Modeling the transport of stored sediment in a gravel bed river, northwestern California

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ABSTRACT

Using a first order Markov chain, we develop a mathematical model that predicts the residence time of coarse sediment in the main channel of Redwood Creek, a gravel bed river in the Coast Ranges of northern California. The model is based on probabilities of transition of particles among four different sediment storage reservoirs, called active (often mobilized), semi-active, inactive and stable (hardly ever mobilized). The probabilities are derived from computed sediment residence times. Two aspects of sediment storage are investigated: flushing times of sediment out of a storage reservoir, and changes in the quantity of sediment stored in different reservoirs due to seasonal sediment transport into, and out of, a reach. Sediment flushing times are highly dependent on the degree of interaction of the stable reservoir with the more mobile sediment reservoirs. Only the case of minimal interaction with the stable reservoir gives flushing times that are reasonable in light of existing data on bedload transport rates and stored sediment volumes. Therefore, if the stable reservoir is dominant in terms of volume, the most infrequent and highest intensity storm events (which mobilize the stable reservoir) are responsible for the long term shifts in sediment storage. Turnover times for channel sediment in all but the stable reservoir are on the order of 1,000 years, suggesting this is all the time needed for (1) thorough interchange between these sediment compartments, and (2) cycling of most sediment particles from the initial reservoir to the ocean. The mean transit time for a particle traveling down a reach of Redwood Creek is an order of magnitude greater than the median transit time. This large range of transit rates makes the results of sediment tracer studies with incomplete recovery difficult to interpret. Finally, the Markov model has adequately characterized sediment storage changes in Redwood Creek for 1947-1980, especially for the active reservoir. The model replicates field observation of the passage of a slug of sediment through the active reservoir of the middle reach of Redwood Creek in the 16 years following a major storm in 1964 that introduced large quantities of landslide debris to the channel. The model therefore has potential as a predictive tool for channel sediment storage changes given a range of future storm scenarios.

INTRODUCTION

Recently, several investigators have pointed to the disparity between drainage basin erosion rates, measured on the upland slopes, and drainage basin sediment yield, measured at a gage at a downstream cross section (Trimble, 1977, 1981; Meade, 1982). The disparity is because part of the sediment entrained in the upper portions of a basin frequently goes into storage further downslope or downstream. Recognition of this process led to the concept of a sediment delivery ratio that describes that portion of entrained upland sediment that is delivered past a point of measurement downstream. These storage sites are initially both a sink for entrained sediment and, at a later date, a major source for sediment moved further down a basin. Both Trimble (1981) and Meade (1982) have pointed out that sediment in storage in the channel can be <u>the</u> major source of erodible material in basins that had previously undergone severe upland erosion and consequent deposition in mid-basin storage sites.

Other investigators, most notably G. K. Gilbert (1917), documented that rapid increases in stored channel sediment, brought on by sudden influxes of debris from hillslopes (in Gilbert's case due to hydraulic mining), can result in the downstream movement of such sediment as a wave or slug. The migrating sediment wave is confined to the active channel and dissipates in height and extends in length with movement downstream.

Gilbert (1917), as well as Meade (1982), also noted that sediment stored on floodplains (by overbank deposition or isolated by downcutting) tends to stay in storage much longer than the more accessible sediment in the active channel. Therefore, floodplain sediment tended to be stable, eroding only by lateral corrasion of the river, whereas sediment stored in the active channel, if delivered rapidly to a channel reach, is subject to further downstream movement as a wave or slug.

Meade (1982) claims that trying to predict the movement of stored sediment verges on a hopeless task because one obviously cannot assume a steady state for channel sediment reservoirs and, at the same time, the predictive period is too long to apply physical theories of sediment transport with any measure of success. However, the dynamics of stored sediment need not be treated as an analytic problem, nor as a deterministic problem only tractable with repeated field measurements. We present a stochastic approach to predicting how stored sediment moves. Also, we apply this approach to Redwood Creek, a gravel bed river in north coastal California Creek (fig. 1), where we are fortunate to have an extensive data base. Sediment storage changes and sediment transport are sufficiently well defined for the period 1947-1982 so that our stochastic modeling of stored sediment changes can be tested by field-collected data.

The stochastic model, if realistic, should predict the sequential movement of coarse sediment down a channel reach after, for instance, a major sediment-producing storm event that delivers a slug of sediment into a channel reach. Such a storm event did occur in December, 1964, in northwestern California (Waananen and others, 1971; Kelsey, 1980). Our study models the dynamics of stored sediment in a 33.3 km reach through the middle of Redwood Creek due to this event.

REDWOOD CREEK: STUDY WATERSHED FOR THE MODEL

The Redwood Creek basin (720 km^2) is an elongate, north-northwest-trending basin with a single 108 km-long mainstem channel that has an average gradient 1.5 percent. The channel is gravel bedded with a median grain size (d_{50}) ranging from 90 mm in the upper reaches to 16 mm near the mouth. Sediment transport rates reflect the rapid rates of erosion in this area: 2,700 mg/km^2/yr in the upper basin (gaging station BL, fig. 1) and 2,200 mg/km^2/yr at the mouth (gaging station OR, fig. 1). Mean annual precipitation is 2,000 mm, most of which falls between October and March.

