ASSESSMENT OF STREAM CHANNEL RESPONSE TO ALTERED STREAMFLOW AND SEDIMENT LOAD

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INTRODUCTION

The assessment of stream channel response to altered streamflow and sediment load depends upon both an accurate description of the natural or initial conditions of the channel as well as the analytical methodology employed. It is quite impossible by any method to predict the hydraulic characteristics of a stream channel following changes in streamflow and sediment load without some knowledge of natural stream conditions. The accuracy and specificity of the predicted channel response improves as the hydraulic characteristics of the unaltered stream are better known.

With this in mind, the available information describing the hydraulic characteritics of Poplar Creek is wholly inadequate to make reasonable predictions of the channel response following the construction of the Dutch Gulch Dam. This deficiency limits the assessment of probable stream channel response far more than our understanding of fluvial processes, or our ability to apply this knowledge.

It has been my personal experience when considering stream channel response that in a majority of situations the hydrologic description of the affected stream is insufficient to address the significant issues of land-use change. The Poplar Creek example is, in fact, quite typical of the situation one faces in evaluating stream channel response to disturbance. Although frequently there is considerable information describing the hydrology of the stream, i.e. annual runoff, daily discharges, annual peak flows, etc., this information is not sufficient to describe the channel morpholoy.

In many instances, an adequate hydraulic and geomorphic description can be obtained rather easily and without great expense. The essential elements of such a geomorphic description are:

1. A study reach of a length of at least 30 channel widths, so that three to four pool and riffle sequences and meanders are described.

2. Several cross sections (10-15) that describe the variation in channel morphology. Each cross section profile should show the bankfull elevation, vegetation, and size distribution of the bed material.

3. Surveyed longitudinal profiles of streambed, water-surface, and bankfull elevations. Longitudinal profiles determined from maps are generally inadequate. In constructing these profiles, channel features should be surveyed at points no more than every one-half channel width apart.

4. A sketch map of the study reach showing the location of surveyed cross sections and longitudinal profiles, and accurately portraying the channel pattern and alignment.

5. Photographs of the study reach are quite valuable, especially sequential aerial photographs. When assessing the future hydraulic adjustment of a river, it is extremely helpful to know something about the character of the river over the past 20-40 years. Aerial photographs are the most readily available and useful sources of the information.

All of this information could have been collected for the Poplar Creek study reach by a two person surveying party in a week. The total cost would be quite modest; approximately $1,000, which is miniscule compared to that of the project. Without this information, the analysis of stream channel response is hampered much more by insufficient knowledge of the stream than the uncertainty of the theoretical or analytical methodologies.

HYDRAULIC CHARACTERISTICS OF POPLAR CREEK STUDY REACH

Due to the lack of hydraulic and geomorphic information about the Poplar Creek study reach, it is necessary to make several assumptions regarding the character of the channel. Each of these assumptions will be noted. To the degree that these assumptions do not agree with the actual character of the Poplar, the anticipated response will be in error.

Several surveyed cross sections of the study reach were provided. It appears that these sections were surveyed for purposes of a flood routing study, because critical geomorphic features were not identified. In each case, an "active" channel was noted; however, it is unclear whether the "active" channel is, in fact, the self-formed or bankfull channel. For lack of a better estimate of the bankfull channel width, however, I have assumed that the "active" channel width is approximately the bankfull channel width. The average width of these cross sections is 460 feet.

Several sediment size analyses were provided. Two samples appear to have been collected at some of the cross sections surveyed by the U.S. Corps of Engineers. These are identified as edge of stream and overbank samples. In addition to the sediment size analysis performed by the Corps, a few bed-material size analyses at a gaging station operated by the U.S. Geological Survey were also provided. The bed-material samples analyzed by the U.S. Geological Survey indicated a median diameter of approximately 4 mm, whereas the Corps of Engineers' samples indicate a median of 28 mm. These values appear to be in conflict, unless the U.S. Geological Survey samples were taken from a pool, and the Corps samples were taken from a riffle or bar. My personal experience with other streams draining the west side of the Sacramento Valley suggests that this is the likely explanation for the discrepancy. The average bed-material size distributions assumed for riffles and pools are (Table 1):

Table 1. Bed-material size distributions for riffles and pools.

	Bed Material Size Riffles (mm)	Pools (mm)
D_{16}	3	.6
D_{35}	15	1.8
D_{50}	28	4.0
D_{65}	43	8.5
D_{84}	67	20.0
D_{90}	85	24.0

A generalized stage-discharge relation for the study reach was computed using a modified form of the Keulagen's logarithmic velocity relation proposed by Bray (1979):

$$\frac{\bar{u}}{\sqrt{gds}} = 3.56 + 6.11 \log \frac{d}{D_{90}}$$

An average slope of 0.0018 was determined from topographic maps for the study reach.

A bedload sediment transport vs. discharge relation was computed using the derived stage-discharge relation, the assumed pool bed-material size distribution, and the Meyer-Peter, Müller bedload transport equation. A few measured bedload transport rates and sizes determined by the U.S. Geological Survey using a Helley-Smith bedload sampler are in good agreement with the computed relation between bedload transport and discharge.

Synthesized daily mean discharge flow-duration relations at the Dutch Gulch Dam site were provided for the natural and regulated conditions. The computed bedload transport vs. discharge relation was combined with these flow-durations to determine the effective discharge for the natural and regulated conditions. Andrews (1980) showed that the increment of discharge that transported the largest fraction of the mean annual sediment load over a period of years, i.e. the effective discharge, was approximately the bankfull discharge; thus the effective discharge measurements will be assumed to be reasonable estimates of the bankfull discharge. The computed unregulated effective discharge was 10,000 ft^3/sec and the computed regulated effective discharge was 7,200 ft^3/sec.

In both the regulated and unregulated conditions, the bankfull discharge will be equalled or exceeded approximately 0.3% of the time, or slightly more than one day per year. This is within the range one would expect for such a drainage basin.

The unregulated mean bankfull hydraulic characteristics of the study reach were determined from the estimated bankfull width, computed stage-discharge relation, and computed bankfull discharge. Estimated bankfull hydraulic characteristics are: velocity, 5.2 ft/sec; mean depth, 4.2 ft; and width, 460 ft.

The regulated mean hydraulic characteristics were determined using the unregulated bankfull hydraulic characteristics and the hydraulic geometry equations developed by Leopold and Maddock (1953).

$$\bar{u} = 2.07\ Q^{0.1}$$

$$\bar{d} = 0.106\ Q^{0.4}$$

$$w = 4.6\ Q^{0.5}$$

The regulated bankfull hydraulic characteristics of the study reach were determined by solving these hydraulic geometry relations, assuming a bankfull discharge of 7,200 ft^3/sec. Thus, the computed bankfull hydraulic characteristics as a result of reduced streamflow due to the construction of Dutch Gulch Dam are: mean velocity, 5.03 ft/sec; mean depth, 3.68 ft; and width, 390 ft.

This analysis has neglected some significant factors affecting the hydraulic geometry of Poplar Creek. Regulation of Poplar Creek by Dutch Gulch Dam will reduce the duration of very large discharges and increase the duration of intermediate discharges. Both of these changes will tend to stimulate the encroachment of vegetation into the channel. As a result, the channel will probably be somewhat narrower and deeper than indicated by the hydraulic geometry relations.

SEDIMENT TRANSPORT AND STREAMBED DEGRADATION

As described above, the transport rate of bedload through the study reach was computed for several discharges from the derived stage-discharge relation, the assumed pool bed material size distribution, D_m = 7 mm and D_{90} = 40 mm, and the Meyer-Peter, Müller bedload transport equation.

The mean annual bedload discharge of Poplar Creek near Olinda was computed to be 60,000 tons under the natural conditions. Assuming that the size distribution of bed material is the same, and using the projected flow duration for the Poplar Creek below the Dutch Gulch Dam site, the mean annual bedload discharge will be reduced to approximately 26,000 tons/year. Construction of the dam will trap the entire 60,000 tons/year of bedload material that is presently transported past the Olinda gage. Thus, the quantity of sediment transported out of the study reach will exceed the supply and the streambed will degrade as long as the supply of sediment from downstream tributaries is less than 26,000 tons/year.

The mean annual bedload-discharge per unit drainage area upstream of the Olinda gage is 150 tons/mi^2-year. Estimated mean annual bedload discharge per unit drainage area for other gaging stations along the west side of the Sacramento Valley ranges from 10 to 200 tons/mi^2-year. The drainage area contributing to the study reach is 80 mi^2. Therefore, the quantity of bedload material supplied to the study reach by tributaries will be approximately 12,000 tons/year. (In the following discussion, it will be assumed that the particle size distribution of the sediment supplied to the study reach by tributaries is the same as the bed-material found in the pools at low flow under present conditions.) Thus, throughout the study reach, the expected annual bedload transport rate will exceed the supply of sediment from tributaries. Immediately below the dam and above the first tributaries, the expected excess of transport over supply will be 26,000 tons/year. This deficiency will decrease downstream to approximately 14,000 tons/year at the downstream end as tributaries supply sediment to the study reach. As a result, relatively small, transportable sediment particles will be eroded from the streambed, and the channel will degrade. Concomitantly, the bed-material will become coarser, and the bedload transport rate will decrease. Ultimately, the quantity of sediment transported will equal the quantity of sediment supplied to the channel (about 12,000 tons/year) at which time the streambed degradation will stop.

The average depth of streambed degradation can be estimated by calculating the maximum size of particles that will be transported by the reduced streamflows following construction of the dam. One method for calculating the threshold particle diameter is to set the Meyer-Peter, Muller bedload equation equal to zero (i.e. no transport), (U.S. Bureau of Reclamation 1973). The calculated threshold particle diameter in Poplar Creek at a bankfull discharge of 7,200 ft^2/sec is 27 mm.

