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## GEOMORPHOLOGIC CONTRIBUTIONS TO FLOOD CONTROL PLANNING

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### FLOOD CONTROL STRATEGIES

The enormity of damage caused by floods and the cost of mitigating their effects have stimulated engineers, geomorphologists, and planners to develop a wide range of flood control strategies appropriate to different physical and cultural settings. The methods most commonly employed for the reduction of flood damage are:

1. Flood warning and emergency action
2. Impoundments
3. Channel alteration and stabilization
4. Diversion and storage of floodwaters above and below ground
5. Land management for soil and water conservation
6. Control of land use on floodplains

Geomorphology can contribute to the choice and design of these strategies. The possibilities range from the correlation of flood potential with simple descriptive indices developed in the early days of quantitative geomorphology to more sophisticated analyses of flow and sediment transport processes. Most applications of geomorphology arise because of the interaction among flooding, sedimentation, and channel behavior. This chapter reviews some of the uses of geomorphology in flood control planning and suggests that inclusion of geomorphologic studies leads to more successful and stable schemes.

#### Flood Warning and Emergency Action

The primary responsibility for flood prediction, forecasting, and response planning rests with meteorologists, hydro-

logists, and planners. However, there are geomorphologic aspects of the flood prediction problem (Reich, 1971; Orsborn, 1976). Physiographic regions have different flood potentials because of variations in elevation and associated climate, drainage density, channel gradients, and width of valley floor. Therefore, in the prediction of flood discharges it is useful to stratify large drainage basins into homogeneous subdivisions, and to design hydrometeorologic networks, and to monitor and route floods from each region, combining them downstream. These regional differences are already taken into account in some hydrologic procedures such as the use of regional flood frequency curves (Dalrymple, 1960; Ward, 1962) and synthetic unit hydrographs (Snyder, 1938). However, with widespread availability of satellite imagery for mapping the large-scale geomorphic features of even remote areas, and recent developments in automatic monitoring and telemetry, there is potential for improving flood prediction and warning through systems designed partly on a geomorphic base.

At a slightly greater level of complexity, Kirkby (1976) and Valdes et al. (1979) have demonstrated how the structure of a drainage network influences flood hydrographs and can be used for their prediction. Much research remains to be done by geomorphologists and hydrologists to follow these suggestions.

On a smaller scale, within flood-prone areas there is often considerable uncertainty about the consequences of a predicted discharge. Subtle changes in channel characteristics can alter the timing and magnitudes of flood waves. Campbell and others (1972) have made some illustrative computations of the effect of channel straightening on flood hydrographs. Burkham (1976) documented how a series of large storms at the head of Safford Valley, Arizona,

during 1914–1927 scoured a wide, deep, and straight channel along which flood waves passed quickly with relatively little transformation. During 1930–1964, floods were generated mainly in the lower part of the drainage basin and were smaller and more turbid than during the preceding period. As a consequence, floodplain accretion accelerated, salt cedar encroached, and the channel became smaller and more sinuous. A larger proportion of the flood discharges traveled slowly over the densely vegetated floodplain, and flood waves were strongly attenuated. Reversal of this trend could increase flood hazard downstream once more.

Changes of channel position may lead to the breaching of banks, causing floodwaters to spill in an unexpected direction. Such changes can be anticipated for the purposes of predicting inundated areas and planning evacuation routes by detailed examination of floodplain topography in the field and on aerial photographs. Examples of such investigations are described by Popov and Gavrin (1970) and by Velikanova and Yarnykh (1970), who present maps of their results. The hazardous area can be updated routinely in this way, and allowance for the dynamic nature of the flood-prone areas of large alluvial valleys enhances the value of flood maps. Remote sensing, such as the use of LANDSAT imagery of large floodplains, is particularly suitable for this task.

A special type of flood hazard results from the potential for catastrophe breaching of natural and artificial dams. Costa (1985) has marshaled geomorphologic and hydrologic evidence of such floods as an aid in their prediction. Dunne and Fairchild (1984a,b) also used geomorphologic field evidence to analyze the potential flood hazard due to breaching of lakes impounded by landslide debris after the 1980 eruption of the Mount St. Helens volcano.

### Impoundments

The role and limitations of storage reservoirs in flood control has been discussed by many authors (e.g., Leopold and Maddock, 1954; Dunne and Leopold, 1978). The following problems exist: (1) dam siting and safety, especially in geologically young, seismically active mountains; (2) the storage volume required to attenuate very large, season-long floods sometimes occurring in monsoon lands; (3) the flooding of valuable agricultural land; (4) the rapid reduction of reservoir effectiveness by sedimentation in some regions; and (5) effects on the river channel and valley floor upstream and downstream of the reservoir. However, in many flood control problems, large reservoirs must be considered, and geomorphologic studies contribute to the prediction of sedimentation rates, design floods, and the effects of dam construction on the channel.

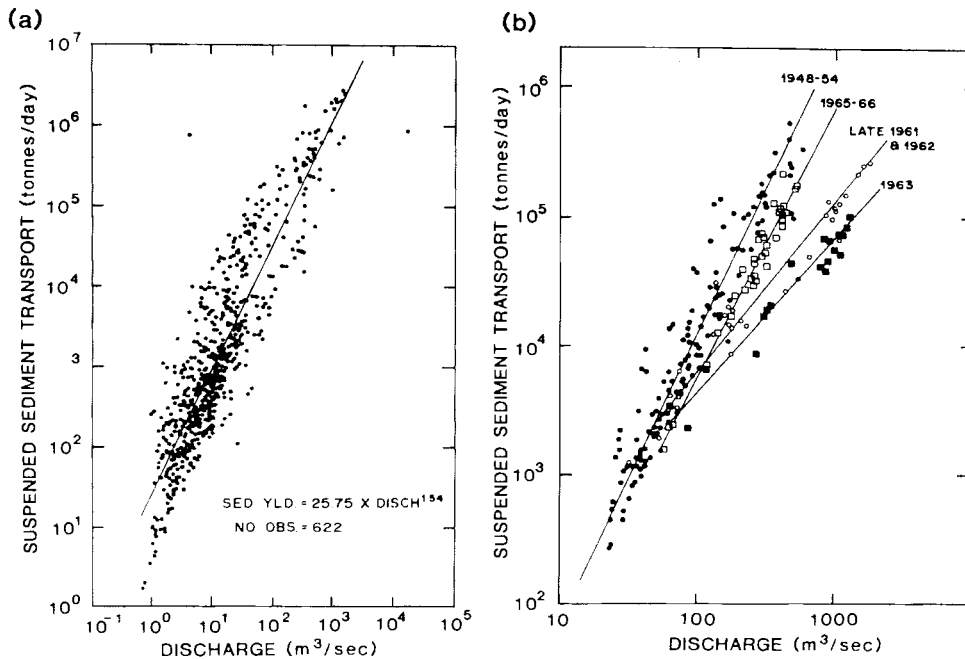
**Sedimentation Rates.** The usual analysis of probable sedimentation rates in reservoirs is inadequate, especially

in tropical and subtropical countries and in mountains. The rate of infilling is usually assessed from a short flow record and a small number of suspended-sediment samples collected during a few years between project proposal and construction. Sediment samples collected earlier than this are frequently obtained by nonstandard procedures and are not interpretable. The two sets of records are usually much too short to sample the variability of sediment transport, and the important high flows, which carry most of the sediment, are often underrepresented because of their rarity and difficulties of sampling. Yet after brief review of the region, such data are used for computing the design life of reservoirs and frequently lead to overly optimistic economic analysis.

Even at stations at which a large number of samples have been collected, there may be considerable uncertainty in the definition of the sediment rating curve because of the large scatter of points. For example, in Figure 1a, it is difficult to judge whether the rating curve should be extrapolated linearly or whether the slope of the curve should decline with increasing discharge. Even greater uncertainties develop when sediment rating curves shift dramatically through time (Fig. 1b).