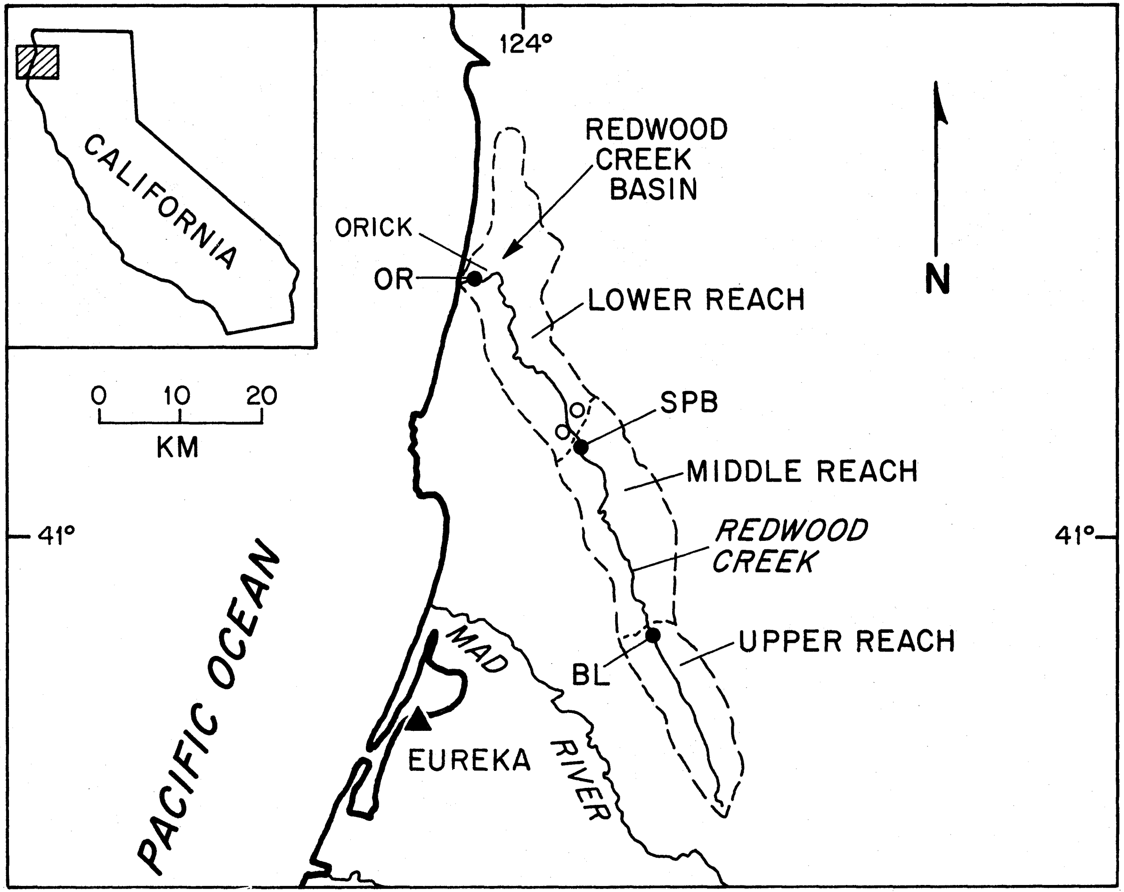

FIG. 1 Location map of the Redwood Creek basin, showing the upper, middle, and lower study reaches, and the location of the six U. S. Geological Survey gaging stations. Closed circles are mainstem gaging stations (OR, Orick; SPB, South Park Boundary; BL, Blue Lake) and open circles are tributary gaging stations.

The period of adequate aerial photographic coverage of the Redwood Creek basin spans from 1947 to the present. Using the photographic data in conjunction with field measurements, various authors have documented the changing character of the main channel and the immediate streamside hillslopes since 1947 (Colman, 1973; Harden and others, 1978; Nolan and Janda, 1979; and Kelsey and others, 1985).

Major storms in December, 1955, and December, 1964 (Harden and others, 1978) initiated numerous streamside debris slides along Redwood Creek. The 1964 storm generated the vast majority of streamside landsliding, delivering 2 x 10^6 m^3 of landslide debris to the upper reach alone (Kelsey and others, 1985). Comparing the dates and magnitudes of prehistoric floods in northern California (Helley, 1973; Kelsey, 1980; Zinke, 1981) with the 1964 flood suggests that a 1964 flood magnitude has a recurrence interval of 60-80 years. Net deposition in the main channel as a result of the 1964 storm was approximately 4.7 x 10^6 m^3. The increased volume of main channel sediment in Redwood Creek was initially concentrated in the upper reach, where most landsliding occurred. During the 1964 flood, gravel berms up to 9 m high were deposited in this reach. During the succeeding two decades after 1964, the sediment gradually migrated downstream. Major transport and deposition events occurred during storms in 1972 and 1975. The changes in volume and loci of sediment storage in Redwood Creek are well documented (Nolan and Janda, 1979; Varnum, 1984; Madej, 1984), and this documentation provides an opportunity to test the model.

For this study, the Redwood Creek watershed was split into an upper, middle, and lower reach (35.3, 33.3 and 35.6 km in length, respectively), with U. S. Geological Survey gaging stations located at the downstream end of each of these reaches (fig. 1). Three additional gaging stations are located on tributary basins (fig. 1).

SEDIMENT RESERVOIRS

During the 1979 and 1980 field seasons, all sediment stored in the main channel of Redwood Creek was mapped and classified into one of four reservoirs: active, semi-active, inactive or stable (fig. 2). The stored sediment was classified on the basis of (1) relative position and elevation in comparison to the active channel, (2) density and age of vegetation growing on the deposit, and (3) presence of partially buried trees or artifacts such as logging cable or cut wood. The estimated discharge recurrence intervals used to classify stored sediment are based on vegetation age classes.

Active sediment, in the presently active main channel, moves with flows of a recurrence interval (RI) of 1-5 years. This sediment is unvegetated or very sparsely vegetated. The active reservoir includes bed material down to the annual depth of scour. Semi-active sediment is mobilized by flows with a RI of approximately 5-20 years. This sediment is directly adjacent to but higher than the active channel, and is often covered with shrubs and young trees. Inactive sediment is mobilized by flows with a RI of approximately 20-100 years. These flows can mobilize coarse lag deposits, 3-5 m high gravel flood berms, intact log jams, and floodplain deposits. The gravel flood berms deposited during the 1964 storm are composed of inactive sediment.

Stable sediment consists of well vegetated floodplain deposits high above the thalweg. These deposits move extremely infrequently. In Redwood Creek, most stable sediment has not been mobilized historically except through localized lateral erosion. Some fine-grained material was added to the surface of stable reservoirs during the 1955 and 1964

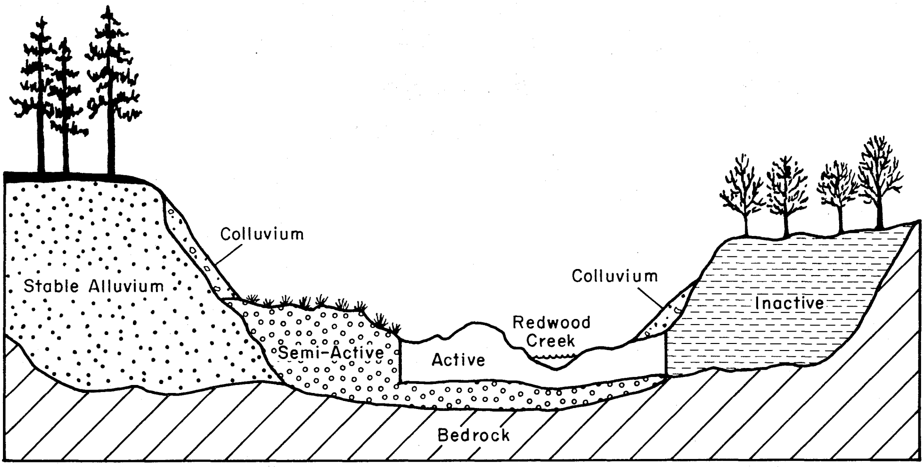

FIG. 2 The four sediment reservoirs in the Redwood Creek channel, based on the relative mobility of sediment. Positions of active, semi-active, inactive, and stable reservoirs are based on the relative position and elevation of stored sediment in comparison to the active channel.

floods. The thick early to mid-Holocene valley fill in lower Redwood Creek was not included in the stable sediment volumes.

Stable sediment may be influenced by tectonic activity due to the generally long intervals between its mobilization. Uplift rates in Redwood Creek are on the order of 1 m/10^3 yr (Kelsey, 1986), so there is a possibility that stable sediment could be isolated by uplift and become the alluvial veneer on a strath terrace. Although strath terraces are prevalent in four reaches along Redwood Creek, the total volume of sediment incorporated in these straths is only a few percent of the total stable reservoir volume. Therefore, even though uplift does isolate stable sediment and effectively remove it from the alluvial transport, the volume involved is insignificant. Strath terrace alluvium is ultimately reintroduced to the channel by valley sideslope corrasion, but this transition probability is too small to be considered in the model.

THE MARKOV CHAIN MODEL

We attempt to model the dynamics of sediment storage through the use of a first order Markov chain. The model is based on the probability of transition of a particle of sediment between sediment storage reservoirs. These probabilities are derived from calculated sediment residence times.