As noted previously, the Poplar Creek study reach appears to have a fairly well developed pool and riffle sequence at this time. The riffles are composed of relatively coarse material (D_{50} = 28 mm), whereas the pools have relatively fine bed material (D_{50} = 4 mm). Because the median diameter of riffle bed material is already as coarse as the threshold particle size that will be transported by the regulated streamflow, degradation of these riffles will be slight, about .25 feet. Nearly all of the pool bed material, however, is smaller than the threshold particle size, and consequently, significant degradation of the streambed through pools, perhaps three feet or more, is likely. Thus, over the next few decades, it seems probable that there will be an enhancement of the pool and riffle sequence in the study reach. However, because the regulated streamflows will be insufficient to transport the size of material that presently makes up the riffles, the existing riffles will become relics from the unregulated hydraulic conditions. Natural lateral migration of the stream channel will, in time, develop an entirely new channel. It appears likely that the new channel will also have a pool and riffle sequence, but the riffle bed-material will be smaller ($d_{max} \approx 27$ mm), due to the reduced magnitude of streamflows.

In spite of the general trend towards degradation, there may be localized areas of aggradation at the mouth of major tributaries, particularly Little Dry Creek and Dry Creek. At present, there is a significant bulge in the longitudinal profile of Poplar Ceek where Little Dry Creek and Dry Creek join. The impact of these tributaries on Poplar Creek will depend on how severely flood flows in Poplar Creek are reduced by the Dutch Gulch Dam, the relative timing of peak flows in Poplar Creek and the tributaries, and the quantity of sediment supplied by the tributaries that is larger than can be transported by Poplar Creek. The tributaries may well have an extremely significant impact on the study reach following construction of the Dutch Gulch Dam. Consequently, it is essential to define the hydrologic and sedimentologic characteristics of the tributaries.

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POPLAR CREEK, CALIFORNIA: A BRIEF EVALUATION OF RIVER BEHAVIOR

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INTRODUCTION

Poplar River is a sandy, gravel-bed river in northern California. Proposed river-management schemes would alter the duration of natural streamflows by reducing peak flows and releasing impounded waters at near and below bankfull stages. Channel response to the redistribution of streamflow is related primarily to bed-material transport.

The present report attempts to predict some of the channel responses to the proposed water-management schemes. The analysis is based on existing data; no field visit to the site was made. Existing data consist of:

1. Selected topographic maps (USGS),
2. Synthesized high flow frequency curves (USCE),
3. Synthesized natural and project flow duration curves by station correlation (unknown),
4. Channel cross-sectional surveys (USCE),
5. Selected streamflow, water quality, and sediment data (USGS 1979),
6. Summary of discharge measurements (USGS), and
7. Flow-duration curves (USGS).

Items 1-4 were provided by the U.S. Fish and Wildlife Service, item 5 is a published library reference, item 6 was solicited from the U.S. Geological Survey office in Sacramento, and item 7 was retrieved from the WATSTORE computer files of the U.S. Geological Survey.

Few of the supplied data were useful to make a river analysis. An experienced river engineer, spending one day in the field, could have collected substantial data to support a more rigorous analysis.

With inadequate data availability, the approach taken in the analysis is an application of approximating channel-geometry relations and comparison with case history data. An assumption is that the behavior of Poplar Creek is not too unlike that of similar rivers. Results of the analysis are adequate for planning purposes, but should not be used as a basis for engineering design.

DESCRIPTION OF STUDY REACH

The study reach is some 50,000 feet in length, extending from Dutch Gulch to the confluence with a principal tributary fork. Drainage area at the upstream end of the reach is some 400 square miles. Bed material is primarily coarse sand and gravel, and is characterized by d_{35} = 1.0 mm, d_{50} = 1.8 mm, d_{65} = 2.2 mm, d_{84} = 8 mm, and d_{max} = 32 mm (USGS 1979:107).

Mean annual precipitation is about 40 inches per year; approximately one-third runs off giving a mean annual discharge of 432 cfs (USGS 1979:102) at the upstream end of the reach. The stream hydrograph is flashy with a peak flow nearly 100 times the mean annual flow (data item 2). Whereas many rivers have peak flow only slightly greater than 1-day flow and only about 1.5 times 30-day (Emmett 1975), Poplar River has peak flow about 1.5 times 1-day flow and about 7 times 30-day flow (data item 2).

Bankfull discharge can be approximated as the 1.5-year flow (Emmett 1972, 1975, Leopold et al. 1964), or about 5,000 to 6,000 cfs (data item 2). The average width of mobile channel is about 175 feet (data item 4, data item 6, and USGS 1979:107, using width data given and applying techniques of Emmett (1975). Bankfull depth and velocity, approximated by channel-geometry techniques (Emmett 1972, 1975), are about 4.5 feet and 7.0 fps, respectively. These numbers multiply to give 5,500 cfs as the bankfull discharge. Although regulation will reduce peak flows by a 3- to 4-fold factor (data item 3), bankfull discharge will be changed in flow duration by only 0.2%, from about 0.8 percent of the time to 0.6% of the time (data item 3). In reality, only peak flows at the upper 0.1 percent of time are being eliminated by regulation. Further, comparison of the actual flow duration for the period of operation, 1972-1979 (data item 7), and the synthesized project flow duration (data item 3) indicates no significant differences in the flow duration between project operation and the actual flows in eight years of data collection (Table 1).

The river drops 100 feet in the 50,000-foot study reach (data item 1), giving a nearly uniform slope of 0.002 ft/ft. Based on a bankfull discharge of 5,500 cfs, this value of slope would indicate a mildly to moderately braided channel, reasonably straight in course but unstable in smaller-scale pattern (Leopold 1964). That is, low-water channel configurations are different from one season to another. Size similarity of bedload and bed material (USGS 1979:107) indicates the river is competent to transport most sizes of sediment occurring on the streambed.

Table 1. Discharge summary.

Percentage of time	Discharge (cfs x 10^3) Actual Record	Synthesized Natural	Synthesized Project
0.03	10.9	15.8	10.9
0.05	10.3	13.4	10.3
0.08	9.6	11.8	9.8
0.1	9.3	11.1	9.6
0.2	8.0	9.2	8.8
0.4	6.5	7.4	7.0
0.8	5.3	5.4	4.7
1.6	3.4	3.7	2.8
3.2	2.2	2.4	1.6
6.4	1.5	1.4	1.0
10.0	1.0	1.0	.8

BED-MATERIAL TRANSPORT

Bedload generally relates to a stream-power term or for constant slope and little changes in width, to the stream discharge. More precisely, the relation is proportional to about the three-halves power of the discharge in excess of the discharge to initiate movement of bed material. Using case history data for similar conditions (Emmett, 1976, Emmett 1978 and Leopold and Emmett 1976) and with some validation of the case history data (Emmett 1980, Emmett and Thomas 1978), at bankfull discharge, bedload transport in Poplar Creek is about 2000 tons/day. At twice bankfull stage, the approximate maximum regulated flow, bedload transport is about 5,000 tons/day. At half bankfull, bedload transport is about 600 tons/day.

Approximately 90% of the bedload transport occurs in 10% of the time. Applying the bedload function to the upper 10% of the synthesized flow-duration values (data item 3), the unregulated flow transports about 23,000 tons of bedload and the regulated flow transports about 18,000 tons. Using the actual flow duration (data item 7), the bedload transported in 10% of the time is about 20,000 tons. A total annual average of bedload transport for the unregulated stream is estimated at 25,000 to 30,000 tons. This compares to a value of 40,000 tons during water year 1978 (USGS 1979, p. 107) when streamflow was two-thirds greater than normal.

CONCLUSIONS

Assuming a reasonable trap efficiency for the proposed impoundment, the stream would desire to transport approximately 20,000 tons of bedload which is not available. Degradation below the reservoir might occur with a concurrent coarsening of the bed by depletion of smaller particles. This will lead to armoring, and any degradation will be modest. Downstream, the stream might not be able to transport all material supplied by its tributaries and modest aggradation might occur in these reaches. Little or no change in other channel characteristics would appear other than a decrease in near-annual floodplain inundation. Adherance to the operating rules (data item 3) imposed on this analysis should minimize channel changes. Monitoring of downstream channel changes could help in any revision needed in operating policy to help eliminate adverse effects.

It is emphasized that this analysis is preliminary and should be used only to evaluate some techniques available for assessment of river behavior.

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CHANNEL ADJUSTMENT TO RIVER REGULATION SCHEMES

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INTRODUCTION

River regulation, including interbasin water transfers, has been advocated as a means of equalizing water supplies and demands in England and Wales. In this way the river is used as a natural aqueduct and it obviates the need for the construction of costly tunnels and pipelines linking the remote source with the demand center.

Rivers can be regulated either by releases from upland impounding or pumped storage reservoirs, interbasin transfers, or by the discharge of pumped ground water. During the last decade there have been several developments of this type in England and Wales and further schemes are either under construction as, for example, the Kielder Reservoir on the River North Tyne or, like the Craig Goch Reservoir on the River Wye, at the planning stage.

By modifying the flow regime and sediment transport characteristics of a river, such developments may be responsible for erosional and depositional activity as the channel adjusts to the new flow conditions. In order to assess whether regulation will cause unnatural amounts of erosion or deposition and, if so, predict the response of the channel to river regulation, it is necessary to briefly consider the mechanisms controlling the development of natural channels.

CHANNEL ADJUSTMENT MECHANISMS

Process-Response Models

Channels respond to variations in discharge and sediment load through the operation of governing or process equations. These equations define the mechanisms whereby channels adjust their hydraulic geometry through erosion and deposition. For gravel-bed rivers there are seven unknowns, velocity, hydraulic radius, wetted perimeter, maximum flow depth, slope, sinuosity and meander arc length, and it follows that there must be seven governing equations. These are the continuity, flow resistance, sediment transport, bank competence (Bray in press), and sinuosity (Bray in press) equations. Two further equations are required for sand-bed channels due to the development of bed forms. Provided these physical processes can be specified mathematically, then their simultaneous solution will define the dimensions of alluvial channels given the discharge, input sediment load, bed and bank material, and the valley slope (Hey 1978).