On the Tana River in central Kenya, three studies of sediment yield at a proposed dam site had concluded that the economic life of the associated reservoir would exceed 100 yr. Dunne and Ongweny (1976) pointed out that this yield was far less than the sum of yields from the tributaries to the Tana. Yet there was no field evidence for extensive deposition along the main stem. They estimated the sediment influx to the channel to be several times greater than anticipated. The suspended-sediment rating curve (based on 53 samples collected over 13 yr and fitted by regression) underestimated sediment transport when extrapolated to high discharges. Ongweny (1978) then instituted a program of suspended-sediment sampling in the Tana and its tributary basins, and he demonstrated that the reservoir would be filled within a period of 30–35 yr under average weather conditions and within 20–25 yr if a run of wet years were to occur. The economic life would be even shorter. Ongweny used the method of Borland and Miller (1958) to calculate that almost all of the dead storage volume of the reservoir and 16–25% of the live storage volume should be filled 8 yr after impoundment. His work, which has been confirmed by reservoir surveys, illustrated the value of improving sediment yield computations based on short records at a single location with field observations and geomorphologic interpretation of the basin sediment budget. His field observations and plot experiments also isolated some of the major sediment sources upon which conservation could be focused to prolong the life of the reservoir, as well as to obtain other benefits.

Much more attention needs to be paid to the prediction of reservoir sedimentation rates, especially in tropical and subtropical mountain regions where erosion rates are gen-



**FIGURE 1.** Suspended-sediment rating curves for two rivers in Kenya: (a) Uaso Nyiro at Archer's Post, indicating the large amount of scatter around a rating curve based on samples collected during more than a decade and the uncertainty involved in linear extrapolation of a best-fit regression line. (b) Tana River at Garissa, showing radical shifts due to variations of weather, ground cover, and animal stocking rates. Data from Kenya Ministry of Water Development, Nairobi.

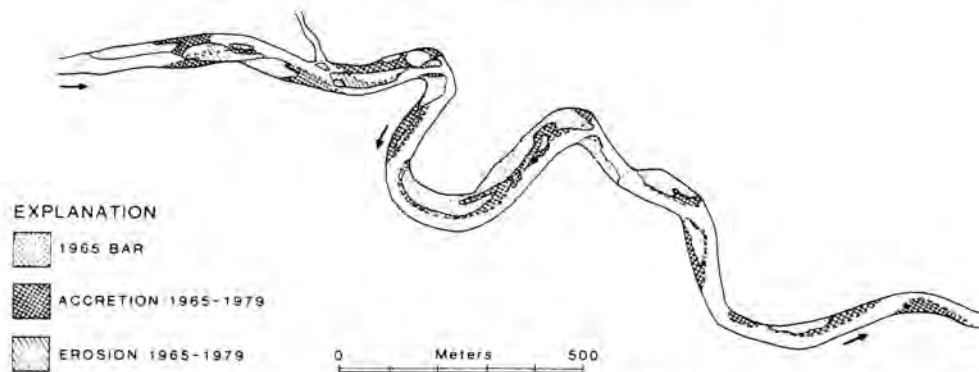
erally high. Because sediment sampling records can give misleading results, more detailed and innovative analysis is required of the stochastic aspects of flow and sediment transport, using techniques such as those described by Fiering and Jackson (1971), to extract the maximum amount of information from limited records and to document the uncertainty in estimates of mean sediment transport.

However, it is not likely that large numbers of monitoring stations will be maintained for many years on all of the rivers with a potential for impoundment. This is especially true for measurements of bedload, which is usually deposited near the inlet of a flood control reservoir where it reduces the live storage volume. Because the empirical record of sediment transport is usually sparse, and the popular computational methods (see Vanoni, 1975) are notoriously unreliable without some independent evidence, it is important to develop some geomorphologic methods for assessing annual sediment fluxes. Lustig (1965), for example, used landscape morphometry as a basis for transferring sediment yields between drainage basins to estimate the life of a proposed reservoir. In some rivers with favorable geomorphologic circumstances, all of the gravel bedload may be deposited in a particular reach, so that the bedload yield can be estimated by repeated survey of the channel cross section (Griffiths, 1979). In other cases it may be

possible to quantify the entire sediment influx to a river using the sediment budget techniques described by Dietrich and others (1981) and Reid and others (1981).

A small-scale example is provided by an estimate of the probable rate of filling of a small reservoir on the South Fork Snoqualmie River, Washington. The river drains a 212-km<sup>2</sup> forested basin in the Cascade Mountains. Average sediment influx to stream channels from mass wasting was estimated by measuring on aerial photographs the density and area of landslide scars supplying sediment to channels over a period of 17 yr. During field work, a volume-area relationship was developed on a sample of these scars, and the grain size composition of the sediment forming the margin of the scars was measured. Thus, it was possible to compute the average annual contribution of each grain size from landslides. Sediment yields and grain sizes eroded by water from roads were estimated by extrapolation of measurements made along roads in the Olympic Mountains of western Washington (Reid et al. 1981). The estimated influx was then partitioned into bedload and suspended load on the basis of the virtual absence of sand in point bars along the South Fork Snoqualmie.

The resulting yields of bedload and suspended load could be checked against independent evidence. Nelson (1971) estimated annual suspended-sediment yield on the



**FIGURE 2.** Erosion and deposition of gravel bars along a portion of a 12-km-long zone of gravel deposition in the South Fork Snoqualmie River, Washington, 1965–1979. The bars were mapped from aerial photographs at similar low flows. The outer banks of the channel were stabilized artificially throughout the period. The mapped areas of growth were converted to volumes of deposition with the aid of surveyed cross sections.

basis of 2 yr of sampling and flow measurements. Measurements of bed material texture along the South Fork showed that all of the gravel bedload accumulates on bars in a low-gradient reach, and the rate of accumulation indicates the annual basin yield of gravel. The rate of accretion and erosion of channel bars along the lower 12 km of the river was measured on aerial photographs taken 14 yr apart and at similar low flows (Fig. 2). Change in bar area was converted to the weight of deposition by surveying channel cross sections and using a typical bulk density of poorly sorted gravels. The various estimates of the average annual sediment load are compared in Table 1. They are close enough to encourage the further use of geomorphologic checks and extrapolations of sediment yield measurements.

Another application of geomorphologic methods in sediment yield prediction was necessary after the 1980 eruption of Mt. St. Helens into the Toutle River valley, and the same methods could be used after other devastations that increase sediment yields. Immediately after the eruption

a vast amount of erodible sediment was emplaced in the upper Toutle valley and was eroded and transported to the lower Toutle and Cowlitz valleys, where its deposition choked the channel, reducing bankfull capacity and causing rapid channel shifting. During the first posteruption winter, the only flood control response possible was diking and dredging, but in later years there has been discussion of the value of impounding all sediment within the upper Toutle valley by means of a high earthfill dam. A short-term estimate of the probable rates of erosion in the upper Toutle valley and of deposition along the Cowlitz channel was made 6 months after the eruption on the basis of a sediment budget and suspended-sediment samples collected by the U.S. Geological Survey. The approach involved the following activities: aerial photogrammetry to map and measure various sediment sources and sinks within the basin; monitoring of erosion rates in the field; measurement of grain sizes of sediment eroded and deposited at various places along the channel; and computations of sediment

**TABLE 1** Comparison of the Average Annual Sediment Load of the 212 km<sup>2</sup> South Fork Snoqualmie from Methods Described in the Text

Method	Suspended Load (tonnes/yr)	Bedload (tonnes/yr)
Sediment budget <sup>a</sup>	42,060	2,630
Suspended sediment <sup>b</sup> sampling by Nelson (1971) and his estimate that bedload = 5% of total load	59,700	2,980
Measured rate of bed material accumulation <sup>c</sup>	—	2,380

<sup>a</sup>Mass wasting supply averaged over 17 yr.

<sup>b</sup>Suspended-sediment sampling over 2 yr.

<sup>c</sup>Bed material accumulation averaged over 12 yr.

transport and deposition. The methods and judgments used were described and critiqued by Dunne and Fairchild (1984a,b), and the updated field results were described by Collins and others (1983), Collins and Dunne (1986), and Lehre and others (1983). The sediment budget of the Toutle valley could be updated and projected into the future for the purpose of assessing the necessary size of the proposed reservoir or of the cost of continued dredging in the Cowlitz River.