The model addresses changes in volume of stored sediment from one reach to the next. We chose this approach because it is exceedingly difficult to assess (even with extensive field measurements) the net total sediment input into, and discharge out of, a reach during a defined time period, or to estimate the time necessary for removing set volumes of bedload from a reach. The problem is complex because bedload-size sediment in the channel and on adjacent depositional surfaces is not all equally accessible to transport. Some of the sediment is readily available for transport in the active channel, and, at the other extreme, some of the sediment resides in vegetated fill terraces from which it is transported only by infrequent, large floods. Furthermore, there is constant interchange during flooding events between the active reservoir

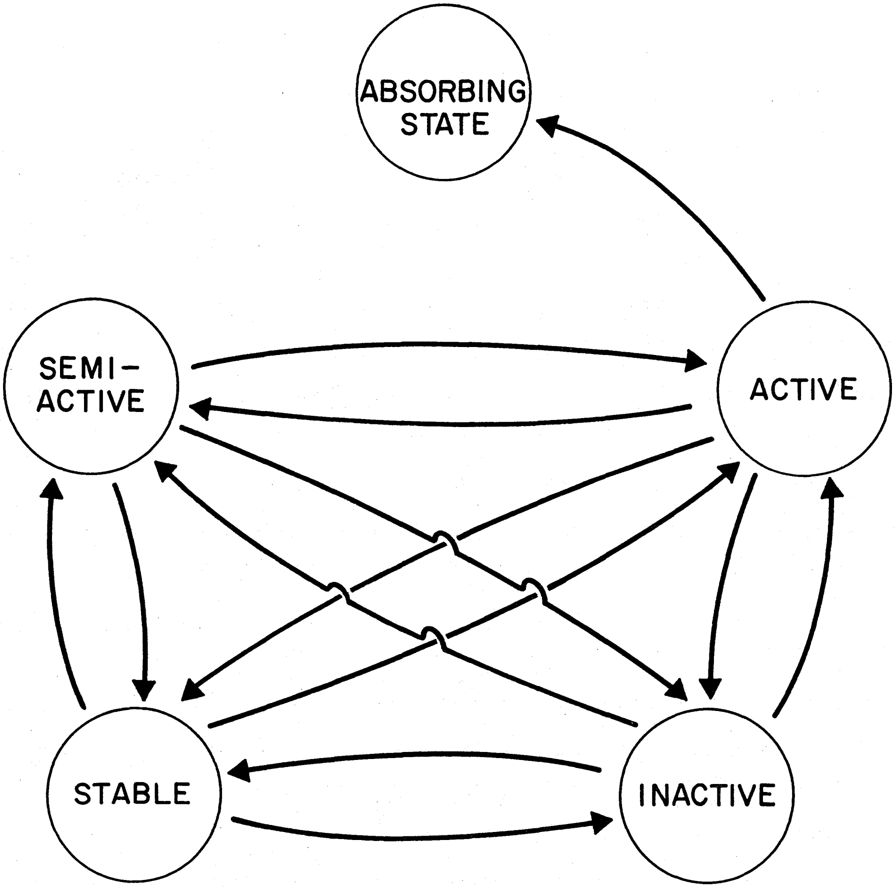

FIG. 3 State diagram showing the possible interchanges between the four sediment reservoirs. Note that sediment can only exit from the system (be absorbed) through the active reservoir. For Redwood Creek, the absorbing state is either a downstream reach, or the ocean, depending on whether the model addresses a single reach or the entire watershed.

and the less active reservoirs (fig. 3), so sediment may be highly mobile for a number of years, then through transport and redeposition in a major flood event, sediment may become virtually trapped for hundreds or thousands of years in relatively inaccessible flood deposits. The stochastic nature of the storms and floods, and the resultant complexity of movement of sediment between reservoirs, argues for a stochastic approach to the problem of modeling changes in sediment storage over time.

Our model will deal with two aspects of sediment stored in the main channel: flushing times of sediment out of a storage reservoir (cases I, II and III), and the changes in the quantity of sediment stored in different reservoirs due to variable seasonal bedload transport into, and out of, a channel reach (case IV). The latter aspect addresses the migration downstream of a wave of sediment as described by Gilbert (1917) and as further discussed by Mosley (1978), Kelsey (1982), Meade (1982), and Madej (1982).

The state diagram in fig. 3 shows the basis for the Markov chain model as applied to sediment transport. For any one reach of stream, the arrows on the state diagram indicate the possible transitions between reservoir states. Within any of the three study reaches, sediment in any one of the four reservoirs is free to interchange with any of the other reservoirs (fig. 3). Sediment may also exit from the system (a process called absorbtion), but only through the active reservoir. Sediment may be absorbed in a downstream reach or in the ocean, depending on whether the model addresses a stream reach or the entire watershed. The major condition of movement is that the downstream motion of a particle of sediment depends only on the reservoir it is presently in, and particle motion does not depend on previous movement history, nor on the amount of time the particle has already been in its present reservoir state.

Data requirements for the model

Three data sets were required to construct the model. First, bedload transport rates were needed for all the gaging stations. These rates were derived from periodic measurements of bedload discharge during 1974-82 by the U. S. Geological Survey. A Helley-Smith bedload sampler was used at moderate discharges and the Meyer-Peter-Muller and modified Einstein bedload formulas were used for high discharges. Annual increments of bedload entering a reach were computed using the bedload transport rates in conjunction with flow duration curves for the gaging station sites. Secondly, measured channel lengths and drainage areas were needed for all the gaged sub-units of the basin (fig. 1). Finally, volumes of sediment in different sediment storage reservoirs were necessary. These volumes were measured in the field in 1979-1980; volumes for 1947 and 1965 (after the December 1964 storm) were calculated using aerial photographs and previous channel cross-section surveys. Only sediment volumes for 1947 are needed to construct the model, and the other two sets of volumes serve as a check on model accuracy.

Basis for the model: sediment residence time

Residence time for a reservoir is the volume of sediment in a reservoir divided by the average transport rate of particles in the reservoir (Q_B). For the active reservoir, this average transport rate is measured in the field using a bedload sampler. The average rate that a particle moves while in the active reservoir is notably different from the average transport rate of all particles that make up the active reservoir. The latter rate is slower because of the probability that active particles may be intermittently stored in semi-active, inactive or stable reservoirs. This slower rate is called the reservoir flushing time, which will be discussed below. Because the average transport rate within a reservoir is only known for the active reservoir, true residence times can only be determined for this reservoir.

To compute residence times for the other reservoirs, increasingly greater reservoir volumes are divided by the same average transport rate of particles in the active reservoir (Q_B). This computational method is a surrogate for computing the three residence times of the successively less active reservoirs, using the particular reservoir volume and successively smaller (and unknown) average particle transport rates. For example, the residence time for semi-active sediment is $[V_{s(active)} + V_{s(semi-active)}]/Q_B$. By this procedure, computed residence time for the semi-active, inactive and stable reservoirs is an index of the size of the reservoir. Under conditions of steady state, this is a reasonable assumption. The technique was necessary to further develop the model, and it appears to give credible residence times in light of the field evidence. This is discussed further below.

Calculations of residence times for the reservoirs in Redwood Creek follow the methods of Dietrich and Dunne (1978). Using available data for the entire basin, sediment volume per unit length (V_S) and bedload discharge (Q_B) were defined as power functions of drainage area (A), and drainage area (A) was defined as a power function of mainstem channel length (X) (Table 1):

$$V_S = aA^m \qquad (1)$$

$$Q_B = bA^n \qquad (2)$$

$$A = cX^p \qquad (3)$$

where a, b, c, m, n, and p are constants. Four separate power functions, for the four different cumulative reservoir volumes (Table 1), were derived to define the relationship of the volume of sediment to drainage area (equation 1). Computation of power function relationships is further discussed in Madej (1984).