The operation of channel feedback mechanisms enables a section of channel to interact with neighboring reaches to adjust its input conditions. This occurs because the processes of aggradation and degradation, through their action on channel slope, flow depth, and bed sediment size promote further instability. The stabilizing influence of negative feedback mechanisms results from the effect of upslope erosion or deposition on the input sediment load. During erosion, drawdown effects are responsible for the upstream migration of erosional activity and the increased caliber and volume of the input load gradually reduce the erosion rate and eventually re-establishes stability. This will be only a temporary phenomenon because the increase in sediment load, as erosion progresses further upstream, will immediately initiate deposition. Similarly the depositional phase will tend to stabilize as the reduced caliber and volume of the input load, resulting from backwater effects promoting aggradation upstream, can be transmitted through the cross section.

Once again the stable condition will be only a temporary phenomenon since the continued reduction in input load, due to the upstream progression of the aggradational phase, will precipitate further erosional activity. The river will then rework some of the sediment which had temporarily been stored in the channel. This indicates that there will be a constant interplay between erosional and depositional activity in time and space. The magnitude and frequency of the oscillation will, however, decline and a regime type condition will eventually become established (Hey 1979).

Dominant Discharge

Although rivers adjust their bankfull shape and dimensions to a range of flows it has been argued that the steady discharge which produces the same gross shapes and dimensions as the natural sequence of events is the dominant discharge (Nixon 1959). Flume experiments and observations of natural channels indicate that flows at, or about, the bankfull stage are the effective ones for channel forming processes (Ackers and Charlton 1970).

Wolman and Miller (1960) in their study of the magnitude and frequency of sediment transport processes showed that the frequency of occurrence of the flow transporting most sediments and the bankfull discharge were approximately equal and this explains why bankfull flow appears to be the dominant or channel forming discharge. The magnitude and frequency of the flow transporting most sediment is dependent on the flow regime and the nature of the sediment transport processes (Figure 1). For stable gravel-bed rivers this is the 1.5 year flood (annual series) while for sand-bed channels the return period of bankfull flow is lower. Thus, although extreme discharges are individually responsible for transporting large volumes of sediment, it is the smaller more frequent flows which collectively transport the largest volume of sediment over a period of years.

Any change in the input sediment load or the frequency of flows which can transport sediment will cause erosion or deposition. During periods of instability the channel dimensions and the bankfull discharge adjust to the flow doing most erosion or deposition. When eroding the capacity of the channel and the return period of bankfull flow are increased and vice versa when depositing. The flow variability is also influenced by these systematic changes in channel capacity. Depositional activity reduces channel capacity, increases flood attenuation, and reduces the flow variability; while erosion increases flow variability (Hey 1975a).

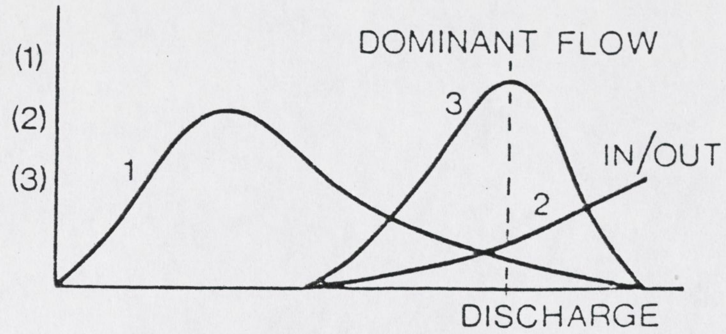

Figure 1. Flow Transporting Most Sediment
Key (1) Frequency, (2) Instantaneous Sediment Discharge, (3) Total Sediment Discharge.

EFFECT OF RIVER REGULATION ON CHANNEL STABILITY

River regulation and interbasin transfers, through their influence on flow variability, mean flows, and sediment transport rates can have considerable effect on the magnitude and frequency of sediment transport processes. Consequently the channel downstream from a regulation point could be susceptible to either erosion or deposition as it adjusts its capacity and hydraulic geometry to the new flow regime (Hey, 1975b).

With surface water reservoirs, regulation can be achieved either directly below the dam site, or at a point farther downstream through the operation of a river intake/outfall. In both cases flow variability will be reduced downstream from the regulation point, because the magnitude and frequency of the flood flows are reduced in order to decrease the number of exceedingly low flows, and the sediment transport characteristics of the channel will be considerably altered. Mean flows will also be modified if interbasin transfers are involved.

Reservoirs

There are many examples of scour effects downstream from dam sites. Principally it results from a reduction in sediment load consequent upon the construction of the reservoir (Komura and Simons, 1967), although modification to the flow regime can be a considerable influence (Gregory and Park 1974).

Immediately downstream from the dam site the channel will initially retain its ability to transport sediment at certain flow stages. As input load is zero erosion will commence which, in turn, will reduce the slope of the channel and the bed shear stress and increase the average size and variability of the bed sediment. Consequently the ability of the channel to transport sediment will progressively decline until all flows are below the threshold discharge for bed material movement (Figure 2). Material flushed out by this process will be deposited lower downstream. Eventually the progressive reduction in sediment output below the dam will cause erosion at sections further downstream and the process is repeated. Even if the channel immediately below the dam site is cut in bedrock, erosion will be experienced in the alluvial reaches of channel further downstream if regulated flows can transmit sediment. If tributaries are unregulated, sediment entering the main channel may not be transmitted by the reduced flow levels and this can result in localized deposition. Reduced main river levels can also promote erosion on the tributary and this can exacerbate the depositional activity on the main stream.

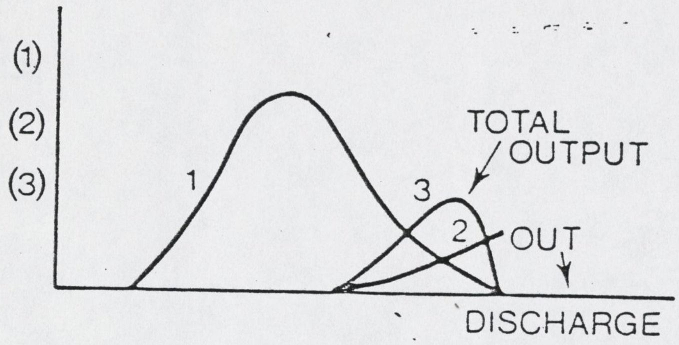

Figure 2. Effect of Regulation on Total Sediment Discharge Below Dam Key (1) Frequency, (2) Instantaneous Sediment Discharge, (3) Total Sediment Discharge.

Natural channel stability can be maintained provided releases are made below the minimum threshold discharge for bed material transport or bank erosion downstream from the reservoir. The maximum release at the dam will therefore depend on the downstream increase in natural flows when releases are being made.

River Intakes/Outfalls

Pumped storage reservoirs are increasingly being used to regulate flows in alluvial channels through the operation of river intakes/outfalls. Interbasin transfers are often associated with such schemes. In this type of development both the flow regime and sediment transport characteristics of the channel are changed dramatically over a short stretch of channel and, unlike the reservoir situation, the sediment input is not necessarily zero.

If regulation alters the number of flows that can transport sediment, channel stability will result. This will be most severe when erosion or deposition occurs at the intake/outfall point because it precipitates instability both upstream and downstream. However, provided channel feedback mechanisms operate very slowly, dynamic stability may be achieved at the intake/outfall site when aggradation balances degradation over a number of years (Figure 3). Downstream the dominant discharge would be defined by the flow transporting most sediment (output). while upstream it would be defined by the flow transporting most sediment (input). If feedback mechanisms operate very rapidly during periods of instability and promote bank erosion and a change in the plan geometry of the channel, this would permanently alter the hydraulic characteristics of the channel, and preclude the re-establishment of the original condition. Equilibrium would be achieved in these circumstances only after the channel had modified its hydraulic geometry and reduced its sediment transport capacity so that all releases were below the threshold discharge for sediment transport.

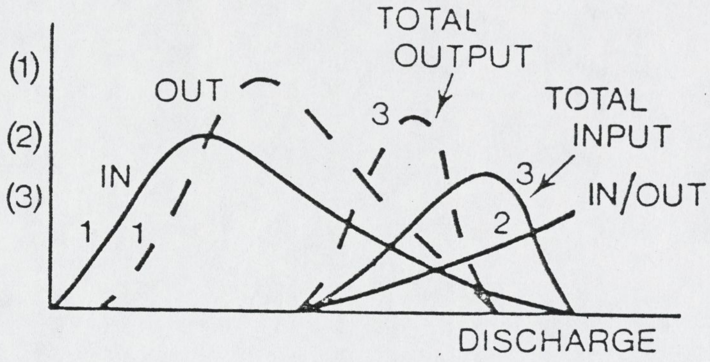

Figure 3. Effect of Regulation on Total Sediment Discharge at a River Intake/Outfall
Key (1) Frequency, (2) Instantaneous Sediment Discharge, (3) Total Sediment Discharge

Provided regulation does not alter the frequency of flows above the threshold discharge for bed material transport and bank erosion downstream from the intake/outfall, the natural character of the channel can be preserved. The associated maximum regulated flow at the intake/outfall will depend on the downstream rate of increase in base flow when abstractions and releases are being made. If natural flows do not increase significantly downstream when regulation is taking place, the maximum regulated flow at the outfall is defined by the minimum threshold discharge for bed material transport or bank erosion downstream from the intake/outfall.

PREDICTION OF CHANNEL RESPONSE TO RIVER REGULATION

Mathematical Models

Potentially mathematical modeling procedures offer the best solution to the problem of predicting channel response to river regulation. This type of model has been successfully used to predict bed scour and deposition in response to changes in discharge and sediment load. Routing procedures based on the continuity, flow resistance, and sediment transport equations are used to determine the volume of sediment transported through a series of channel reaches in a given time interval. Changes in bed elevation and bed material size enable the flow geometry and sediment transport to be determined in the succeeding time interval (U.S. Army Corps of Engineers 1977).