When an estimate of sediment transport has been made for a proposed reservoir site, it is useful to examine the geomorphologic context of that sediment flux rate. Where are the major sources of sediment? Are they strongly affected by land use or can they be so affected in the future? What is the pattern of channel sedimentation upstream from the site for which the estimate was made? For reasons that are not well understood, some sediment temporarily accumulates in large waves along some river reaches and then is scoured and transported downstream over a period of years, presumably after some threshold of channel gradient or width is attained by the accumulating wedge of sediment. Griffiths (1979) has documented the migration of large waves of bedload in the Waimakariri River, New Zealand. If measurements of bedload transport were made for only a few years, beginning immediately upstream or downstream of such a wave, one could obtain values of transport that were not representative of the long-term mean flux rate. To discern whether such wedges of sediment are confounding long-term estimates requires examination of channel migration and depositional forms through long reaches of valley above the measurement site. The observations can be made on sequences of aerial photographs covering a time interval before and during the sampling period. Trimble (1977, 1983) has made detailed stratigraphic and sedimentologic studies of the effect of sediment storage in valleys, fans, and footslopes on the downstream sediment yield of a drainage basin undergoing land-use changes. Failure to take such storage changes into account can lead to large underestimates or overestimates of sediment yields and the effectiveness and longevity of flood control reservoirs.

**Prediction of Design Floods.** Estimation of the magnitude and frequency of large floods that might damage a flood control dam is usually based on statistical analyses of relatively short streamflow records. The problems resulting from this technique include the difficulty of extrapolating flood frequency curves based on small, frequent floods; the difficulty of agreeing upon which theoretical probability distribution best fits the recorded data as a basis for extrapolation; the effect of runs of years of high and low flood potential associated with weather fluctuations; and the relatively large number of ungauged rivers. Where the instrumental record is short or absent, it is usual to design

spillways to accommodate the maximum probable flood, which must be calculated on the basis of the maximum probable rainfall, a judgment about rainfall-runoff relations in the basin, and some means of computing the temporal distribution of storm runoff from the basin. Binnie and Mansell-Moulin (1966) describe an example for a large dam in Pakistan. The method is fraught with many uncertainties and begs for empirical confirmation.

The simplest applications of geomorphology to flood prediction involve regional statistical relationships between channel geometry, especially the active-channel width, and flood discharges of various frequencies (e.g., Osterkamp and Hedman, 1982). Such correlations allow the transfer of flood predictions from gauged basins to ungauged sites. However, they are subject to large errors when rare floods are estimated from short records.

Geomorphologic studies have provided ways of extending the record of floods far beyond the length of instrumental observations. The earliest studies of this type involved mapping the distribution of fine-textured, bedded flood deposits to define the highest levels of floods before gauging stations were established. Jahns (1947) examined the distribution of overbank sediments deposited by the 1936 and 1938 floods along the Connecticut River valley and found no evidence of higher floods during the period of European settlement and probably for several hundred years prior to invasion. From such evidence, outliers in a flood record can be assigned a more realistic recurrence interval than is possible from the duration of the instrumental record alone. Later studies along steeper, gravel-bedded rivers recognized local bar deposits, gravel levees, and flood channels, which could be dated by radiocarbon measurements on buried debris and tree stumps or by dendrochronology (Helley and LaMarche, 1973). This kind of work has been combined with strictly botanical methods of extending flood records (Sigafos, 1964; Yanosky, 1983).

The most extensive and longest geomorphologic flood records are provided by slackwater sediments, which accumulate in embayments, at tributary junctions, and in other portions of a valley floor where velocity declines and suspended sediment settles from overbank flows (Kochel and Baker, 1982). Each successive flood with a stage higher than earlier floods adds a layer to the sequence of sediments. The age of the sediment and associated flood can be obtained from the radiocarbon content of buried wood, fine organic detritus, or the humus of paleosols. These dates are used for correlation between sites along a river valley, and for indicating the duration of the entire sedimentary record. The water level indicated by a sediment layer is used to compute a flood discharge by the slope-area method. These discharges are then ranked and their recurrence intervals can be computed in the normal way. Kochel and Baker (1982) used this method to construct a 2000-yr-long record of floods.

Another contribution of geomorphology to spillway and reservoir design is the recognition that in some physiographic situations the most damaging flood may not originate as runoff from rainfall or snowmelt but from a glacial outburst (jokulhlaup) or the catastrophic breaching of a natural lake impounded by landslide or other debris or the rapid melting of a snowpack by a pyroclastic flow or the triggering of a large debris flow. Such events are most common in glaciated, tectonically active mountains or around active volcanoes. They leave sediments and other evidence, which although not unequivocal, can usually be recognized and interpreted genetically. Glacial outburst floods may leave particularly coarse sediments and large bars in outwash sediments (Birkeland, 1968; Church, 1972). Birkeland used such sedimentologic evidence together with field evidence of flow depth and slope to compute peak discharges. Clague and Mathews (1973) have compiled field evidence of the magnitude of jokulhlaups, and Clarke and Mathews (1981) have calibrated a predictive model of these flood hydrographs against field data.

The design of flood control dams around active volcanoes requires that some estimate be made of potential peak discharge, volume, and other properties of mudflows. Such flows or more dilute muddy floods could be generated around volcanoes by a number of mechanisms, including rapid snowmelt as a consequence of a pyroclastic flow, pyroclastic surge, or stream explosion; liquefaction of saturated, unconsolidated sediments as a result of shaking during an eruption; and a rapid breach of debris dams impounding lakes. The deposits of such mudflows can be mapped to give a general idea of the presence of such hazards (e.g., Mullineaux and Crandell, 1962), but the deposits give no indication of peak discharge, and their elevation above the present valley floor may be misleading if the channel bed has been lowered since deposition. The number of these deposits occurring within a datable period gives a rough indication of the average frequency of large mudflows. However, because it is difficult to relate individual deposits to their generating mechanisms and because the configuration of the cone and of surrounding lakes may have changed significantly during that period, it may not be obvious how the stratigraphic record can be extrapolated into the future without some interpretation.

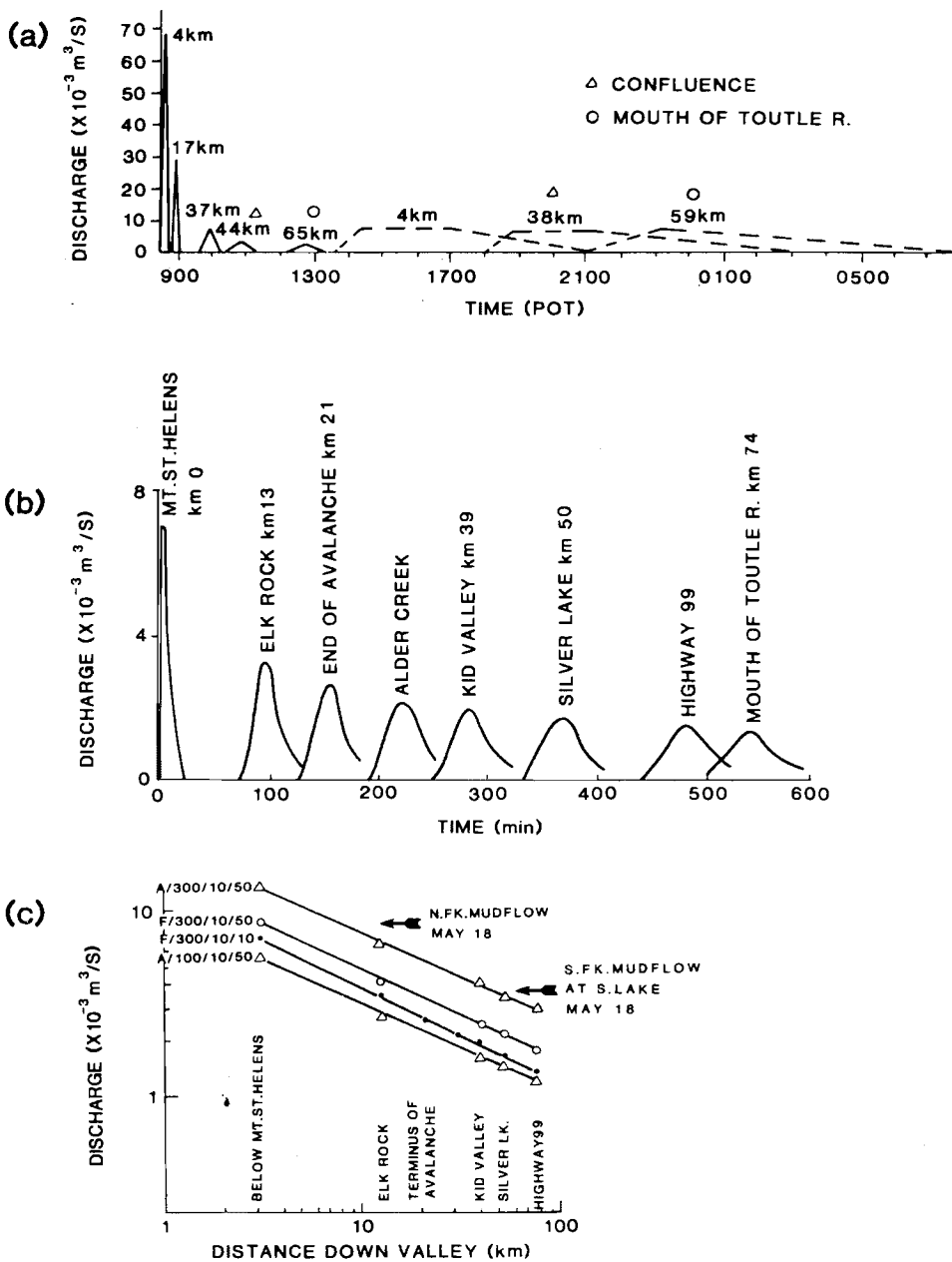
Dunne and Fairchild (1984a,b) and Fairchild (1985) considered the various mechanisms that might generate mudflows or muddy floods around the Mount St. Helens volcano. They first considered the probable volume, peak discharge, and location of flows that might occur due to pyroclastic flows eroding snowpacks and to the catastrophic breaching of lake barriers. These initial hydrographs were then routed downvalley (see Fig. 3b, and 3c), using a Muskingum flood-routing model that had been calibrated against mudflow hydrographs resulting from the eruption of May 18, 1980 (Fig. 3a). The hydrographs were constructed