Combining equations (1)-(3) yields the following relationship between residence time per unit channel length (V_S/Q_B) and the power functions of equations (1), (2), and (3)

$$\frac{dt}{dx} = \frac{V_S}{Q_B} = \frac{a(cX^p)^m}{b(cX^p)^n} = \frac{a}{b}\, c^{(m-n)}\, X^{p(m-n)} \qquad (4)$$

Integration of equation (4) allows calculation of residence time for a reach of channel of length x_2-x_1

$$\int_{t_1}^{t_2} dt = \int_{x_1}^{x_2} \frac{a}{b}\, c^{(m-n)}\, X^{p(m-n)}\, dx \qquad (5)$$

(Dietrich and Dunn, 1978). In such a manner, using the values for the constants in Table 1, residence times for the four reservoirs were computed for three reaches of Redwood Creek (Table 2). Sediment in the active reservoir has the shortest residence time, and this residence time decreases downstream. Residence times for the inactive reservoir are approximately an order of magnitude greater than for the active reservoir, and residence time for the stable reservoir is an order of magnitude greater than for the inactive reservoir (Table 2).

Calculated values of residence time (Table 1) are generally consistent with the type of vegetation growing on the different reservoirs. Stable sediment supports coniferous forests, implying stability on orders of hundreds of years. Inactive sediment was mobilized by the 1964 storm approximabely a 60-80 year recurrence interval event), but these deposits have been otherwise stable and now support a young hardwood riparian forest. Semi-active sediment has moved on at least four occasions in the two decades since 1964. Therefore, despite the assumptions we must make to calculate residence time for the three less active reservoirs, the calculated results are consistent with field observations and will therefore be used in the next step of model development.

Residence time gives the average amount of time a particle would spend in a reservoir, based on the mobility of that reservoir. However, a residence time does not indicate how long any one particle will take to totally leave a reach. For example, if a particle in the active reser-

TABLE 1 Definition of power functions used to compute sediment residence time.

Reservoir	Relation	a	b	c	m	n	p	r^2
Entire channel	$Q_B = bA^n$		272			1.04		0.88
	$A = cX^p$			1.28×10^{-4}			1.34	0.98
Ac sediment	$V = aA^m$	0.64			0.70			0.49
Ac + Sa sediment	$V = aA^m$	1.29			0.65			0.47
Ac + Sa + Ia sediment	$V = aA^m$	0.79			1.05			0.45
Ac + Sa + Ia + St sediment	$V = aA^m$	0.04			2.20			0.45

*Ac = Active; Sa = Semi-active; Ia = Inactive; St = Stable sediment reservoirs.

TABLE 2 Sediment residence times for sediment in each of the four reservoirs in each of the three reaches.

Reservoir	Reach*	Residence time (years)
ACTIVE	U	26
	M	11
	L	9
SEMI-ACTIVE	U	50
	M	19
	L	15
INACTIVE	U	104
	M	99
	L	106
STABLE	U	700
	M	3,100
	L	7,200

*U, upper reach; M, middle reach; L, lower reach

voir is mobilized, it may be carried out of the reach (be absorbed), or it may be redeposited within the reach in another reservoir such as the inactive reservoir, where it will reside for a much longer time before being remobilized and ultimately flushed out of a system. Therefore, a residence time only provides the basis for assigning a probability that a particle of sediment will leave a certain state within a set time period.

MATHEMATICAL TREATMENT

Our Markov chain model models the transport of stored sediment in discrete time steps of one year duration. For any given time interval, such as one year, we assume there is a fixed, known probability, p_{ij}, that a particle residing in state i at the beginning of the year will reside in state j at the beginning of the next year. These probabilities comprise the entries in the transitional matrix, T. For example, if state 1 is the active reservoir in the upper reach of Redwood Creek, and state 3 is the inactive reservoir for that reach, then p_{13} represents the fraction of sediment residing in the active reservoir at the beginning of a given year that one might expect to reside in the same reach but in the inactive reservoir at the end of that year. If $p_{ii}=1$, then i is said to be an absorbing state and once a particle enters that state it can never leave it. All other states are known as transient states.

The states are numbered beginning with the absorbing states. As a result, the matrix has the general form

$$T = \left[\begin{array}{c|c} I & O \\ \hline R & Q \end{array}\right] \qquad (6)$$

where I is an identity matrix (representing the absorbing state) and 0 is a zero matrix. The submatrix Q represents movement amongst the various transient states while R gives the probabilities for movement directly from a transient state to an absorbing state.

For the Redwood Creek study, there are twelve transient states representing four different sediment reservoirs in each of three reaches. In addition, there is one absorbing state, the ocean. The numbering of the transient states is organized so that the submatrix Q may be further broken down into submatrices Q_1, Q_2, and Q_3

$$Q = \begin{bmatrix} Q_1 & \cdot & \cdot \\ 0 & Q_2 & \cdot \\ 0 & 0 & Q_3 \end{bmatrix} \qquad (7)$$

which individually represent the transient states for the upper, middle, and lower reaches of Redwood Creek respectively.

If we wish to study a single reach of the stream rather than the entire channel length, then the T matrix has the general matrix form (6) and

$$T = \left[\begin{array}{c|cccc} 1 & 0 & 0 & 0 & 0 \\ \hline r_1 & & & & \\ r_2 & & Q_i & & \\ r_3 & & & & \\ r_4 & & & & \end{array}\right] \qquad (8)$$

where Q_i is the 4 x 4 submatrix of transient states just for that reach. The r_i's are chosen so the row sums will each be one. For each of the three study reaches, we developed a transition matrix (Q_1, Q_2, Q_3) for sediment movement through the reach. The transition probabilities of the Q matrices are for movement in any one year period, and are determined as follows. If we assume for reservoir i a residence time of n_i years, the probability that sediment will remain in that reservoir state after one year is $(n_i-1)/n_i$ and the probability that sediment will leave the reservoir during the year is $1/n_i$. The transition probability p_{ii} must equal $(n_i-1)/n_i$; and the sum of the remaining probabilities, p_{ij}, must equal $1/n_i$. For the transition matrices for each reach (fig. 4), the probabilities on the matrix diagonal are therefore computed directly from residence times, and the other probabilities of movement between the different states are partitioned from the relatively small probability of transition from one state to another state or to the absorbing state. Determination of these off-diagonal probabilities is discussed below. Aspects of our model are similar to a model of Dacey and Lerman (1983) who investigate sediment growth and aging as a Markov chain.

The volumes of sediment stored in the various states at the beginning of the n^{th} year are recorded in the vector $D^{(n)}$. For example, in one of the examples below, $D^{(1)}$ is the 1 x 4 row vector defining volumes of sediment as of 1947 in the active, semi-acive, inactive, and stable reservoirs of the middle reach. Markov models have the property that

$$D^{(n)} = D^{(n-1)}T. \qquad (9)$$

UPPER REACH:

$$Q_1 = \begin{array}{c} \begin{array}{cccc} A & Sa & I & St \end{array} \\ \left[\begin{array}{cccc} .9615 & .0081 & .0027 & .00077 \\ .011 & .98 & .008 & .001 \\ .0043 & .0043 & .9904 & .00096 \\ .00029 & .00064 & .0005 & .9986 \end{array}\right] \end{array} \begin{array}{c} \\ A \\ Sa \\ I \\ St \end{array}$$

MIDDLE REACH:

$$Q_2 = \left[\begin{array}{cccc} .9091 & .0191 & .00636 & .0018 \\ .0289 & .9474 & .021 & .0026 \\ .0045 & .0045 & .9899 & .001 \\ .000065 & .000145 & .000113 & .99968 \end{array}\right] \begin{array}{c} A \\ Sa \\ I \\ St \end{array}$$

LOWER REACH:

$$Q_3 = \left[\begin{array}{cccc} .8889 & .0233 & .0078 & .0022 \\ .0367 & .9333 & .0267 & .0033 \\ .0043 & .004 & .99056 & .00094 \\ .000028 & .000063 & .000049 & .999861 \end{array}\right] \begin{array}{c} A \\ Sa \\ I \\ St \end{array}$$

FIG. 4 Transition matrices (Q_1, Q_2, Q_3) for the upper, middle, and lower reaches respectively. These matrices were determined based on residence times for the sediment reservoirs plus trial runs of study reach flushing times. A: active reservoir; Sa: semi-active reservoir; I: inactive reservoir; St: stable reservoir. Note that for each matrix, the row sum of Sa, I, and St equals one, whereas the row sum of A is less than one, the difference being equal to the probability of a sediment particle being absorbed out of the active reservoir.