Unfortunately existing mathematical models are limited in their application and further research is required on bank erosion/deposition and meander processes before it will be possible to predict changes in channel width, plan shape, and valley slope. Even when applied to predict scour and fill in gravel-bed rivers inaccuracies can result due to the deficiencies of the flow resistance and sediment transport equations used in the model. Bray (in press) has shown that the Strickler type flow resistance equations can produce an error of 40% in the predicted velocity, while the entrainment function for graded gravel material can be as low as 0.03 (Neill 1968).

Empirical Models

Until mathematical models have been satisfactorily developed recourse has to be made to much simpler empirical methods for prediction purposes. Regime equations can give an indication of the type of channel response to river regulation but they cannot be used to predict the new equilibrium hydraulic geometry of the channel. Feedback mechanisms enable the channel to adjust its own dominant dicharge, sediment load, and bed material size and these values cannot be predicted in advance. However simple field methods can be used to establish the general response of the channel to regulation.

The first requirement is to investigate the natural stability of the river as this enables the sections of channel which will be most susceptible to changes in the flow regime to be identified. The next stage involves the determination of the critical threshold discharges for bed material transport and bank erosion at a number of representative sections along the river. This enables an upper limit to be established for regulated flows which will preserve the natural stability of the channel downstream from any proposed intake/outfall or dam site. In addition it enables the sections of channel which will require maintenance and protection to be identified if regulated flows are required above the threshold discharges for bed material transport and bank erosion.

Natural Channel Stability. Unstable sections of channel can be identified in a variety of ways. Direct evidence of erosional and depositional activity, or evidence of systematic changes in the cross section or plan shape of the river over a number of years are the best indicators. However if this type of information is unavailable it is possible to make an assessment based on the morphological or hydrological characteristics of the river.

Several common morphological features develop as a channel responds to erosional and depositional activity. During erosion the river incises into the bed of the channel and this produces relatively deep channel sections, steep gradients, large bed material, and high average flow velocities. In contrast rivers that are actively depositing produce relatively wide shallow channels with low gradients, small bed material, and low average flow velocities.

These systematic changes in channel capacities have important repercussions on the frequency of overbank flooding. In gravel-bed rivers the return period (annual series) of bankfull flow for eroding sites is greater than 1.5 years while for depositing sites it is less than 1.5 years.

Bed Material Transport Thresholds. Threshold discharges for bed material transport can be obtained either from rating curves, from calculations based on sediment entrainment functions or by direct observations of bed material tracers during flow events of varying magnitudes.

Although rating curves offer the simplest solution to the problem, in practice insufficient sites are calibrated, especially in gravel-bed channels.

For sand-bed channels the Shields entrainment function can be used to establish threshold discharges for movement given hydraulic data for various flow levels and information on the grain size frequency distribution of the bed sediment. Considerable error can arise when this method is applied to gravel-bed channels because transport thresholds are significantly affected by the degree of imbrication and the packing of the gravel.

Field experiments with bed material tracers offer the best solution to the problem of assessing threshold discharges for sediment transport in gravel-bed rivers. At each site the bed material size distribution is defined by sampling and measuring the intermediate axis of a hundred pebbles obtained from the bed of the channel using a grid sampling procedure. This sample is divided and half of the pebbles are painted and replaced in a line across the channel perpendicular to the banks. On practical grounds material less than 10 mm is not used for tracing purposes. In addition, as tracers are unlikely to be replaced in a natural position, some movement is expected at flows below the actual transport threshold until they become re-established on the bed of the channel. Any movement less than 0.5 m is considered to be due to this process and is disregarded in the analysis.

Observations of the tracers during and after various known flow events enables the maximum peak flow which does not cause movement, and the minimum peak flow which causes movement, to be defined. Given a favorable range of flow conditions these values converge and the threshold discharge for bed material movement can readily be defined. If the peak flows do not range around the threshold discharge during the period of the experiment it is necessary to estimate its probable value given the two limiting flows.

Bank Erosion Thresholds. To assess the limiting threshold discharge for bank erosion several sites which display fresh evidence of bank collapse need to be instrumented. At each site 1 m long steel reinforcing rods are driven horizontally into the coarse material underlying the bank at approximately 4 m centers along the length of the eroding bank. Any subsequent exposure of the rod indicates the amount of gravel removed. To monitor erosion of the overlying cohesive sediment a line of reinforcing rods are driven vertically into the surface of the flood plain exactly 1 m from the edge of the bank and at approximately 4 m centers. This serves as a datum for resurveying purposes. Regular site visits enable the threshold discharge for bank erosion to be established.

Channel Response to Regulation. Given information on threshold discharges for bed material transport and bank erosion at a number of representative locations along a river, it is possible to define a regulation strategy which will maintain the natural stability of a channel downstream from any proposed regulation point. Provided natural flows do not increase significantly downstream when regulation occurs, the maximum regulated flow at the dam site or river intake/outfall is defined by the minimum threshold discharge for bed material transport or bank erosion downstream from the regulation point. However, if natural flows increase rapidly downstream during periods of regulation, the maximum regulated flow at the dam site or river intake/outfall is defined by the threshold discharge for bed material transport or bank erosion where instability would first occur minus the downstream increase in base flow.

If regulation alters the frequency of flows which can transport sediment, instability will result. Erosion will take place at any point where regulation increases the frequency of flows above the threshold discharge for bed material transport and bank erosion. The degree of incision will largely be governed by the occurrence of bed rock ledges or the extent to which the bed becomes armored by coarser material. Severe degradation can promote the upstream migration of erosional activity and this will cease only after the channel has adjusted its hydraulic geometry and bed sediment size until all regulated flows are below sediment transport thresholds. Bed rock outcrops restrict headward erosion but they cannot prevent scouring further downstream. Material derived from these reaches will be deposited lower downstream at sections where maximum regulated flows are below transport thresholds. If depositional activity is persistent this may promote aggradation further upstream.

Any erosion which occurs at an intake/outfall point will promote upstream degradation unless this is balanced by aggradation during periods of abstraction. Although it is theoretically possible to maintain a dynamic stability by this process, in practice this is unlikely due to changes in channel width and plan shape during periods of erosion which cannot be reversed. By locating the intake/outfall in a section of channel containing large boulders or bedrock, or by constructing an artificial ledge across the channel it is possible to prevent erosional activity progressing upstream. However aggradation can still occur unless abstractions take place at flows below transport thresholds.

Simply by comparing regulated flows with threshold discharges for transport and erosion at a number of locations it is possible to identify which sections of channel will require maintenance and protection. While it is not currently possible to predict the new hydraulic geometry of the potentially unstable reaches for reconstruction purposes, guidance can be given on the nature of the necessary protection works or maintenance procedures to minimize the effects of instability. In alluvial sections where erosion is predicted it will be necessary to protect the channel banks because the river will tend to reduce its gradient by incision and meandering. Artificial barriers or drop structures will also need to be constructed to decrease channel slope over selected reaches. These could be designed to reduce the strength of the secondary flows which influence erosional activity. Where bedrock is exposed or where the bed will rapidly become armored by coarse material it may not be necessary to carry out any major protection or maintenance works. Sections of channel which will be subject to deposition can best be maintained by the systematic removal of sediment using earth excavators.

The methods outlined in this paper have been used to assess the effect of river regulation on the stability of the Rivers Wye, Severn and Dulas in the United Kingdom and to prescribe a regulation strategy which will preserve the natural stability of these rivers. The lack of bed material transport information in the United Kingdom precludes the use of any mathematical modeling procedures.

EFFECT OF PROPOSED DUTCH GULCH LAKE ON POPLAR CREEK

Reservoir operation will considerably modify the flow in Poplar Creek downstream from the proposed Dutch Gulch Lake. At the dam site the maximum release will be 12,590 cfs and the frequency of flows less than this value will be increased. The sediment discharge immediately below the dam site also be negligible because the trap efficiency of the reservoir will probably be 100%.

Unfortunately insufficient is known about all the governing equations for gravel-bed rivers to similate the effect of these changes on the hydraulic geometry of Poplar Creek. Equally it is not possible to identify exactly which reaches will undergo erosion or deposition as no information is available on threshold discharges for bed material transport. Ideally this information should be available for pool and riffle sections in reaches of channel which are naturally eroding, depositing, and stable. The available cross-sectional information and bed material data were insufficient to calculate these values. However, a sediment rating curve derived using the Meyer-Peter, Müller equation for a site 2.0 miles upstream from the dam and above the North Fork tributary predicts that flows of 500 cfs can transport 150 tons of bed load per day. Reference to the regulated daily flow duration curve indicates that bed material will be transported at least 20% of the time and probably as much as 50% of the time as this particular equation tends to underestimate transport rates. As this material will not be replenished erosion will take place immediately below the dam.

Qualitatively it is possible to assess the general effect of the reservoir on Poplar Creek on the basis of case studies (Kellerhals in press), geomorphological principles (Hey 1979, Schumm 1977) and regime equations (Bray, in press and Hey, in press). The amount of erosion below the dam partly depends on the rate at which the bed becomes armored by the coarser fraction of the bed material. If the banks were non-erodible the supply of sand would be limited and the bed would quickly become armored. However, as the banks are erodible there will be considerable amounts of sand available for transport and this will retard the armoring process.

Over the short time scale, less than 100 years, slight scouring will reduce the slope of the channel below the dam and increase the flow depth and bed material size. The reduction in flood flows will enable vegetation to colonize the exposed bars and this will tend to stabilize the point bars and probably promote increased bank erosion. Channel width will probably be reduced by this process. The sinuosity of the channel is likely to be increased slightly due to the reduction in channel slope and the pool/riffle spacing will also be reduced as this is controlled by the width of the channel. Erosion will continue below the dam site until releases can no longer transport bed material. The presence of bed rock outcrops would limit the degree of incision but there is no evidence for rock outcrops on Poplar Creek. Erosional processes will progress downstream in response to the progressive reduction in sediment load.