from geomorphic evidence at six locations on the South Fork Toutle River and three on the North Fork Toutle River (Wigmosta, 1983; Fairchild, 1985). These geomorphologic studies also yielded density and rheologic parameters for the 1980 mudflows (Wigmosta, 1983) and for mudflows of other grain size distribution and water content (Fairchild, 1985). Such information is useful for designing engineering structures to withstand impact and shear forces from mudflows.

#### ***Channel Changes above and below Impoundments.***

Rivers entering a reservoir deposit all or most of their load. The coarser fractions of the load are deposited near the mouth of the stream, either in the live storage zone of the reservoir or in the backwater zone of the stream channel. Below the dam, clear water may scour the channel bed and banks. The best studied case of this development occurred after the closure of Hoover Dam on the Colorado River. The channel was degraded for more than 500 km downstream, rendering useless many intake structures for municipal supply and irrigation, and undermining bridge foundations. At Yuma, Arizona, 560 km downstream of the dam, the river bed was lowered 2.8 m. In gravel bed streams of western Washington, the trapping of gravel behind hydroelectric dams and the scouring of grain sizes finer than cobbles from sediments downstream have led to a coarsening of the channel bed so that the gravel bars are now too coarse for salmon spawning. In some gravel bed streams in the same region, the opposite situation exists. Before impoundment, large floods carried away coarse sediment entering the river from steep tributaries. The lowered peak discharges cannot remove this sediment, which accumulates as alluvial fans, raising the bed of the stream and in some places causing the river to develop a braided, unstable channel.

Williams and Wolman (1984) summarized the literature on case studies of the downstream effects of dams on alluvial rivers and compiled the results into a statistical summary of the changes observed in bed elevation, width, bed material texture, sediment concentration, and load as functions of downstream distance and time since dam closure. The results, though mainly from the subhumid western United States, exhibit enough scatter to emphasize that useful predictions require consideration of the sediment sources and transporting flows in particular rivers. An estimate of sediment influx and texture can be made by the methods referred to above, and sediment can be routed downstream to predict sediment flux, scour, and fill by methods proposed by Komura and Simons (1967) and the U.S. Army Corps of Engineers (1977). However, there remains an important difficulty in the prediction of channel width by these one-dimensional computations of sediment transport. Two-dimensional methods of sediment routing are now being developed, but they incorporate little of the



**FIGURE 3.** Definition of mudflow hazard in the Toutle Valley, Washington. (a) Hydrographs of 1980 mudflows in the South Fork (solid lines) and North Fork (dashed lines) Toutle valley reconstructed on the basis of field evidence. Source: Fairchild (1985). (b) Computed hydrographs of a mudflow generated by a pyroclastic flow onto a snowpack on the slopes of Mount St. Helens volcano (km 0) and routed along the North Fork Toutle valley. Source: Dunne and Fairchild (1984a,b). (c) Downstream variation of peak discharge for mudflows originating as pyroclastic flows on Mount St. Helens. The sequence of symbols refer to various assumptions made to generate the mudflows, as follows: month of average snowpack used; width of pyroclastic flow track (m); speed of mudflow on the volcano slopes (m/s); depth of snowmelt under the depositional fan of the pyroclastic flow (cm of water). Also shown are field estimates of peak mudflow discharges during the 1980 eruption. These estimates are based on geomorphic evidence. Source: Dunne and Fairchild (1984a,b).

complexity governing adjustments in channel width to changes of flow and sediment transport. Leopold and Bull (1979) discussed the simultaneous adjustment of width, slope, and hydraulic roughness that results from changes of base level and deposition above a dam, and they summarized the scanty field data on this process. However, much remains to be understood about these aspects of river channel response.

In the absence of theoretical techniques prediction of the geomorphologic consequences of dam construction and flood reduction relies on empirical relationships and qualitative arguments, which are nevertheless useful predictors. For example, Lane (1955) proposed that an alluvial river attains an equilibrium that can be described by the following proportionality between flood magnitude ( $Q$ ), bed material flux ( $Q_b$ ), bed material grain size ( $D$ ), and channel slope ( $S$ ):

$$Q \cdot S \sim Q_b \cdot D$$

Despite the imprecise definition of the terms, this relationship is remarkably useful in the initial, qualitative stages of predicting the downstream effects of flood control reservoirs. For example, if flood flows are reduced moderately and sediment load drastically, Lane's relationship suggests that the river would respond by reducing its slope and increasing the texture of its bed material by selective transport and armoring. The relationship does not predict the magnitude of these changes or of associated effects that might be expected, but it suggests critical variables to be measured in field studies and analyzed by more formal modeling. Schumm (1969, 1977, pp. 133–137) extended Lane's approach on the basis of empirical equations developed by himself and others relating channel form, flow, and sediment properties. This more extensive analysis, heavily weighted by data from sand-bedded streams in subhumid environments, allows qualitative consideration of the effects of dam construction on channel width, depth, gradient, sinuosity, meander wavelength, and bed material texture. The relations need to be extended into regions with gravel-bedded rivers.

More quantitative prediction of the effects of dam construction on channels upstream and downstream awaits a more rigorous, quantitative theory of the mutual adjustment among the hydraulic and sedimentologic parameters that control channel form in cross section and in plan.

### Channel Alteration and Stabilization

River channels are frequently deepened, widened, straightened, or diked to increase their capacity. In other cases the main aim in flood control is to prevent deposition within the channel and to confine the channel so that it will not migrate laterally and shift the flood-prone zone

into occupied parts of the valley floor. Such alterations require the design of stable river channels.