That is, the distribution in year n is equal to the distribution in the previous year times the transition matrix. This assumes that no new sediment enters the system during that year. However, new sediment enters the Redwood Creek channel each year, so we modify the model and let

$$D^{(n)} = D^{(n-1)}T + L^{(n-1)} \qquad (10)$$

where the i^{th} entry in the vector $L^{(n-1)}$ is the volume of new sediment residing in state i at the end of the year n-1 that was not accounted for in any of the volumes $d_i^{(n-1)}$. The case where $L^{(n)}$ is always the same has previously been discussed by Lamberson (1977).

Using the above procedure, we generate four applications of the model (cases I-IV) that explore different aspects of the transport of stored sediment in Redwood Creek. We will discuss modifications of the general procedure in each section as they apply to the specific application.

FOUR MODEL ANALYSES OF TRANSPORT OF STORED CHANNEL SEDIMENT IN REDWOOD CREEK

Sediment flushing times out of each of the three mainstem reaches (case I)

The first analysis (case I) generates flushing times for sediment, that is, the expected length of time for a particle starting in a certain reservoir to be flushed out to the absorbing state. Flushing time is significantly different from residence time. Residence time is the average time a particle would take to leave a particular reservoir if it did not interact with other reservoirs; however, because of reservoir interactions, the actual flushing time is slower.

The flushing time is calculated using the Q transition matrix by the methods outlined below, which are described in Isaacson and Madsen (1974). If we define N_i to be $(I-Q_i)^{-1}$ (Isaacson and Madsen, 1974), then the sum of the j^{th} row in N_i gives the expected length of time for a particle starting in the j^{th} reservoir to be flushed out to the absorbing state (the ocean or a lower reach). In our first analysis (case I), we compute flushing times for sediment out of each of the three study reaches, using $Q_i = Q_1, Q_2$, and Q_3.

To run the model for case I and subsequent cases, we first had to determine the off-diagonal matrix probabilities of fig. 4, representing the probabilities of movement between reservoir states. The row sum of these probabilities is in all cases small (always smaller than 0.111 and averages 0.034 for the 12 possible cases), but the determination of accurate off-diagonal matrix probabilities is critical because these probabilities determine reservoir flushing times. Comparisons of cumulative distance of actively eroding channel banks among the four reservoirs, as well as data on how frequently the reservoirs are mobilized (see above), provided a basis for estimating a range of possible exchange probabilities among reservoirs. We formulated three different sets of Q matrices (three different sets of off-diagonal probabilities) that represent different degrees of interaction (minimal, moderate, and substantial) with the stable reservoir. Because the stable reservoir in the short term is a sink (due to extremely long residence times, Table 2), it can substantially influence flushing times. The resulting flushing times (Table 3) show that flushing time is sensitive to partitioning of the off-diagonal matrix probabilities.

Insufficient field data prevent us from unequivocally choosing the best Q matrix from the three used to compute the flushing times in Table 3. Lacking this data, we determined which result appears to be most reasonable. We evaluated residence time compared to flushing time estimates for the stable reservoir (Table 2 vs. Table 3). Based on the definition of flushing versus residence times, the two should be similar for the stable reservoir because stable reservoir particles only interact with more active reservoirs and the probability of such interaction is quite small. Using this criteria, only flushing times based on minimal interaction with the stable reservoir are similar to stable reservoir residence times. Based on these results, we selected Q_1, Q_2, and Q_3 with minimal interaction with the stable reservoir to be the transition matrices (fig. 4) that are used in all succeeding models (with slight modification for cases II and IV).

Minimal interaction with the stable reservoir cannot be readily defined in terms of frequency of mobility. However, minimal interaction implies that the stable reservoir only moves during climatically extreme events because it was only mobilized to a minor degree by isolated incidences of bank erosion during the 1964 flood.

In a physical sense, through varying the extent of activity of the stable reservoir, we modeled different ways that stable sediment can move down a specified reach length. Storm events are the cause of major episodes of sediment transport. The flushing time results (Table 3) therefore compare the effects of a few major storms that move stable sediment great distances but occur infrequently (minimal interaction with stable reservoir), and a number of frequent, smaller storm events that move stable sediment often (substantial interaction with stable reservoir) but never move it very far. The results suggest that infre-

TABLE 3 Average number of years to empty initial reservoir (sediment flushing times from the reservoir) given varying amount of interaction with the stable reservoir: 1, minimal interaction; 2, moderation interation; 3, substantial interaction.

Initial reservoir of sediment particle	lower reach flushing times			middle reach flushing times			upper reach flushing times		
	1	2	3	1	2	3	1	2	3
Active	655	1,787	2,729	318	804	1,228	156	266	371
Semi-active	1,622	4,732	7,074	773	2,135	3,138	368	681	944
Inactive	2,009	5,283	7,978	969	2,392	3,612	447	780	1,093
Stable	8,772	11,237	13,106	3,882	4,987	5,799	1,075	1,319	1,523

quent, high intensity flood events, which mobilize the stable reservoir, are the only type of events that can be responsible for the major long term shifts in sediment storage in Redwood Creek. In light of this, it is noteworthy that even though the 1964 flood brought major geomorphic change to this basin, it essentially did not mobilize the stable reservoir.

Sediment flushing times to ocean from twelve different initial sediment reservoirs along Redwood Creek (case II)

The second analysis (case II) determines the expected length of time for a particle starting in any of the 12 initial reservoirs (four reservoirs in each of the three reaches) to be flushed to the ocean. The second analysis therefore uses a 12 x 12 Q matrix, which is in the general matrix form (7). The flushing times for sediment moving from any state in the system to the ocean in this model are given by the appropriate row sum in N where N = $(I-Q)^{-1}$.

Once the flushing times are computed we can compute their variance by evaluating the matrix equation

$$\begin{bmatrix} v_i \\ v_2 \\ \cdot \\ \cdot \\ \cdot \\ v_n \end{bmatrix} = N \begin{bmatrix} 2f_i-1 \\ 2f_2-1 \\ \cdot \\ \cdot \\ \cdot \\ 2f_n-1 \end{bmatrix} \qquad (11)$$

where v_i is the variance given that the sediment began in state i, the f_i's are the flushing times and N is the appropriate matrix (Isaacsen and Madsen, 1974).

