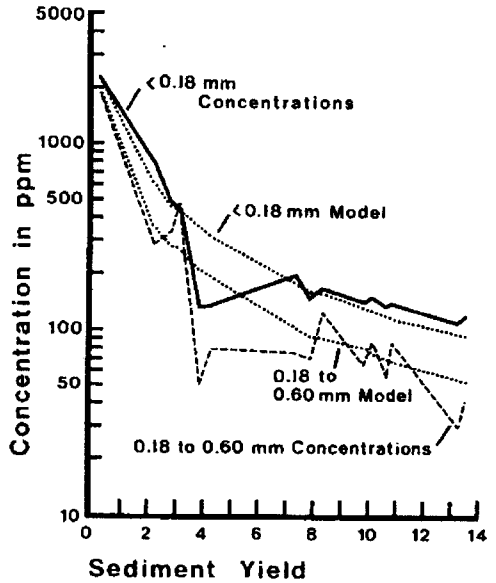

Figure 8. Metal dispersion patterns: mixing model—sediment yield (10,000 m^3/yr) vs. concentration

The mixing model has several advantages. Unlike the regression model, it can be used to predict heavy metal concentrations in the main channel without the use of constants peculiar to one stream basin. It is also non-linear, having the ability to incorporate sudden leaps or falls in heavy metal concentrations due to influxes of new sediments from different tributaries and multiple sources.

The use of sediment yield as the independent variable produces a closer fit to the actual dispersion pattern in upper reaches of the stream than does the use of basin area (Figures 7 and 8). This result probably occurs because the Strand (1975) equation used to estimate sediment yield predicts decreasing sediment yield per unit area as basin area increases, a commonly documented occurrence in U.S. rivers in recent times (e.g. Branson *et al.*, 1981). The higher per unit sediment yield for smaller basins means that the tributary model using sediment yield gives the smaller basins in upper Queen Creek, which have higher copper concentrations, a greater influence on main channel concentrations.

POSSIBLE CAUSES OF CONCENTRATION VARIATIONS

The good simulation of trends in copper concentrations provided by the mixing model indicates that mixing of in-channel and tributary sediments is probably the major process controlling heavy metal dilution in the ephemeral Queen Creek sediments. There are, however, several departures from modelled concentrations that point to processes other than uniform mixing of sediments as major controls on metal dispersion patterns. Because the sporadic nature of flow in Queen Creek made it difficult to directly study dispersion processes within the streambed, the following comments should be viewed as speculative rather than the result of direct observation.

The abrupt decrease in copper concentrations downstream of the adjacent basins of Silver King and Happy Camp Washes (Figure 7) suggests a local dilution effect, such as might be caused by the local, severe thunderstorms that commonly occur in Central Arizona, particularly in summer. Brazel and Ziriax (1979) found that summer occurrences of rainfall for stations only ten kilometres apart were very poorly correlated, which means that summer flow commonly occurs over only a small portion of an entire drainage basin at any one time. If the mixing model is applied to only the sediments from Silver King Wash and Happy Camp Wash, the resultant theoretical concentrations below their confluence with the main channel are 84 ppm and 146 ppm, very close to the observed concentrations of 80 ppm and 135 ppm. This implies that a storm centred

over Happy Camp and Silver King Washes may have flushed a slug of sediment from only these drainages into the main channel.

Entrapment of bedload by vegetation at low flows possibly explains the increase in bedload copper concentrations at sites 44 and 46. In contrast to other portions of the Queen Creek channel less than one kilometre upstream (Figure 9) and downstream, these two sites are heavily vegetated (Figure 10). In a localized flow event carrying sediments with high copper concentrations from the tailings and adjacent tributaries, this vegetation may trap a large portion of the bedload while allowing suspended sediments to wash downstream, thus producing a relative peak in bedload copper concentrations at sites 44 and 46.

There is also more variability from site to site within the bedload dispersion pattern than within the suspended sediments (Figure 8), which may be a function of sediment flow dynamics. While metals in suspended load are generally well mixed during transport, bedload transport can sort the heavy metals in sedments by size, shape and density (Brady, 1971; Haushild *et al.*, 1975; Hubbell and Glenn, 1973; Sayre and Hubbell, 1965; Wertz, 1948). Furthermore, heavy metals in bedload sediments from different tributaries may move downstream as discrete units for some time before mixing. Concentrations in bottom sediments can therefore vary considerably over short distances because of the mechanics of bedload movement.

Concentrations of copper in the less than 0·18 mm fraction were consistently higher than those in the 0·18 to 0·60 mm fraction. This may be the result of several factors, including: (1) the primary source of copper, the tailings, largely consist of sediments in the less than 0·18 mm fraction; and (2) solution processes, which tend to increase metal concentrations in finer sediments with time (Levinson, 1980).

SUMMARY DISCUSSION

The results of this study indicate a probable relationship between dispersion patterns of heavy metals in stream sediments and parameters related to sediment mixing processes in an ephemeral stream in Central Arizona. A mixing model based on sediment yield and metal concentrations in main channel and tributary sediments accurately depicted heavy metal concentrations in the main channel downstream from copper tailing piles. This model can be used in streams with either point or multiple heavy metal sources. Regression models also provided adequate representations of dispersion patterns, but did not effectively simulate the effects of different tributary sediment yields and metal contents on main channel concentrations.

Figure 9. The Queen Creek channel upstream of sites 44 and 46 at site 51

Figure 10. Site 46 in Queen Creek

Departures from the modelled dispersion patterns may have been related to: (1) variability in the sediment yield from tributaries; (2) the entrapment of bedload by vegetation; (3) the segregation of metal-bearing sediments during bedload flow; and (4) dispersion of metals in solution. Because flow events in Queen Creek were not directly observed, the degree to which any one of these processes played a role is uncertain.

The mixing model used in this study could be used to develop a heavy metal–sediment budget, simply by multiplying sediment yield by concentration at different points along the stream. This model, however, does not provide concentrations of heavy metals in areas of slack water deposition, nor does it take into account the sporadic and non-uniform movement of sediments that occurs in ephemeral stream basins. Furthermore, the mixing and regression models have not been tested in basins of more than several hundred square kilometres in area, where the probability of factors such as sediment sinks, changes in water chemistry, groundwater solution, vegetative uptake of heavy metals, and human activities affecting patterns of heavy metal dispersion is greatly increased. If the close link of heavy metal dispersion and sediment movement in ephemeral streams indicated by this study is to be utilized, then clearly our understanding of spatial and temporal variations in the chemical mobility of metals and sediment transport throughout entire river basins must first improve.

ACKNOWLEDGEMENTS

I wish to thank William Graf for his comments and advice. Brad Mueller provided laboratory guidance and assistance. Funding was provided by the Center for Environmental Studies, Arizona State University.

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