Hydraulic engineers have developed a set of empirical equations, relevant mainly to sediment-transporting canals, which describe the width, depth, and slope of straight, stable channels as functions of discharge and the grain size of bed and bank materials. These "regime" equations are summarized by Blench (1969) for rivers with fine bed material and by Kellerhals (1967) for gravel bed channels. Geomorphologists have extended this approach to meandering and braided rivers through definition of the hydraulic geometry: a set of empirical equations representing the variation of width, depth, mean velocity, water surface slope, hydraulic roughness, and sediment concentration as functions of discharge, as it varies temporally at a single cross section and spatially downstream at a single discharge frequency (Leopold and Maddock, 1953). Schumm (1977) has extended such relationships to meander wavelength, amplitude, and sinuosity and has incorporated the effect of bed and bank materials. It is also possible to use regional relationships between each of these hydraulic and morphologic characteristics and the drainage area, which is a surrogate for both flood discharge and sediment supply (Fig. 4). Channel alterations for flood control are more likely to remain stable if the designed channels conform approximately to such empirical relationships.

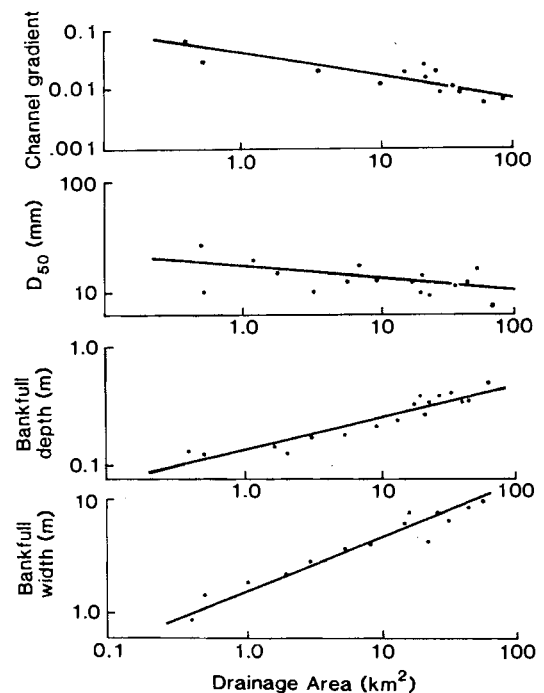


FIGURE 4. Relations between channel characteristics and drainage area for streams in forested drainage basins of the Puget Lowland, western Washington. Source: Madej (1982).



Radical alteration of river geometry will usually require that the channel be rendered immobile. Otherwise, it will regain its original form by erosion and deposition to adjust its cross-sectional area and sinuosity (Keller, 1976). Severe erosion and deposition usually occur if the discharge-slope relationship is upset in channels with easily erodible beds, either by channel straightening or by the focusing of flow from several braided channels into a single channel. Daniels (1960) and Ruhe (1971) documented how the straightening and steepening of Willow River in Iowa provoked deep entrenchment (to a maximum of 14 m), widening of the channel, and lowering of the base levels of tributary drainage networks (Fig. 5). The downstream end of the entrenched channel was later filled by the accelerated sediment flux. Such changes are irreversible in the short term and extremely expensive to stabilize. Yet the application of current geomorphologic knowledge can indicate how to avoid and to minimize such problems (Schumm et al., 1984).

The planform aspects of rivers are the most difficult characteristics to predict. One is often limited to a strictly empirical approach of examining the position of a channel on sequences of aerial photographs and developing some locally relevant insights into its behavior. Some meander forms are more stable than others and can be used as models for designing channel widths, meander wavelengths, gradients, and sinuosities to which a channel should be coaxed by means of dredging, diking, groynes, or bank afforestation. Winkley and others (1984) outline some geomorphologic principles that have proved useful in stabilizing rivers in the horizontal plane.

Geomorphologic interpretation of alluvial features and historical evidence can also be used to assess the likelihood of successful diking and channel stabilization. Figure 6 illustrates the positions of the channel along a reach of the Green River, Washington, at three times during this century. The channel positions were obtained from an early topographic map and two sets of aerial photographs. The record of shifting could be extended through dendrochronology on older point bar deposits as illustrated by Everitt (1968) and by Hickin and Nanson (1975). Maps of this kind provide several important types of information for river engineering.

For example, Figure 6 indicates that the river moves across its floodplain by gradual lateral shifting: mid-channel bar formation and avulsion are rare. Second, it is possible to measure rates of lateral migration. When such rates are plotted on a graph (Fig. 7a) that also indicates the downstream pattern of boundary shear stress, it is clear that lateral migration is most intense along reaches that experience a rapid downstream decrease in boundary shear stress. The ability of the river to carry coarse sediment declines with decreasing boundary shear stress. The result is a general downstream decrease in bed material size between kilometers

67 and 40 (Fig. 7b), accumulation of sediment on point bars, and the rapid shifting of the channel (Fig. 7a) in response to their growth. Diking along this reach would be very costly and unlikely to succeed.

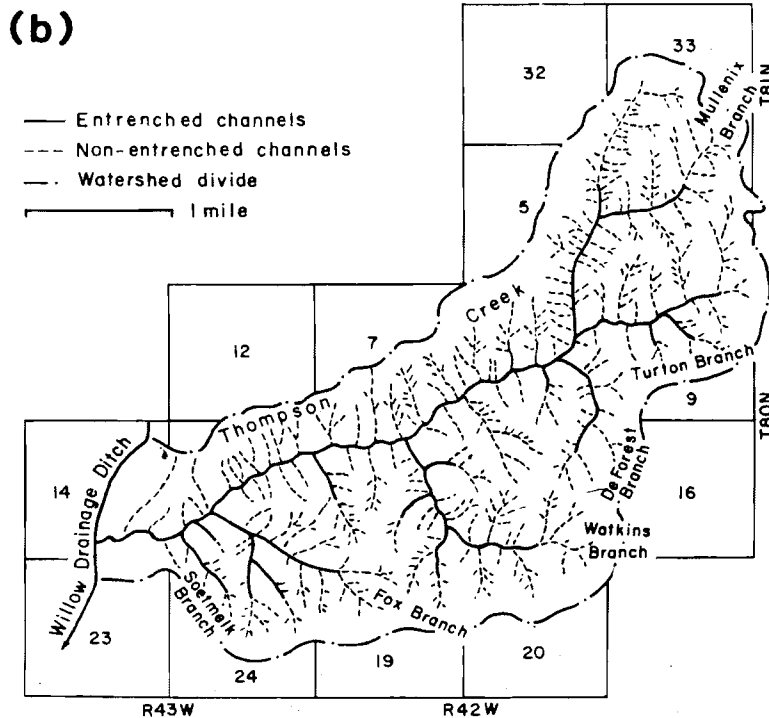
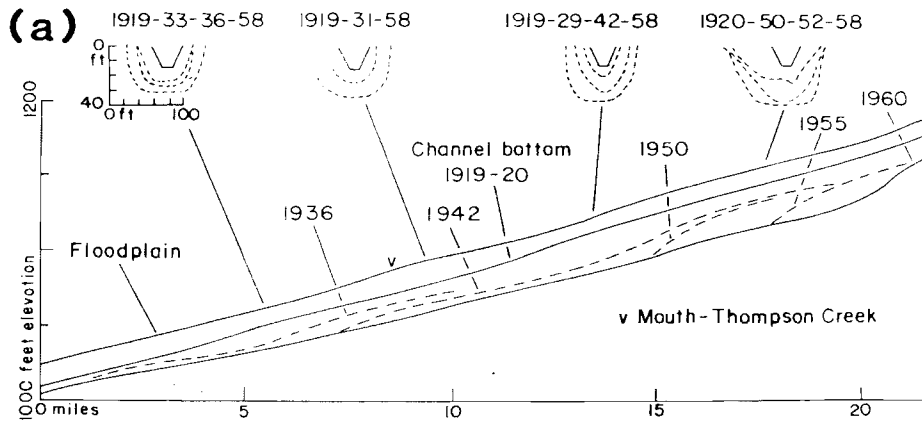
Between kilometers 40 and 19, boundary shear stress remains constant or increases, and there is little or no deposition of the sand and silt entering the reach. In this zone shifting is very slow and dikes have been stable. In the lower reach, where shear stress again declines, there is deposition and slow shifting that causes some damage to dikes, but the stresses on the channel boundaries are much lower than those above kilometer 40.