The Q transition matrix (fig. 5) is derived from Q_1, Q_2, and Q_3 but is slightly modified from of Q_1, Q_2, and Q_3 in order to reflect an increased number of transition probabilities among reservoirs. The greater number of possible transitions in this composite model allows sediment to enter a downstream reach from an upstream reach through the semi-active and inactive reservoirs as well as through the active reservoir. In addition, sediment can enter the ocean from the lower reach through both the active and semi-active reservoirs. Therefore, for 6 of the 12 initial states the modified model allows sediment to travel to the next downstream reach in one year. The off-diagonal probabilities in these cases were altered from fig. 4 and were designated according to the priority scheme in fig. 5. The priority scheme ranks transitions from the most likely to the least likely based on qualitative field observations of reservoir interaction. It was not possible to quantitatively determine the off-diagonal probabilities for the 12 x 12 Q transition matrix from field data. Because these probabilities are no more than professional judgments based on field observations, the calulated flushing times are necessarily suspect. We did a sensitivity test to determine if the flushing times vary significantly with variation in the off-diagonal probabilities. The test, consisting of 5 different model runs with different off-diagonal probabilities, revealed that the flushing times did not substantially differ. The conclusions stated below are valid for all 5 model runs.

Table 4 summarizes the results of case II. For active sediment, flushing times are longest if the sediment starts in the upper reach and

$$Q = \begin{array}{c|cccccccccccc}
 & (A_1) & (Sa_1) & (Ia_1) & (St_1) & (A_2) & (Sa_2) & (Ia_2) & (St_2) & (A_3) & (Sa_3) & (Ia_3) & (St_3) \\
\hline
(A_1) & 0.9615 & 0.0081 & 0.0027 & 0.00077 & 0.0217 & 0.0040 & 0.0010 & 0.00014 & 0 & 0 & 0 & 0 \\
(Sa_1) & 0.00778 & 0.9794 & 0.00784 & 0.00016 & 0.00322 & 0.0006 & 0.00098 & 0.00002 & 0 & 0 & 0 & 0 \\
(Ia_1) & 0.00414 & 0.00343 & 0.99036 & 0.00004 & 0.00095 & 0.00087 & 0.00016 & 0.00005 & 0 & 0 & 0 & 0 \\
(St_1) & 0.00031 & 0.00094 & 0.00005 & 0.9986 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
(A_2) & 0 & 0 & 0 & 0 & 0.9091 & 0.0191 & 0.00636 & 0.0018 & 0.0512 & 0.00954 & 0.00254 & 0.00036 \\
(Sa_2) & 0 & 0 & 0 & 0 & 0.02122 & 0.94597 & 0.02062 & 0.00038 & 0.00868 & 0.00248 & 0.0009 & 0.00005 \\
(Ia_2) & 0 & 0 & 0 & 0 & 0.00412 & 0.00245 & 0.9898 & 0.00011 & 0.00205 & 0.00099 & 0.00038 & 0.0001 \\
(St_2) & 0 & 0 & 0 & 0 & 0.000065 & 0.000024 & 0.000231 & 0.99968 & 0 & 0 & 0 & 0 \\
(A_3) & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.8889 & 0.0233 & 0.0078 & 0.0022 \\
(Sa_3) & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.02731 & 0.93155 & 0.02623 & 0.00324 \\
(Ia_3) & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.0043 & 0.004 & 0.99056 & 0.00114 \\
(St_3) & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0.000028 & 0.000063 & 0.000049 & .99986
\end{array}$$

initial state	possible transitions in descending order of priority						
A_1	A_2	Sa_1	Sa_2	Ia_1	Ia_2	St_1	St_2
A_2	A_3	Sa_2	Sa_3	Ia_2	Ia_3	St_2	St_3
Sa_1	A_1	Ia_1	A_2	Sa_2	Ia_2	St_1	St_2
Sa_2	A_2	Ia_2	A_3	Sa_3	Ia_3	St_2	St_3
Ia_1	A_1	Sa_1	A_2	Sa_2	Ia_2	St_1	St_2
Ia_2	A_2	Sa_2	A_3	Sa_3	Ia_3	St_2	St_3

FIG. 5 (Top): 12 x 12 transition matrix (Q matrix) used for the flushing time analysis of case II. The 12 transient states constitute the four different reservoirs in each of the three study reaches. A: active; Sa: semi-active; I: inactive; St: stable. The varying number of significant figures reflects the fact that all row summations must equal one except for A_3 and Sa_3. (Bottom): tabular presentation of priority scheme for assigning transition probabilities for different initial reservoir states.

TABLE 4 Expected length of time for particle starting in specified reservoir to be flushed to the ocean.

Initial reservoir*	Flushing time (yrs)+ $\bar{x}$	s
U-A	1,050	3,700
U-Sa	1,100	3,700
U-I	1,150	3,700
U-St	1,850	4,050
M-A	900	3,650
M-Sa	950	3,650
M-I	1,050	3,750
M-St	4,100	6,250
L-A	600	3,050
L-Sa	1,350	4,600
L-I	1,800	5,250
L-St	8,500	11,900

*U: upper reach; M: middle reach; L: lower reach; A: active reservoir; Sa: semi-active reservoir; I: inactive reservoir; St: stable reservoir.

+Computed value rounded off to nearest 50 years. $\bar{x}$ = mean; s = standard deviation.

shortest for active sediment starting in the lower reach. However, as the reservoir becomes less likely to be mobilized, the situation reverses. For the stable reservoir, the relatively small amount of sediment that starts in this reservoir in the upper reach is likely to reach the ocean before the large amount of stable sediment that is in more permanent storage in the lower reach.

Flushing times of Table 4 also suggest that, for the active, semi-active, and inactive reservoir, the expected time a particle arrives at the ocean is not significantly different regardless of which reach the particle started in and irrespective of whether the particle started in the active, semi-active or inactive reservoir. Therefore, for the Redwood Creek channel, the average length of time for particle turnover in any one of these reservoirs is approximately 1,100 years. Variability for the individual flushing times is quite large, indicated by the standard deviations about the mean (Table 4). This large variability is expected given the exceptionally long residence times for particles in the middle and lower reach stable reservoirs (Table 2). The stable reservoirs can retain sediment for times on the order of 1,000-9,000 years (Tables 3 and 4). Stable sediment reservoirs in the upper two-thirds of Redwood Creek take the form of heavily forested terraces along the channel. Near the mouth, forested floodplain deposits on top of the Holocene valley fill constitute the stable reservoir.

Sediment distribution and depletion in the four middle reach reservoirs over time (case III)

It is worth looking further at the flushing time model for a single study reach, such as the middle one, and compare the flushing time to the transit time for the majority of sediment particles moving through a reservoir. For case III, we continuously load the same amount of sediment into the active reservoir of the middle reach on a yearly basis. In equation (10), $L^{(n-1)} = (L, 0, 0, 0)$ and

$$T = \left[\begin{array}{c|ccc} 1 & 0 & 0 & 0 \\ \hline r_1 & & & \\ r_2 & & Q_2 & \\ r_3 & & & \\ r_4 & & & \end{array}\right] \tag{12}$$

$D^{(n)}$ (see equation (9)) in this analysis gives the sediment distribution through the four reservoirs after n years assuming continuous loading.

The Markov model will yield the distribution of sediment among reservoirs and depletion of sediment from reservoirs in the reach at any given year after input starts (table 5). For instance, 35 years (the time span of the case IV, discussed below) after we started to trace the sediment entering the middle reach, 30% was in the active reservoir, minor amounts were in the other reservoirs, and 51% had been absorbed into the lower reach. However, the average flushing time for sediment entering the active reservoir of the middle reach is 318 years (table 3). The discrepancy between a 318 year average flushing time and a transit time through the system of 35 years for 51% of this sediment is seemingly problematical. However, the first is the mean transit time while the second is the median transit time. The difference is explained by the fact that if a particle from the active reservoir happens to enter the stable reservoir, it can stay there thousands of years, substantially influencing average flushing time. This result has significance for sediment tracer studies where only a fraction of marked particles are recovered. A recovered marked particle most likely will travel near the median transit time but will not furnish information on the mean transit time (which should be much longer) for particles in that reservoir population.