The downstream limit of erosional activity will probably be the confluence of Dry Creek, Little Dry Creek, and Poplar Creek. Deposition is likely to occur downstream from Little Dry Creek and Dry Creek due to reduced river levels in the main streams during flood events on the two tributaries. This reduction in river level could also promote erosion in the tributaries. Aggradation will probably progress upstream on Poplar Creek as material scoured from below the dam is deposited. This action will help to limit the amount of scour below the dam and also promote deposition in the tributaries. As a result of aggradation the slope and width of the channel will be increased while the depth and bed material size will be reduced. There will probably be a tendency for the channel to braid.

Simultaneously deposition will be occuring further downstream at the confluence of South Fork and Poplar Creek. Reduced flow stages on the main river could also promote erosion on South Fork.

In the longer term, over 100 years, the sediment yield of the tributaries is likely to be reduced by headward deposition. The main stream will probably begin to erode the material deposited at the tributary confluences and a new, less vigorous, scour/fill cycle will be initiated.

The projected net changes for short and long time periods are summarized in Table 1.

CONCLUSIONS

In spite of the deficiencies of the data base, particularly the lack of information on the hydraulic geometry and associated bed material at pool/riffle sections in the naturally eroding, depositing, and stable reaches, the absence of bed material transport data and the non availability of historical maps and aerial photographs, it is possible to assess the general response of Poplar Creek to the construction of Dutch Gulch Lake. Quantitative estimates of the degree and rate of channel response to regulation are dependent on the availability of more precise survey data.

Even if the requisite data were available it is doubtful whether there would have been complete agreement between the various modeling methods on the predicted outcome. Moreover there is no way in which the various modeling techniques can be assessed. This clearly identifies the need for basic information on the systematic changes in the hydraulic geometry and sedimentary characteristics of rivers affected by regulation so that existing predictive models can be evaluated or new more appropriate modeling procedures developed.

Table 1. Predicted short and long term response of Poplar Creek to construction of Dutch Gulch Lake.

	POPLAR CREEK (Dam to Little Dry Creek)		POPLAR CREEK (Downstream Dry and Little Dry Creeks)		DRY AND LITTLE DRY (Downstream Sections)	
	less than 100 years	greater than 100 years	less than 100 years	greater than 100 years	less than 100 years	greater than 100 years
Nature of Instability	E	S	D	E	E	D
Slope	-	0	+	-	-	+
Width	-	0	+	-	-	+
Depth	+	0	-	+	+	-
Bed Material Size	+	0	-	+	+	-
Pool/Riffle Spacing	-	0	BRAID	-	-	BRAID
Sinuosity	+	0		+	+	

+ increase; - decrease; 0 no significant change; D deposition; E erosion; S stable.

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A PREDICTION OF THE DOWNSTREAM RESPONSE OF POPLAR CREEK, CALIFORNIA TO THE DUTCH GULCH DAM

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INTRODUCTION

The present paper represents my effort to predict the likely hydraulic and morphologic response of Poplar Creek downstream of the proposed Dutch Gulch Dam to the extent that is allowed by the voluminous but incomplete data provided to me by the workshop organizers.

If the reader considers the use of the first person pretentious, allow me to remark that a prediction of this sort is by nature a highly personal one. "Intelligent" guessing is required in step after step in order to fill the gaps in even the most comprehensive data set. By using the first person, I hope to elucidate the thought processes of the subjective decisions necessary for this prediction.

The prediction proceeds in 11 steps outlined below.

1. Delineation of the reaches.
2. Geometric data.
3. Bed material.
4. Geometric data synthesized from hydrologic considerations.
5. Natural and project flow duration curves.
6. Water and gravel routing for natural conditions.
7. Short-term water and gravel routing for project conditions ignoring tributary degradation.
8. The short-term effect of tributary degradation.
9. Long-term changes in channel geometry.
10. Meandering and the pool-and-riffle structure.
11. Summary of predictions for "Poplar" Creek and its tributaries.

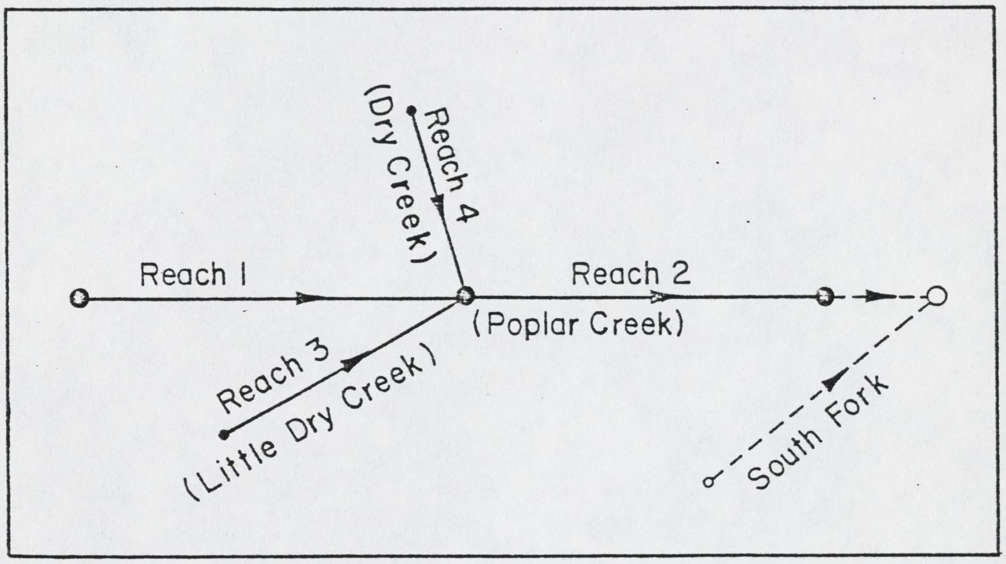

Figure 1. Definition of reaches.

DELINEATION OF THE REACHES

I considered the four reaches schematized in Figure 1. They are:

Reach 1. Poplar Creek from Dutch Gulch to just upstream of Dry Creek.

Reach 2. Poplar Creek from just upstream of Dry Creek to elevation 430 feet.

Reach 3. Little Dry Creek from the confluence with Poplar Creek to elevation 540 feet.

Reach 4. Dry Creek from the confluence with Poplar Creek to elevation 560 feet.

The elevations refer to stream elevations on the 1965 U.S. Geological Survey 1:24000 map of the Hooker, California quadrangle. The 430-foot point is about 2 km upstream of the confluence with the South Fork.

In fact, Dry Creek and Little Dry Creek join Poplar Creek at points so close together that for the purposes of the analysis I decided to proceed under the assumption that the confluences coincide at a point corresponding to the average of the two.

The reason for the above choice of reaches is as follows. Having been given practically no information about the South Fork or any projects on it, I assumed that it remains unchanged. To be on the safe side, Reach 2 was chosen so as not to include it. There are no tributaries of any consequence in Reach 1, which would be the one immediately below the dam. Reach 2 contains two tributaries of consequence; namely, Reaches 3 and 4 at its upstream end.

Both water and gravel can be routed through the system of four reaches for natural and project conditions. Down-channel reach lengths are given in Table 1.

Table 1. Down-channel reach lengths.

REACH	LENGTH (km)
1	8.26
2	6.23
3	6.13
4	4.57

MEASURED GEOMETRIC DATA

I determined overall down-channel slopes S for the four reaches by considering the elevation drop over lengths chosen to contain, but be

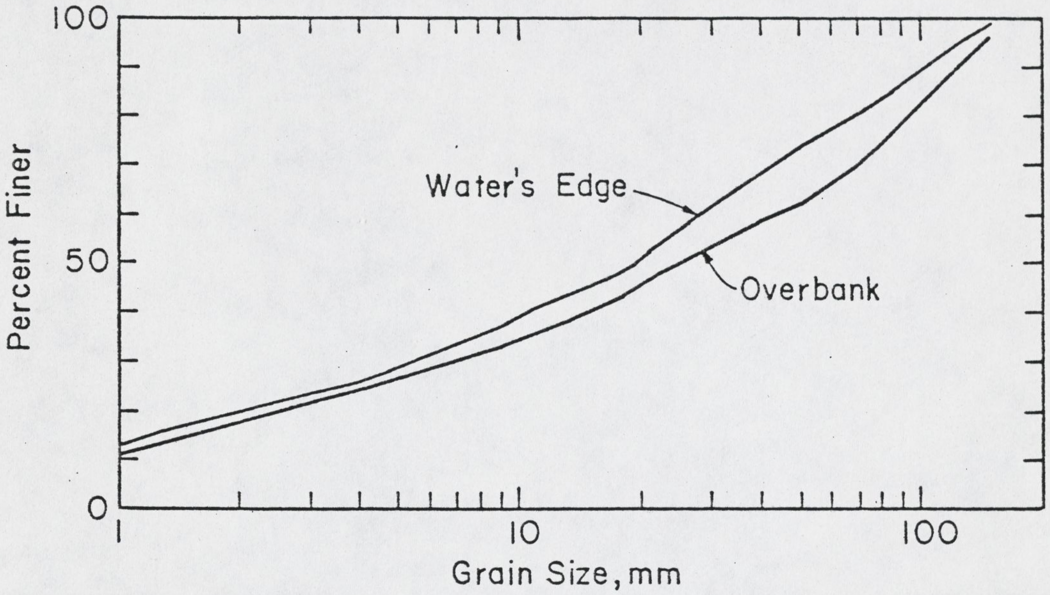

Figure 2. Grain-size distributions.