### Diversion and Storage of Floodwater

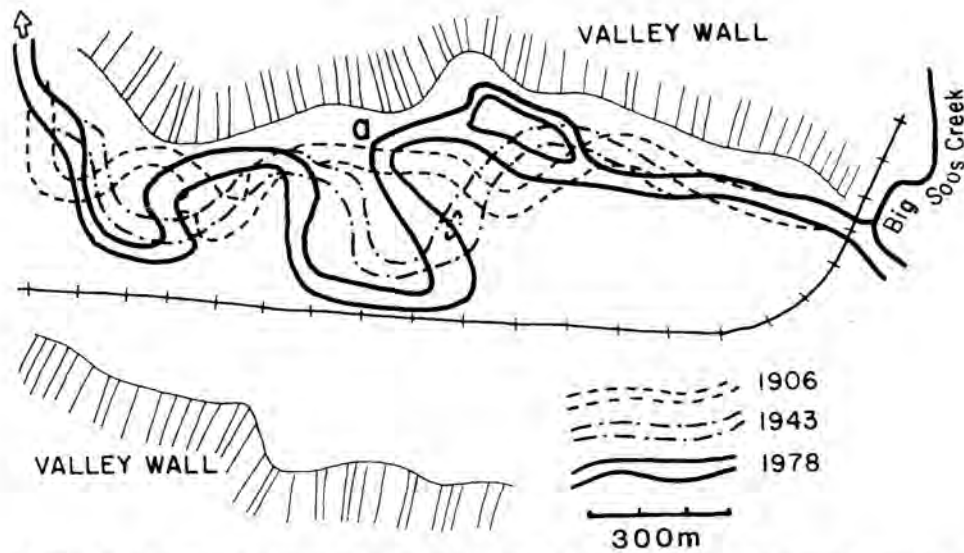
Where other means of control are impossible and where conditions are suitable, a portion of a flood may be diverted into a low-lying area of floodplain, by opening gates in a natural levee or artificial dike. The strategy may involve simply holding the water in a surface depression until the flood peak has passed, and then opening a gate further downstream to allow the water to flow back into the channel. In other cases the valley alluvium may be so permeable that a significant proportion of the diverted floodwater will infiltrate over succeeding weeks and be stored below ground, recharging the groundwater for use during the low-flow season. The groundwater table may even be lowered deliberately by pumping during the dry season as part of a coordinated program of water supply and flood control. Both surface and subsurface storage of floodwater require conditions that are not ubiquitous on large floodplains and consequently require detailed geomorphologic and hydrologic analysis.

Large, unoccupied depressions, such as former river channels, drained ox-bow depressions, and backwater swamps behind natural levees offer the best possibilities for temporary storage, but to effect a significant reduction in flood flow the depression must be very large. For example, a diversion of 500 m<sup>3</sup>/s for one day would fill a 10-km<sup>2</sup> depression to a depth of 4.3 m. Depressions of this depth are not common on large floodplains. If depressions are not occupied by cultivated lands and villages, they tend to be thickly forested, which makes an assessment of the storage volume and consequences of diversion extremely difficult. In such conditions the assessment of surface detention opportunities should involve a detailed geomorphologic analysis of subtle alluvial landforms. This might include aerial photograph interpretation with conventional photography, radar or LANDSAT imagery; photogrammetry, field mapping and topographic survey of critical areas; and perhaps dye or float tracing and aerial photography during floods, when the potential storage sites are inundated and it is possible to trace flow patterns through

## STREAM REGIMEN



**FIGURE 5.** (a) Longitudinal and transverse profiles of Willow Creek drainage at various times after channelization, which occurred between 1906 and 1920. Source: Daniels (1960). (b) Extension of entrenched channels through the drainage basin of a tributary of Willow Creek. Source: Ruhe (1971).



**FIGURE 6.** Sequence of channel positions on the Green River, western Washington, showing rapid lateral shifting and downstream migration of meanders. The maps were constructed from two sets of aerial photographs and a topographic survey.

the complex microtopography. Popov and Gavrin (1970) and Moore and North (1974) present examples.

The conditions for successful groundwater recharge are even more stringent because not only is a large surface depression required but it must be floored with thick, highly permeable alluvium to allow infiltration within a useful period of time. Fine sediment settling out of floodwater may reduce the infiltration capacity of the detention basin and must be excavated periodically. Much lowland river alluvium is not very permeable because of its fine texture, but there are some opportunities in sandy or bouldery alluvium. Such zones often occur in reaches of declining shear stress at the transition from hilly terrain to a lowland (e.g., between kilometers 40 and 67 in Fig. 7b), where thick sequences of sand or gravel are deposited by braided streams or by rapidly shifting, meandering rivers that have extensive point bar deposits. Other potential recharge zones exist in sandy or gravelly river channel, levee, and splay deposits, which have a coarser texture, better sorting and higher permeability than the surrounding overbank and backswamp deposits, or in alluvium deposited under earlier hydrologic regimes. The sedimentology and stratigraphy of favorable situations for groundwater recharge are illustrated by the case studies summarized by Reineck and Singh (1980, pp. 257–314) and Miall (1978).

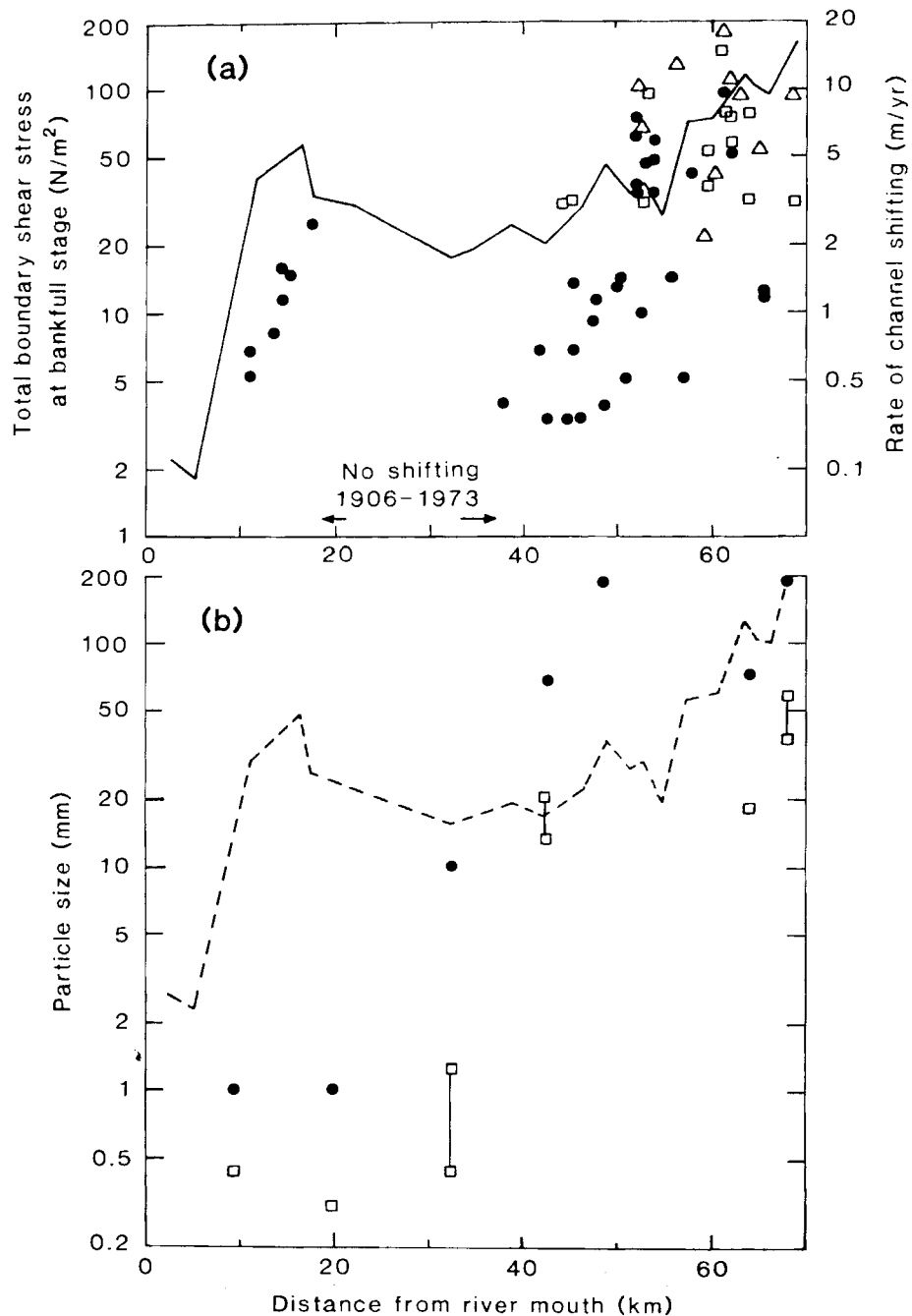
Estimating the potential for groundwater recharge would require a mapping and drilling program and the cooperation of a hydrogeologist, a sedimentologist, and a geomorphologist to interpret subsurface alluvial forms and to quantify the hydrologic properties of the sediment. Maps of hydraulic conductivity (Fig. 8) would be needed, and