A model of sediment storage changes in the middle reach for 1947-1982 (case IV)

The final application (case IV) involves modeling the changes in storage volumes of the middle reach reservoirs during the period 1947-1980. We use the same transition matrix for the middle reach (fig. 4), except that during the study period, the stable reservoir was not eroded at all, and the inactive and semi-active probabilities are increased accordingly. Data generation is as follows. At the start of year 1947, there are four initial reservoir volumes. These volumes constitute a 1 x 4 row matrix, which is multiplied times the transition matrix to give a new set of reservoir volumes. The bedload input for the succeeding year is then added to the active reservoir giving reservoir volumes at the

TABLE 5 Distribution of sediment with time among the four reservoirs and the absorbing state, given the case of continuous loading of sediment into the active reservoir, middle reach of Redwood Creek.

Years Since Sediment Input	Distribution of Sediment (% of Total)				
	Active	Semi-Active	Inactive	Stable	Absorbed
5	76	5	2	0	16
10	62	7	3	0	27
15	52	7	4	1	35
20	44	8	5	1	41
25	38	9	6	2	45
30	34	9	6	2	49
35	30	9	7	2	51

start of year 1948. These volumes are then multiplied times the transition matrix, and so on. This procedure is reiterated 36 times to give reservoir volumes at the start of each year from 1947 to 1982.

Case IV predicts the changes in the amount of sediment storage in different reservoirs due to seasonal bedload transport into, and out of, a channel reach. As a test of the capability of such a model, we used sediment volume and bedload transport data for the middle reach of Redwood Creek for the 36 year period 1947-1982. The period also encompasses the two major storms in 1955 and 1964. For the model, we know the amount of sediment in each of the four middle reach reservoirs as of 1947 based on aerial photographs and field mapping, and we calculated the annual addition of bedload sediment into the top of the middle reach for the years 1947-1980, based on measurements at gaging station BL (fig. 1).

Calculations of the annual bedload increment used the following procedure. For years 1974-1982, bedload discharge was calculated directly from bedload transport curves for those years in conjunction with flow duration curves for the gaging station. For the years of bedload sampling, calculated annual bedload averaged 31% of total annual load. For 1947-1973, annual bedload discharge was calculated from suspended sediment discharge assuming bedload to be 31% of total load. Suspended sediment was sampled only during gaging station operation from 1954-1958 and 1974-1982, so suspended sediment from 1947-1954 and 1959-1973 was estimated from suspended sediment records at a gage in an adjacent basin of similar size (Van Duzen River at Bridgeville, California), normalized to the suspended sediment discharge at the Redwood Creek gage in 1958 (the only year both gages were operating concurrently). In addition, an additional component of bedload was added for the 8 years following the 1964 flood, based on field volume measurements of the amount of coarse sediment that was transported out of the upper reach of Redwood Creek in the 8 years following the 1964 flood. This additional component reflects the shift in the suspended sediment discharge relationship after the flood such that a given discharge carried more suspended sediment than in pre-flood conditions. Although a lack of data precludes documentation of this shift in Redwood Creek, the shift occurred in all adjacent river basins that had sediment discharge measurements before and after the 1964 flood (Knott, 1971; Brown, 1975).

The model results show yearly incremental changes in volume of the three more active reservoirs in the middle reach for 1947-1980 (fig. 6). The stable reservoir has not moved historically and shows no change. Changes in the active reservoir initiated by the 1955 and 1964 storm events are apparent (fig. 6). We only used the 1947 reservoir volumes to generate these results, and the model yields 1965 and 1980 reservoir volumes that are very close to the field measured volumes (table 6), indicating a reasonable degree of accuracy for the model.

Response of the semi-active and inactive reservoirs to the 1964 storm event was slightly more abrupt (based on field measurements) than suggested by the model results. This is probably because the model is stochastic and smooths out volume changes that actually occur sporadically. However, the model suggests that the observed downstream-moving wave of sediment was mainly confined to the active reservoir. This observation is confirmed by the channel cross-section measurements of Varnum (1984). Our results show that the Markov chain process can effectively treat the modeling of variable annual bedload input to a reach and the consequent changes in sediment storage. As such, it is potentially a predictive tool for storage changes given a range of future storm scenarios.

DISCUSSION

Although the model replicates changes in sediment storage in Redwood Creek, it does have limitations as well as providing insight into the dynamics of sediment storage. The data set needed to compute sediment residence times in not generally available for most drainage basins. Bedload transport rates must be estimated along several points in the channel, and initial volumes of stored channel sediment must be accurately estimated. The model will predict bedload movement in a reach only if a given bedload transport rate for each year is entered into the upper end of the study reach. The model then processes sediment through a reach based on probabilities of movement between reservoir states. Finally, the off-diagonal transition probabilities between reservoir states must be estimated. These estimates are narrowly constrained by the residence time and by existing bank erosion and sediment mobilization data for the reservoirs. Nonetheless, computed flushing times are sensitive to minor changes in the off-diagonal probabilities, and it was necessary to choose the best set of probabilities based on the most reasonable computed results. The lack of a better method of evaluating the off-diagonal probabilities is the weakest element in the method, and can be improved by more data on reservoir exchange rates.

Another consideration in using the model is the origin of stored sediment in the basin of interest. Sediment in storage due to tectonic subsidence or due to different climatic regimes, such as glacial outwash, may have a residence time many orders of magnitude longer than the more active sediment moving through the present channel.

How well does the model simulate geomorphic process? Coarse sediment particles on the channel bed do move by a Markov process inasmuch as present movement is not dependent on previous movement history. To make the model workable, however, it is designed to trace the downstream movement of stored sediment on a reach-to-reach basis. In the model, sediment can only be delivered to the channel at the beginning of each

TABLE 6 Modeled total amount of sediment in sediment reservoirs vs. field measured total amount of sediment in sediment reservoirs, 1965 and 1980.

Method	1965 Total sediment*	1980 Total sediment*
Field measurement	10,597,000	11,280,000
Model estimate	9,960,000	10,490,000

*Mg (Mg = megagram; 1 Mg = 1 metric tonne)

study reach. Any mid-reach sediment contributions cannot actually be accounted for until the bedload input at the beginning of the next reach.

The model could be tested and refined with additional studies. Erosion pins, scour chains, and successive surveys could define annual changes in reservoir volumes. These studies are ongoing. Dating of reservoirs using ^{14}C techniques (although charcoal and wood are extremely scarce) and possibly cesium-137 (Wilkin and Hebel, 1982) would help define the minimum age for channel deposits and test the accuracy of flushing time estimates. These techniques may lead to better defined estimates of the off-diagonal probabilities in the transition matrix.

Given the limitations, the Markov model for tracing the movement of stored sediment particles nonetheless provides insight into a number of aspects of sediment storage: particle longevity in the channel, degree of interchange of particles among reservoirs, the type of events that move the stable reservoir, and movement of slugs of stored sediment. The mean longevity of a particle (average flushing time) from a designated initial point in the channel until the time it leaves the system is on the order of 1,000 years for the active, semi-active, and inactive reservoirs in all three reaches of Redwood Creek. This somewhat surprising result was replicated using five different sets of off-diagonal probabilities in the 12 x 12 transition matrix (fig. 5), suggesting the conclusions are not particularly sensitive to the exact values of these probabilities. Equal flushing times for particles starting in any one of these reservoirs implies that the average particle spends time in each of the three more active reservoirs in a thousand year period. The scatter about the mean flushing time value is large (mean coefficient of variation for flushing times from the nine initial reservoirs is 3.66) because some particles visit the stable reservoir, which is mobilized infrequently.