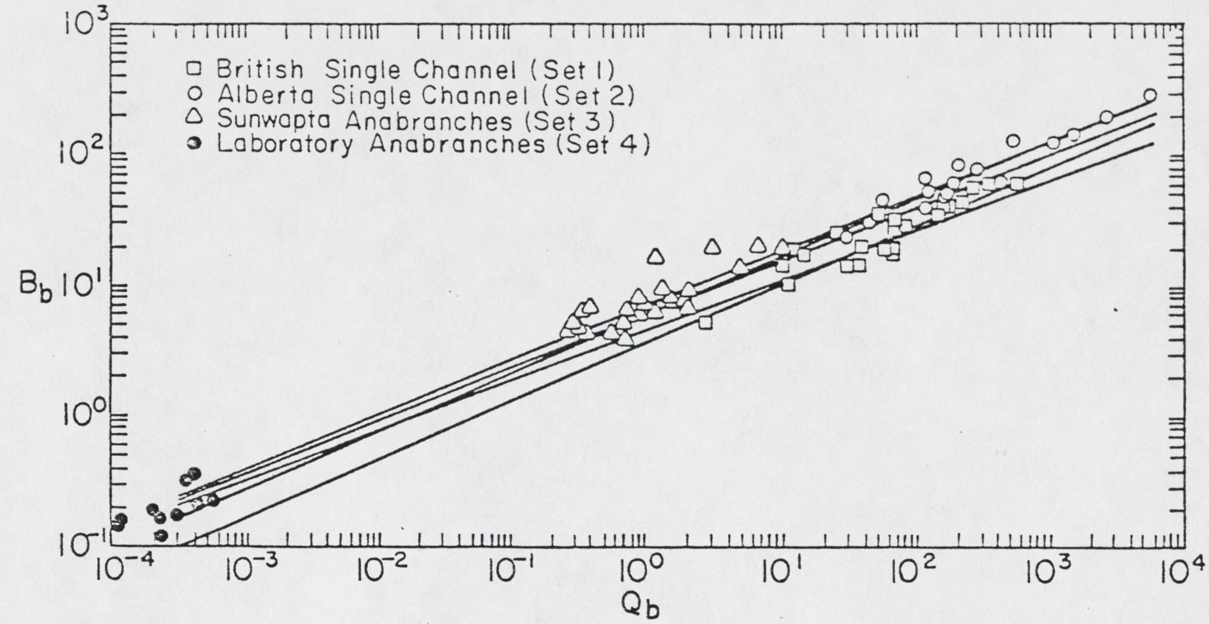

Figure 3. Width relations.

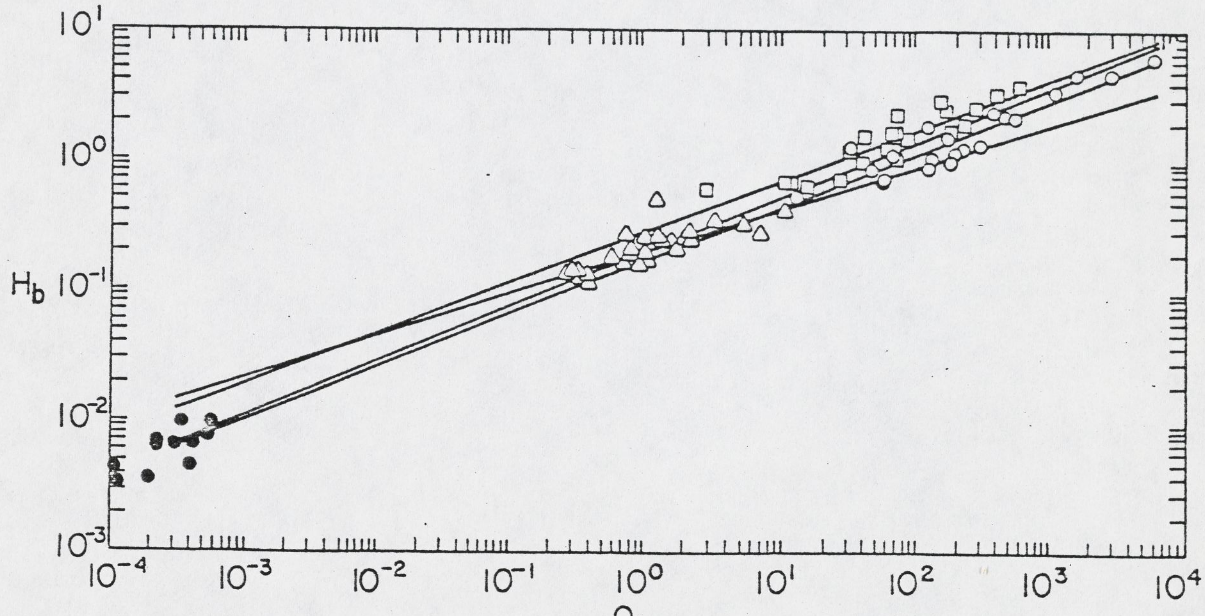

Figure 3b. Depth relations.

a little longer than, each reach. The values were read from the supplied 1:24000 topographical maps. The values are S = 0.00180, 0.00186, 0.00390, and 0.00569 for Reaches 1 to 4, respectively.

Data on channel cross-sectional geometry were supplied only for Reach 2. I determined average bankfull water-surface width B_b and cross-sectionally averaged depth H_b for the cross-sections labeled 57 to 65. The values are $B_b = 119$ m and $H_b = 2.25$ m.

Values for B_b and H_b for the other three reaches were synthesized in the fashions outlined subsequently.

BED MATERIAL

The bed material data on Poplar Creek dated August 1978 were used to obtain a representative grain size distribution. Of the seventeen samples listed therein, I could not locate samples 2F-78-3, -4, or -5 on the attached map. Of the remaining fourteen samples, seven were taken at the water's edge, and seven were from overbank. Each sample is a bulk sample of at least two sacks.

Most gravel-bed streams have a surface pavement which is two or three times coarser than the underlying subpavement. A large bulk sample taken in the submerged channel typically contains mostly subpavement, but considerable amounts of pavement. However, Parker and Klingeman (1980) have argued that large bulk samples taken on exposed bars near the water's edge provide a reasonable approximation of the subpavement of the channel proper. I used this assumption in analyzing the seven data sets from the water's edge.

The sample 2F-78-1 proved to be markedly finer than the six others, so I rejected it as being uncharacteristic. The other six samples were averaged to yield a "typical" expected subpavement distribution for Poplar Creek, including Reaches 1 and 2. The average size distribution is given in Figure 2. Subpavement D_{50} and D_{90} are seen to be about 20 and 106 mm, respectively; fines (sand) content is about twenty percent.

None of the seven overbank samples appeared to be anomalous. I averaged them to obtain a "typical" overbank sediment distribution with $D_{50} = 25$ mm, $D_{90} = 130$ mm, and eighteen percent fines content. The average overbank size distribution is also known in Figure 2.

Several relevant observations can be made here. The values of subpavement D_{50}, D_{90}, and fines content for Poplar Creek are very similar to the values for four gravel-bed streams on which extensive gravel bedload measurements have been made; namely Oak Creek, Oregon, Elbow River, Alberta, Vedder River, British Columbia, and Snake River, Idaho. Parker, Klingeman, and McLean (1980) have used this data to determine a bedload relation for field gravel-bed streams. Thus, I feel at least partially justified in applying the relation to Poplar Creek.

Also, the overbank size distribution is about the same as that of the subpavement. This suggests that vegetation and cohesive material do not act as significant controls on channel width. Recently I (Parker, 1980) determined several sets of empirical relations for bankfull hydraulic geometry. One set, using twenty-one reaches mostly from Alberta and British Columbia, Canada corresponds to gravel-bed streams with gravelly banks and little cohesion, in regions that are semiarid or only moderately humid. The width and depth relations are shown in Figure 3; they and the corresponding correlation coefficients are:

$$B_b = 5.86\ Q_b^{0.441} \qquad r^2 = 0.931 \tag{1a}$$

$$H_b = 0.188\ Q_b^{0.416} \qquad r^2 = 0.860 \tag{1b}$$

where Q_b is bankfull discharge. The units are S.I. I assumed these relations to hold with a reasonable degree of accuracy for Poplar Creek and its tributaries.

A third point concerns roughness height k in the Keulegan resistance equation; where V is flow velocity and g is gravitational acceleration,

$$\frac{V}{\sqrt{gHS}} = 2.5\ell n\ (11\frac{H}{k}) \tag{2}$$

Parker and Peterson (1980) have followed the lead of several other investigators and have provided justification for the approximation

$$k = 2D_{p90}$$

at flood stages (the only stages which normally move gravel in gravel-bed streams). The subscript p refers to pavement.

Pavement size distributions for Poplar Creek were not available. However, experience suggests to me that a bulk surficial median pavement size should be two to three times coarser than the subpavement D_{50}; i.e. in this case $D_{p50} \approx 50$ mm. However, the same experience suggests that pavement D_{p90} and subpavement D_{90} are in most cases not much different. With this in mind, I estimated $k = 0.212$ m.

Available data for Reaches 3 and 4 were at best sketchy. The only bed samples pertaining to them were hole number 5 for Little Dry Creek, with a D_{50} of 10 mm, and hole number 1 for Dry Creek, with a D_{50} of

20 mm. Under these circumstances, and considering that all four reaches receive their gravel from adjoining areas which are likely to have similar lithology and weathering, I decided to assume that subpavement D_{50} is 20 mm and roughness $k = 212$ mm for all four reaches.

GEOMETRIC DATA SYNTHESIZED FROM HYDROLOGIC CONSIDERATIONS

Equation 2 can be used to relate discharge to geometric parameters at flood stages in wide channels.

$$Q = 2.5 \sqrt{gS}\, H^{3/2} B \ln \left(11\frac{H}{k}\right) \qquad (3)$$

I used this equation to predict bankfull discharge Q_b in Reach 2, using the previously-determined values of k, H_b, B_b, and S. The predicted value of Q_b is 646 cumecs.