could be superimposed on maps of topography and land use to define useful recharge areas. It is also necessary to take account of groundwater conditions during the flood season. Water tables rise early in the wet season in permeable deposits that receive small natural inflows. It may be necessary to draw down the water table quickly by pumping from a proposed subsurface reservoir, and it may be uneconomical to install the necessary pumping capacity, unless there is a local means of using such water at high cost during the wet season.

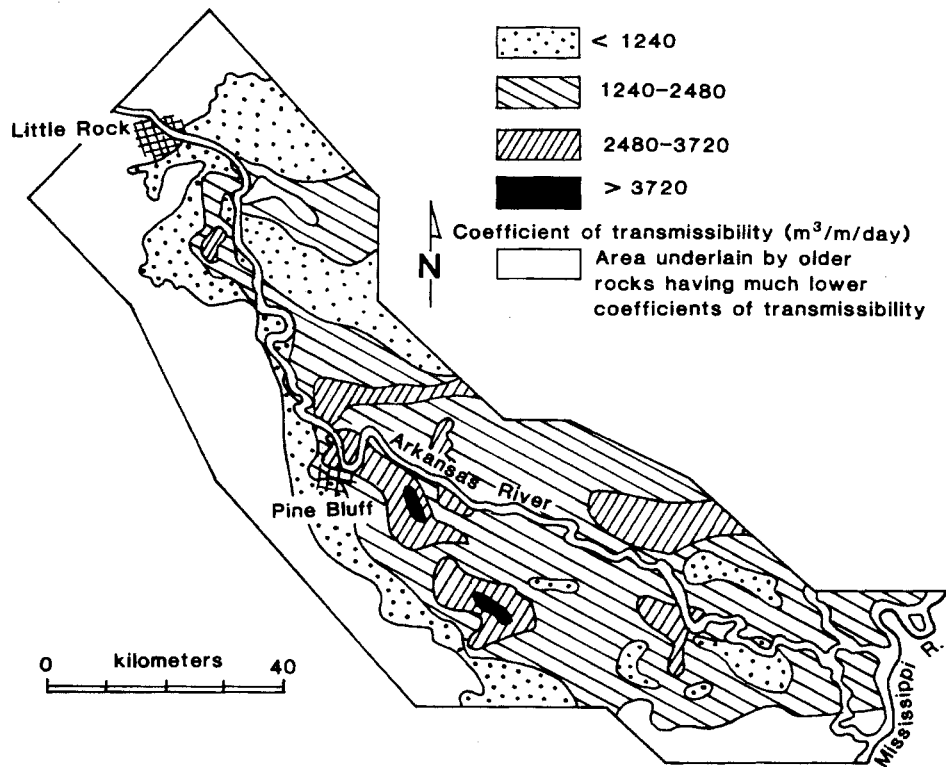
### Land Management for Soil and Water Conservation

Soil and water conservation does not significantly reduce the size of flood peaks generated by long rainy periods on large drainage basins. It is more effective during short, intense rainstorms on small basins. Hoyt and Langbein (1955) and Leopold and Maddock (1954) discussed this issue in some detail, and their conclusions have been verified by more recent empirical and theoretical studies. However, in some cases where deposition of sediment in river channels causes aggradation and channel shifting, a reduction of soil erosion through watershed management may facilitate river engineering for flood control. Before an expensive watershed management program is relied upon for flood control benefits, several geomorphologic issues should be clarified.

The first issue involves the nature and distribution of sediment sources and the extent to which they are affected by land use. For this purpose a sediment budget defining



**FIGURE 7.** (a) Downstream variation of maximum total boundary shear stress (solid line) at bankfull discharge in the Green River, computed from thalweg flow depth and gradient, and the rate of channel shifting during three time periods: 1960-1943 (solid circles), 1943-1973 (triangles), and 1968-1978 (squares). (b) Downstream variation of computed stream competence (dashed line), and the sizes of the largest (solid circles) and mean (squares) particle sizes found on the bed in each measured reach. Connected squares indicate two sample means from the same reach.



**FIGURE 8.** Map of transmissibility of floodplain sediments along the Arkansas River. The map was based on measurements in the down-valley direction, but similar measurements of permeability and depth could be made in the vertical direction to estimate the capacity of the sediments for infiltration and storage of floodwaters. Source: Bedinger and Emmett (1963).

the rates of sediment production by individual processes on disturbed and undisturbed areas may be useful, as discussed above. Large natural inputs of sediment from glaciers and landslides, for example, cannot be reduced by land management. If individual sediment sources cannot be isolated with the resources available, then it is usually possible to follow the approach used by Ongweny (1978) and Dunne (1979) of measuring sediment yields from subcatchments with various dominant land uses and to interpret the results in the light of field observation and plot experiments on erosion processes.

A second issue concerns the size distribution of sediment entering the channel. Some accelerated erosion processes, such as sheetwash, selectively remove finer soil particles, which may become washload when they enter major stream channels and travel to estuarine and deltaic zones. Thus, a relatively large reduction in the supply of fine sediment may not reduce channel instability if the latter is associated with the deposition of sand and gravel from landsliding or the undermining of glacial outwash deposits. Conclusions about this aspect of the problem should be based on geo-

morphic field work, involving the mapping of sediment textures along the main channel, sampling of the grain size distributions of major sediment sources, and lithological or other studies of the provenance of sediment.

Finally, it is necessary to clarify whether there is a relatively simple relationship between apparent sediment sources and the sediment deposited in major river channels. This problem is not always as obvious as it seems. For many years high sedimentation rates in the rivers of the Canterbury Plains, New Zealand, were blamed on sheep grazing and disturbance of the natural forest vegetation by "noxious," introduced wild animals. With the accumulation of measurements of sediment transport along rivers (Griffiths, 1979) and of sediment mobilization on the disturbed hillsides, it is becoming apparent that the high sedimentation rates and channel instability in the plains result from undermining of glacial terraces and similar coarse deposits, and is mainly a natural phenomenon not accelerated by land use. Conversely, Haggett (1961) and Trimble (1977) have demonstrated that long after reforestation or soil conservation practices have diminished erosion on agricultural land,

large amounts of sediment stored on footslopes, fans, and floodplains may continue to wash downstream. Geomorphologic mapping and measurement of sediment sources is again required to clarify the situation.

### Control of Land Use on Floodplains

The general aim of land-use control on floodplains is to limit occupancy of flood-prone areas by activities that suffer heavily from flooding. Control may be accomplished by forbidding certain activities or by specifying standards of construction for buildings. Further details are given by Dunne and Leopold (1978, Ch. 11).

Planning of land-use control depends on methods for delineating the area that would be inundated by floods of chosen frequencies. Various hydrologic techniques, such as field or aerial mapping during or immediately after a large flood and a combination of flood routing and topographic surveying (Wiitala et al., 1961), are useful for small areas of valuable land but are too slow and expensive for large floodplains (Dingman and Platt, 1977). However, the delineation of flood-prone areas can be facilitated and accelerated through use of geomorphologic techniques.

Wolman (1971) has summarized methods of mapping geomorphic and pedologic features that can be correlated to areas flooded with a specific frequency. For example, Jahns (1947) and Costa (1974a) mapped alluvial deposits associated with particular large floods, and Costa (1974b) outlined various types of evidence for recognizing prehistoric floods. Along many valley floors it is then possible to recognize topographic features such as terraces or the currently forming floodplain, which are flooded by events of known magnitude and frequency, and to map them quickly and cheaply. Witwer (1966) and Cain and Beatty (1968) have shown that characteristic soil types are also associated with such surfaces and can also be used to outline areas subject to flooding with a definable frequency.