The mature forest cover on the stable reservoir attests to its infrequent mobility compared to the more active reservoirs. Mean flushing times for particles starting in the stable reservoir are 4-10 times longer (tables 3 and 4) than particles starting in any of the other reservoirs. The relative mobility of the stable reservoir profoundly affects the dynamics of all the sediment reservoirs. Initial model runs where the stable reservoir was allowed to interact more frequently with the other reservoirs gave reservoir flushing times that were unreasonably long for the stable reservoir, based on residence time estimates for that reservoir. A minimal interaction of more active particles with those in the stable reservoir gave the most realistic model. Although the 1964 flood is the largest sediment-transporting event of record, and caused changes in channel morphology that have lasted for decades, it was not

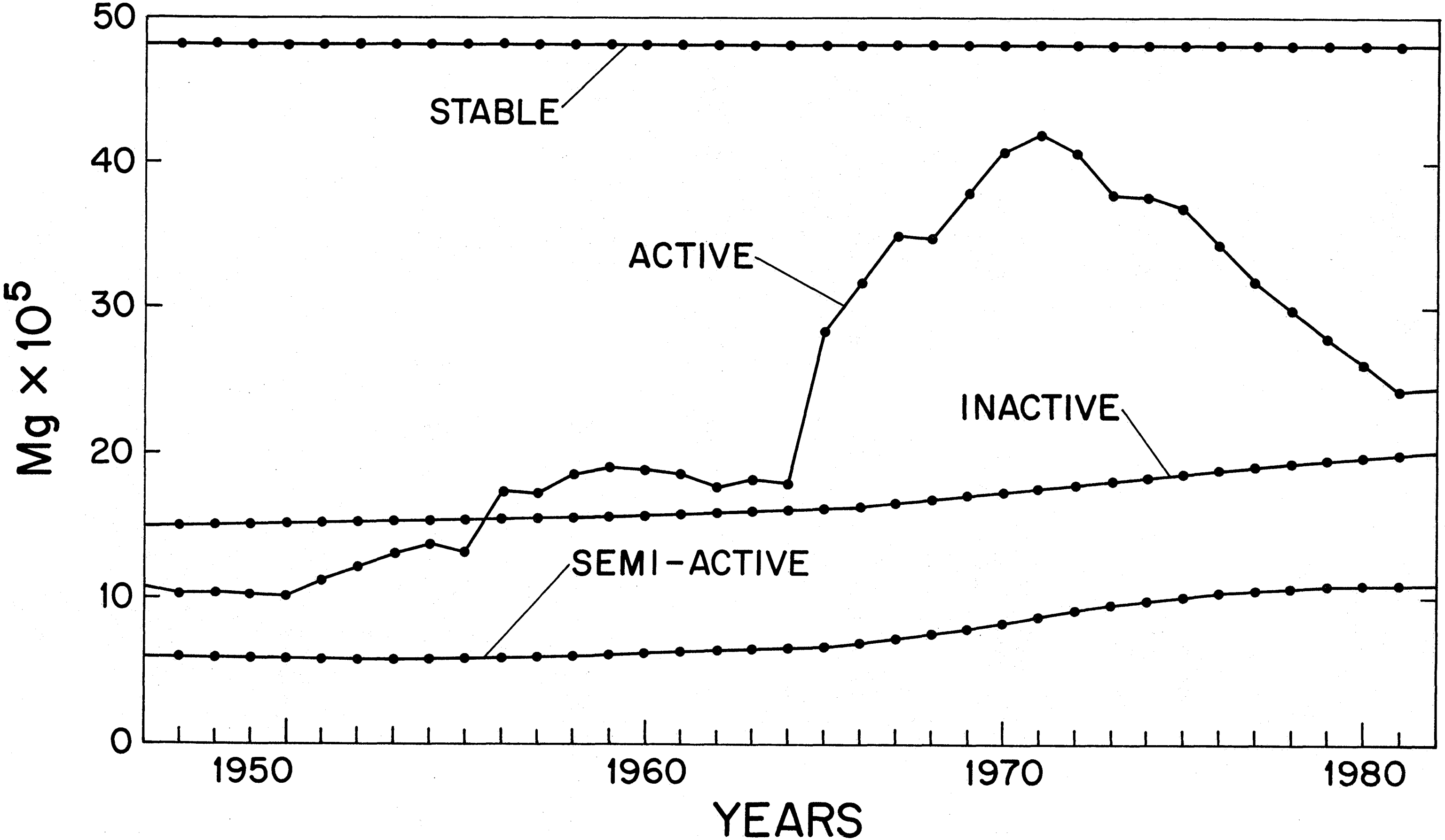

FIG. 6 Annual changes in the mass of sediment reservoirs (Mg = megagram = metric ton) for the middle reach of Redwood Creek for 1947-1982. Note that the stable reservoir was not mobilized during this period.

such an infrequent event as to significantly mobilize the stable reservoir. "Minimal" in the case of Redwood Creek therefore means remobilization of the stable reservoir by an event that has a recurrence interval greater than approximately 100 years. This suggests that infrequent, high intensity flood events are responsible for major long term shifts in sediment storage, and more frequent, moderate intensity flood events, which do not significantly mobilize the stable reservoir, cannot effect such changes.

One application of the model lends insight into the use of individual sediment particles as tracers for measuring sediment mobility. The median transit time for a particle traveling down the middle channel reach was an order of magnitude greater than the mean transit time. Sediment tracer studies are therefore limited in that any single particle has a large range of possible transit rates, and the distribution of transit times has a strong positive skew. Unless a large number of particles are marked, and most of them recovered, it is difficult to characterize the flux of the reservoir being studied.

The Markov model can graphically portray the passage of a slug of sediment through time in a channel reach, following a brief period of major sediment input. For example, the model for the middle reach of Redwood Creek graphically shows the passage of a slug of sediment through the active reservoir in the 18 years following the 1964 storm. Such movement behavior of concentrations of channel-stored sediment has been observed elsewhere (Gilbert, 1917; Mosley, 1978; Kelsey, 1982; Meade, 1982; Madej, 1982), as well as in Redwood Creek (Nolan and Janda, 1979; Madej, 1984). The model suggests the wave form is primarily due to sediment mobilization in the active reservoir and that sediment that visits the semi-active or inactive reservoir will cease to contribute to the downstream migration of the wave form. Temporary storage in the semi-active reservoir may well contribute to diffusion of the wave. Probably for this reason, as well as sorting by size (Mosley, 1978), sediment waves have increasing wavelengths and decreasing amplitudes in the downstream direction.

Because the model appears to accurately portray the movement of such sediment slugs, it can predict the length of time for a channel to recover from the aggradation that accompanies such a change. In the middle reach of Redwood Creek, the interval of peak flux of stored sediment through the active reservoir was approximately 18 years. The time for stored sediment volumes to decrease to those of pre-1964 conditions will be approximately 30 years. The capability to predict future sediment storage changes in Redwood Creek, given different possible annual discharge scenarios, may be an especially valuable management tool for this basin. The lower third of the basin is part of the Redwood National Park, and the upper two-thirds are owned mainly by timber companies who manage the land for logging. Modeling possible sediment storage changes along Redwood Creek could predict the depth and duration of periodic channel aggradation. Such aggradation may result from erosion by infrequent storms acting alone or in concert with various degrees of logging-induced ground disturbance upstream.

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