In order to check this value, I back-calculated Q_b from each of Equations 1a and 1b; the average of the two values determined thus is 656 cumecs. In addition, an evaluation of the flood frequency of this discharge (outlined subsequently) indicated that a peak flow of 646 cumecs corresponds to a return period of 3.6 years. A typical value for Alberta streams that are incised is about five years; in more humid regions the value drops to about two years. Thus the estimated value of Q_b for Reach 2, whether right or wrong, is at least reasonable.

The hydrologic data include monthly flows for Poplar Creek near Dutch Gulch, (i.e., Reach 1) the South Fork, and Poplar Creek near Cottonwood. Also provided are flood frequency curves for Poplar Creek near Dutch Gulch and Poplar Creek near Cottonwood. There are only four tributaries of consequence from Dutch Gulch to the gaging station at Cottonwood; they are in order downstream: Dry Creek, Little Dry Creek, South Fork, and Hooker Creek. Thus I assumed the following hydrologic algorithm.

$$Q_{DG} + Q_{DC} + Q_{LDC} + Q_{SF} + Q_{HC} = Q_C$$

Q_{DG} = discharge in Poplar Creek at Dutch Gulch (Reach 1)

Q_{DC} = discharge from Dry Creek

Q_{LDC} = discharge from Little Dry Creek

Q_{SF} = discharge from South Fork

Q_{HC} = discharge from Hooker Creek

Q_C = discharge in Poplar Creek near Cottonwood

Insofar as gravel-bed streams usually only move gravel at flood stages, I concerned myself only with high flows. The flood frequency curves for natural conditions indicate that

$$Q_{DG} = 0.556\ Q_C \tag{5}$$

at both the two- and five-year floods. The monthly flows indicate that the river is highest for the months of January, February, and March. The average natural monthly flows for these three months obey the relations

$$Q_{DG} = 0.537\ Q_C \tag{6a}$$

$$Q_{SF} = 0.262\ Q_C \tag{6b}$$

Note the good correspondence between Equations 5 and 6a. After some adjustment, I finally adopted the relations

$$Q_{DG} = 0.556\ Q_C;\ Q_{SF} = 0.271\ Q_C \tag{7}$$

for flood stages.

It is seen from Equations 4 and 7 that typically 17.3 percent of the flood discharge observed at Cottonwood must originate from Dry Creek, Little Dry Creek, and Hooker Creek. Any estimate for partitioning flood flows among them based on the data provided to me must of necessity be very crude. I thus rowed with the oars I had. I measured basin areas A_{DC}, A_{LDC}, and A_{HC} from the topographical maps provided; the map of normal annual precipitation allowed me to estimate annual precipitations P_{DC}, P_{LDC}, and P_{HC}. The values are listed in Table 2.

Table 2. Annual precipitation values.

	BASIN AREA (km^2)	ANNUAL PRECIPITATION (mm)
Dry Creek	71	740
Little Dry Creek	154	700
Hooker Creek	83	600

Now let $r_{DC} = Q_{DC}/Q_C$ be the ratio of discharge from Dry Creek to the discharge measured in Poplar Creek at high flows under natural conditions: r_{LDC} and r_{HC} are assumed to be similarly defined. Note that from Equations 4 and 7,

$$r_{DC} + r_{LDC} + r_{HC} = 0.173$$

I related the values of r to the ratios of annual volumes of water falling on each of the basins; to wit

$$r_{DC} \{ \frac{A_{DC}\ P_{DC}}{A_{DC}\ P_{DC} + A_{LDC}\ P_{LDC} + A_{HC}\ P_{HC}} \} 0.173$$

and likewise for r_{LDC} and r_{HC}.

The results of this computation are:

$$Q_{DC} = 0.0433\ Q_C \qquad (9a)$$

$$Q_{LDC} = 0.0887\ Q_C \qquad (9b)$$

$$Q_{HC} = 0.0410\ Q_C \qquad (c)$$

Now since the gaging station at Dutch Gulch is within Reach 1, it is appropriate to define $Q_{DC} = Q_1$. Likewise, one may define $Q_{LDC} = Q_3$ and $Q_{DC} = Q_4$. From Equations 7 and 9, these definitions,

$$Q_3 = 0.160\ Q_1 \qquad (10a)$$

$$Q_4 = 0.078\ Q_1 \qquad (10b)$$

By definition, the discharge in Reach 2, Q_2, is gven by the algorithm

$$Q_2 = Q_1 + Q_3 + Q_4$$

or thus

$$Q_2 = 1.238\ Q_1 \qquad (10c)$$

Equations 10 are assumed to hold for high natural flows. They involve the very drastic assumption that the tributaries are always perfectly in phase with the main stem. The total basin for Poplar Creek is not large, and both annual rainfall patterns and the rainfall pattern for the storm of January 14-18, 1974 (assumed to be fairly typical) do not suggest the tributaries to be strongly out of phase with the main stem. Dry Creek and Little Dry Creek have considerably smaller basins than Poplar Creek upstream of Dutch Gulch, and so would normally be flashier. However, even this is mitigated by the fact that the upper reaches of the Poplar Creek basin typically receive much more rainfall than the two tributary basins; the lag time for infiltration in the typically drier tributary basins may counteract their flashiness.

Now if bankfull discharge for Reach 2 is taken to be 646 cumecs, Equation 10c indicates a bankfull discharge for Reach 1 of 521 cumecs, assuming the same flood frequency for both. The flood frequency curve for Poplar Creek at Dutch Gulch indicates a return period of 3.6 years for this discharge, as was mentioned previously.

Extending the assumption of equal bankfull flood frequency to the tributaries, it follows from Equations 10a and 10b that Q_b = 83.3 cumecs for Reach 3 (Little Dry Creek) and 40.6 cumecs for Reach 4 (Dry Creek).

Data on bankfull hydraulic geometry must now be synthesized for Reaches 1, 3, and 4. Of Equations 1a and 1b, the former has the higher coefficient of correlation; I decided to use it to estimate bankfull width B_b in Reaches 3 and 4, and then to estimate bankfull depth H_b from the friction relation, Equation 3. The values thus obtained are B_b = 41 m and H_b = 1.03 m for Reach 3, and B_b = 30.0 m and H_b = 0.74 m for Reach 4.

A word of caution is in order about these values. The empirical width-discharge relation is one of the most consistent relations of river mechanics. Widths estimated from it can be expected to be fairly accurate in most cases if an accurate value of Q_b is used. However, herein Q_b itself has been estimated for the tributaries in a very approximate fashion. The subsequently-presented gravel bedload calculations are rather sensitive to variations in B_b, H_b, and Q_b. In addition, the 1:24000 topographical map of the Hooker, California quadrangle indicates that much of the valley of Reach 4 (Dry Creek) is filled with dredge tailings. It is possible that the stream channel itself is ill-defined there.

A value of B_b for Reach 1 can also be estimated from Equation 1a directly, but this would not recognize the fact that this reach is adjacent to another reach of the same stream for which B_b is known, i.e. Reach 2. It is thus useful to cast Equation 1a in the form

$$\frac{B_{b1}}{B_{b2}} = \left(\frac{Q_{b1}}{Q_{b2}}\right)^{0.441} \qquad (11)$$

so that the previously-determined value of B_{b2} has a role in determining B_{b1}. Bankfull width for Reach 1 is thus found to be approximately 108 m. (If Equation 1a were used directly, the value would be fourteen percent smaller.) Bankfull depth can then be estimated from Equation 13 as 2.12 m.

The values of B_b and H_b for Reach 1 are later adjusted slightly to facilitate gravel routing.

The measured and estimated bankfull parameters, and several others, for the four reaches under natural conditions are summarized in Table 3. L denotes the length of each reach, and B_G denotes the typical width of mobile gravel on the bed during floods sufficient to mobilize the bed. B_G has been estimated as

$$B_G = B_b - 10H_b \qquad (12)$$

based on information on the cross sections and Parker (1979).

At this point, I questioned whether or not "bankfull" is even a valid concept for Reaches 1 to 4. Many gravel rivers are incised and have little or no genetic floodplain area. Both the cross sections and the topographic maps supplied indicate that Poplar Creek does have a floodplain in Reaches 1 and 2. The topographic map suggests that Little Dry Creek has a floodplain in most of Reach 3. The status of Dry Creek in Reach 4 is, however, open to question. Its valley seems to have been filled with dredge tailings. Whether this aggradational surface acts as a "surrogate floodplain," or whether the stream has incised into the deposits, remains unclear.

Table 3. Measured and estimated bankfull parameters, and several others, under natural conditions.

	REACH 1	REACH 2	REACH 3	REACH 4
Q_b (m^3/s)	521	646	83.3	40.6 H_b
(m)	2.12*	2.25	1.03	0.74
B_b (m)	108*	119	41	30
B_G (m)	87	96	30.7	22.6
S	0.00180	0.00186	0.00390	0.00569
D_{50} (mm)	20	20	20	20
k (mm)	212	212	212	212
L (mm)	8.26	6.23	6.13	4.57

*subject to later adjustment

NATURAL AND PROJECT FLOW DURATION CURVES

The flow duration curves for both natural and project conditions at Dutch Gulch (Reach 1) were provided to me by the workshop organizers.

For a gravel routing scheme it is necessary only to consider flood flows high enough to break the pavement and mobilize the bed gravel. Parker and Klingeman (1980) have found a criterion due to Neill (1968) for bed motion in terms of pavement, namely

$$\tau_p = \frac{HS}{1.65D_{p50}} \geq 0.03$$

to take the approximate form in terms of subpavement

$$\tau^* = \frac{HS}{1.65D_{50}} \geq 0.0742 \qquad (13)$$

for many paved gravel-bed streams. (The implication is that D_{p50}/D_{50} is roughly 2.5.)

I used criterion (13), Equation 3, and an at-a-station relation for water-surface width as a function of discharge in gravel-bed streams due to Parker and Peterson (1980) to estimate values of H and Q required for breaking the pavement. The at-a-station relation is

$$\frac{B}{B_b} = \left(\frac{Q}{Q_b}\right)^{0.16} \qquad (14)$$

The value of Q so determined for each reach was reduced to an equivalent discharge Q_{e1} in Reach 1 via Equation 10. A frequency of exceedance was then determined from the natural flow frequency curve at Dutch Gulch, and converted to a number of days per year for which each reach could be expected to have a mobile gravel bed. The results are given in Table 4.