These methods are particularly useful where the flood-prone zone is relatively stable over time. However, on many large floodplains, the flood hazard changes as the channel shifts across the valley floor. Through subtle alterations of valley floor hydraulics, channel migration may alter the total area flooded by a particular discharge. More commonly, migration, enlargement, or filling of channels causes only a redistribution in the depth and velocity of floodwaters and the susceptibility of land to scouring or undermining. Each of these changes affects the susceptibility of structures or crops to inundation, the viability of roads and bridges across the floodplain, and the possibility of evacuating people in the event of a flood warning. Thus, prediction of the location and behavior of the channel is an important requirement for flood damage abatement in some valleys. For example, Coleman's (1969) study of the Brahmaputra floodplain revealed channels that now

receive only small discharges during major floods but that will probably become the site of future diversions of the main channel.

Figure 9 shows a reach of the Yakima River, Washington, along which there was a need to predict possible channel locations over the succeeding 25 yr as part of a land-use plan for the valley floor. The intention was to minimize flood damage by locating facilities where they would not be inundated after channel migration. Sequences of aerial photographs spanning 35 yr were superimposed, and maps of channel changes, similar to Figure 6, indicated that channel migration occurs by two mechanisms. The first

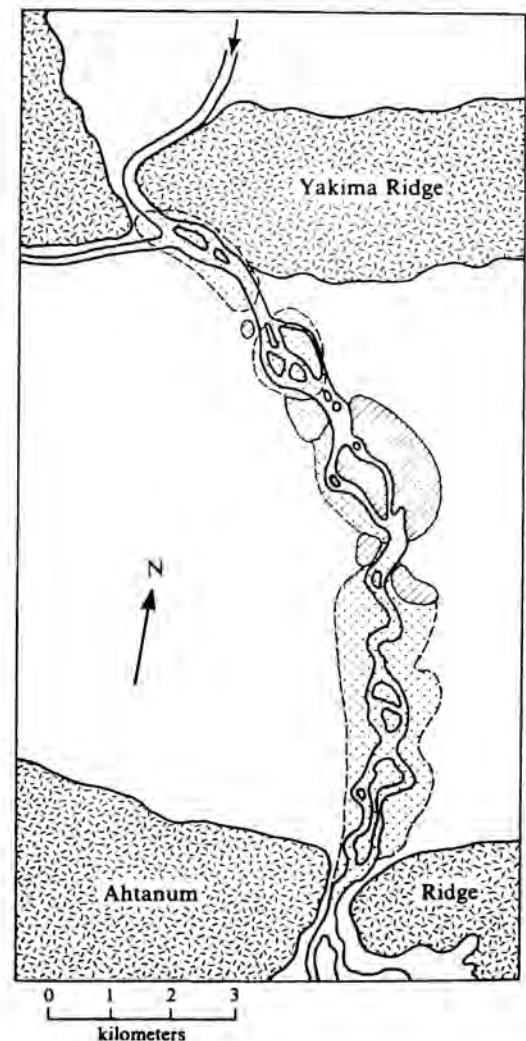
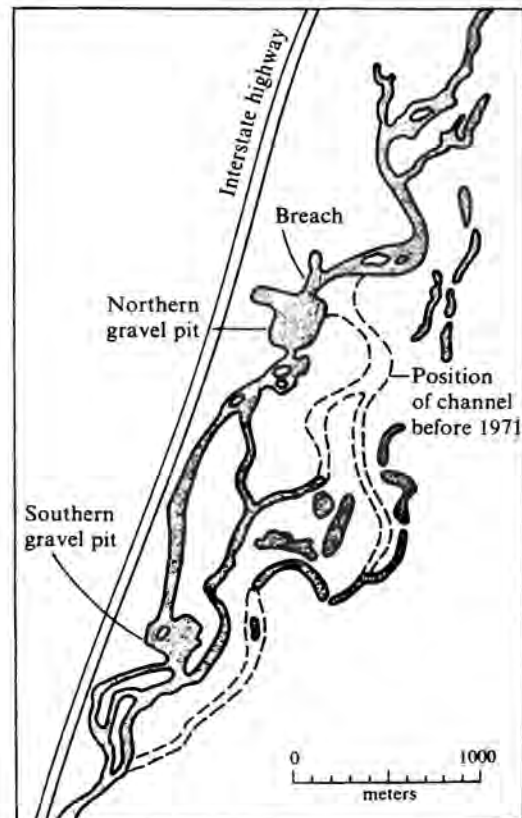


FIGURE 9. Map of the braided channel of the Yakima River near Yakima in eastern Washington, showing relatively stable zones of the floodplain (lined areas) not threatened by channel migration in the next 25 yr and threatened areas (dotted). The map was used as a basis for planning the siting of facilities.

consists of rather uniform lateral shifting of river bends at an average rate of 10 m/yr. The other mechanism of migration involves sudden avulsion by which a portion of the flood flow breaches the bankline and follows a new course, sometimes in a radically different direction from the original channel, and sometimes taking advantage of a former main channel or a smaller braided channel downstream. Succeeding floods may exploit the breach until the new channel is enlarged and conveys all or most of the flood. There is often a vigorous readjustment of channel morphology immediately above and below the diversion as the river alters its width and sinuosity to accommodate the new discharge. Severe bank erosion results. Such avulsions increase flood hazard because they can suddenly divert dangerous, fast, deep flows into zones that were formerly above water or were inundated only by shallow, slow drainage. Structures can be undermined and scoured away, and people and livestock can be trapped and drowned. The danger is enhanced because of the suddenness of breaching and the difficulty of its prediction.

Avulsion is a common, natural process along large, fast, braided rivers with weak bank materials, but along the Yakima the process has been accentuated by gravel mining in the valley floor. Deep pits are excavated, and after abandonment they are isolated from the river only by gravel dykes. Figure 10 indicates a location at which the river invaded a gravel pit, flowed out of its downstream end into an old channel, and re-entered the main channel via a second pit 1800 m downstream. The river was suddenly diverted 600 m to the west and is now undercutting the embankment of a major highway built with gravel from the pits. Subsequent readjustments of the new channel have isolated buildings situated on terraces above flood level. Similar channel diversions can result from alterations of the floodplain topography through irrigation and other engineering works unless a detailed geomorphologic analysis of the microtopography, hydraulics, and history of the floodplain is undertaken to define zones that should be avoided or strengthened. Although it is only possible to make short-term predictions of channel migration on a braided river of this kind, a longer term "worst-case" analysis is also possible. A map of zones threatened by channel migration over the succeeding 25 yr (Fig. 9) was drawn by examining the channel banks and valley floor on sequences of aerial photographs and in the field for likely avulsion sites. Some were obvious, and the path of the river after diversion could easily be foreseen; a few were more equivocal but were included in the interest of conservative design. After the probable diversions were mapped it was conservatively assumed that they would all occur in the next few years, and recent directions and rates of gradual shifting from the diverted courses were projected over the next 25 yr to define the hazard. The prediction was insensitive to the assumed timing of breaches because



**FIGURE 10.** Map of an avulsion of the Yakima river caused when the channel breached a dyke surrounding the northern gravel pit, and floodwaters drained out of the southern end of the pit and into another pit downstream before re-entering the main river course. The shaded zone is now the main river channel, while the former course (dashed lines) is occupied only during infrequent, large floods and is being filled with fine sediment from local sources.

avulsion usually causes much larger shifts than persistent migration on this river.

## CONCLUSION

Fluvial geomorphology can play a more extensive role in flood control planning than is commonly realized. The most useful applications are those that recognize the relationships between the control of floodwater and the control of sediment and of channel form and activity. Geomorphologic studies are also valuable for extending information on flood magnitudes, sedimentation, and channel stability over long periods of time and between river basins. Since mathematical modeling of these phenomena is still relatively crude and unreliable, geomorphology is the only means

of providing the required historical background for flood and sediment control.

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