Table 4. Conditions for bed gravel mobilization.

	REACH 1	REACH 2	REACH 3	REACH 4
H (m)	1.36	1.32	0.63	0.43
Q (m^3/s)	210	215	29.5	13.0
Q_{el} (m^3/s)	210	174	184	167
days exceeded per year	1.43	2.31	2.02	2.56

These values suggest that when applying the Dutch Gulch flow duration curve for natural conditions to gravel routing, flows less than 5912 cfs (142 cumecs) need not be considered. This corresponds to between a 1.1 and 1.2 year peak flood in Reach 1.

The portion of the Dutch Gulch flow duration curve relevant to gravel routing can then be converted to a histogram of discharge intervals $i = 1, 2, 3, \ldots$, typical discharge Q_i (geometric mean) on each interval, and the fraction of time per year p_i at which discharge falls in the interval. This is given for Dutch Gulch (Reach 1) for both natural and project conditions in Table 5: $(Q_i)_N$ refers to natural values, and $(Q_i)_p$ to project values in cumecs.

Table 5. Discharge intervals, typical discharge, and fraction of time per year discharge fall in that interval for natural and project conditions.

INTERVAL NO.	p_i	$(Q_i)_N$	$(Q_i)_p$
1	0.0038	159	141
2	0.0028	200	192
3	0.0016	252	244
4	0.0009	318	277
5	0.0003	400	307
6	0.0001	503	328
7	0.0001	634	339
8	0.0001	798	350

Thus Table 5 constitutes the natural and project flow frequency relations for Reach 1. In accordance with the assumption that Reaches 1-4 are all perfectly in phase under natural conditions, the corresponding natural relations for Reaches 2, 3, and 4 can be obtained from Equation 10 by multiplying $(Q_i)_N$ by 1.238, 0.160, and 0.078, respectively, without altering the corresponding value of p_i.

The project flow frequency relations for Reaches 3 and 4 can be taken to be approximately the same as the natural ones, as the only effects of a dam at Dutch Gulch on these tributaries would be backwater effects due to lowered baseline. The project relation for Reach 2 is rather more difficult to synthesize.

In the absence of any other guidelines, I made a sweeping assumption that I know is often erroneous. I assumed that the dam is operated only so as to chop off the peaks of flood flows more or less uniformly, the water thus stored being released at low flow or lost to evaporation or use. If this is the case, then the system of Reaches 1-4 are approximately in phase even under project conditions.

Before proceeding on this assumption, it may help to analyze how it might lead to error. Suppose the dam is operated so as to completely eliminate rather than just lower, say, spring snowmelt floods. In the spring flooding, Reaches 3 and 4 flow into a main stem that is not in flood. In this case, the tributary baseline is much lower than if flood peaks had simply been lowered. Tributary degradation and head-cutting should occur in either case, but these processes would be much more severe when the main stem and tributaries are significantly out of phase.

Proceeding ahead boldly or foolishly as the case may be, perfect phasing under project conditions allows one to write

$$(Q_2)_P = (Q_1)_P + (Q_3)_N + (Q_4)_N = (Q_1)_P) + 0.238\ (Q_1)_N$$

where the subscripts 1, 2, 3, and 4 refer to Reaches 1-4, N and P stand for natural and project, and Equation 10 have been used. The project flow frequency relation for Reach 2 is then found from Table 5 by replacing $(Q_1)_N$ with $(Q_1)_P) + 0.238\ (Q_1)_N$, but leaving p_i unaltered.

WATER AND GRAVEL ROUTING FOR NATURAL CONDITIONS

The two basic tools for water and sediment routing are a resistance relation and a sediment transport relation. Herein Equation 3 is used for a resistance relation. The selection of a sediment transport relation, however, merits more care. Parker, Klingeman, and McLean (1980) have determined an empirical relation for bedload in paved gravel-bed streams based solely on field data. The relation is

$$W^* = 0.0025 \exp\{14.2\ (\Phi-1) - 9.28\ (\Phi-1)^2\} \qquad (15a)$$

where W^* is a dimensionless bedload and ϕ is a measure of relative stress;

$$W^* = \frac{Rq_B}{\sqrt{g}\,(HS)^{3/2}}$$

$$\Phi = \frac{\tau^*}{\tau_r}$$

In the above relations $\tau^* = HS/RD_{50}$ is a Shields stress based on subpavement D_{50}, τ_r is a reference Shields stress equal to 0.0876 for field streams, q_B is volumetric bedload per unit width of bed gravel, and R is submerged sediment specific gravity.

Equation 15 is shown in Figure 4, along with field data used to determine it. Among the field streams listed on that figure, the Vedder River, British Columbia is quite similar to Poplar Creek. D_{50} is about 19 mm, D_{p50} is about 44 mm, D_{p90} is about 90 mm, and the subpavement contains about sixteen percent sand. S is near 0.00195, although it is affected by backwater from the Fraser River to a certain extent, and the ranges of width, depth, and discharge at which bedload has been measured are respectively, 85 ~ 90 m, 1.34 ~ 1.60 m, and 216 ~ 370 cumecs. In the context of computing bedload in Poplar Creek and its tributaries, this lends a glimmer of hope to an otherwise futile task.

In fact, Equation 15a is valid only for $0.95 < \phi < 1.65$. For $\phi \geq 1.65$, the extension

$$W^* = 11.2\left(1 - \frac{0.821}{\Phi}\right)^{4/5} \tag{15b}$$

may be used. For $\phi < 0.95$ gravel loads are so small that W^* can be set equal to zero in a calculation of annual gravel yield.

It must be understood, however, that Equation 15 cannot predict total bedload in paved gravel-bed streams. Implicit in its incorporation of only a subpavement median grain size to describe grain size distribution is the assumption that the size distribution of the annual yield of bedload is similar to that of the bed material. This is in fact the case in many gravel-bed streams. Other such streams, however, may transport considerable quantities of sand as bedload over a gravel bed, so that the content of sand in the bedload far exceeds its bed content. The quantity of sand moving at any given time is a function of supply from outside sources. Thus sand moves through the stream without increasing sand content in the bed, and acts very much like wash load. As long as the bed material remains essentially a gravel matrix containing not more than about twenty-five percent sand in its pores (i.e. not exceeding the porosity of the gravel matrix), this and "throughput" load plays only a negligible role in the process of slow aggradation or degradation; thus the use of Equation 15, which neglects it, is justified.

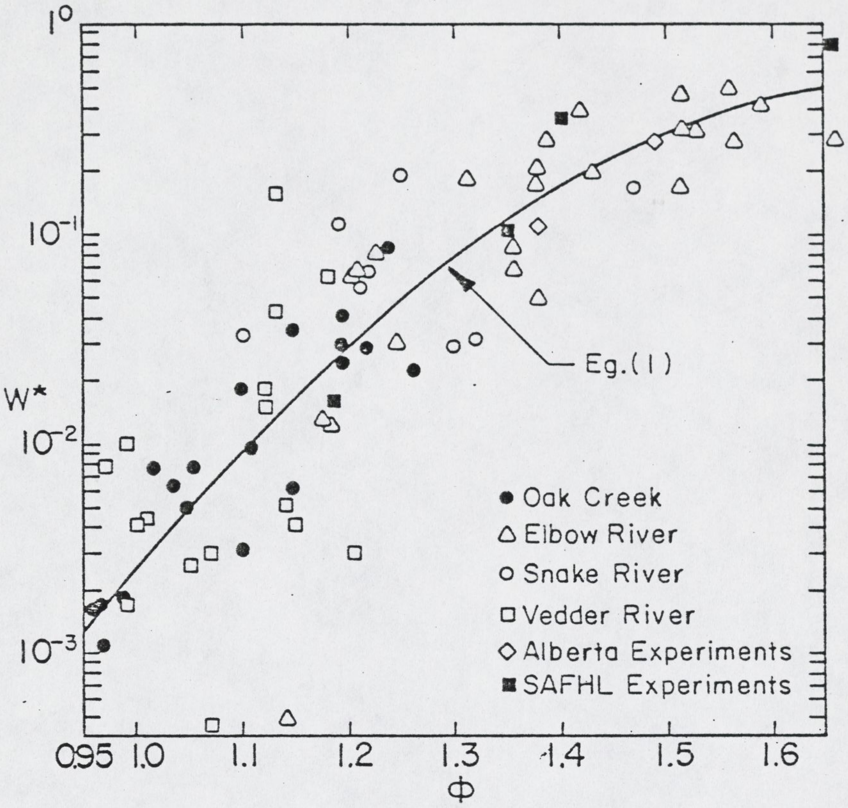

Figure 4. Gravel transport relation.

There is one case, however, where it would appear that throughput sand can be incorporated in large quantities in the bed, namely, rapid deltaic aggradation at, e.g., the mouth of a tributary. The author has observed this in pilot laboratory experiments at the University of Alberta, and Milhous (1980) reports several field occurrences.

Let M_{Ni} i = 1, 2, 3, 4 denote this mean annual yield of gravel from Reaches 1 to 4, in metric tons, based on the natural flow frequency curve. Assuming that the stream system is in grade, it follows from the definitions in Figure 1 that

$$M_{N2} - (M_{N1} + M_{N4} + M_{N3}) = 0 \tag{16}$$

In fact, there are enough vagaries in a natural system and uncertainties in such simple equations as Equations 3 and 15 so that predictions based on them rarely satisfy Equation 16 exactly. However, a sediment routing that does not predict graded conditions when conditions actually are in grade can hardly be expected to predict stream response to imposed changes accurately. I resolved the problem by "zeroing" the system. Herein this is accomplished by making slight changes in bankfull width of one of the reaches until Equation 16 is satisfied.

The calculation of annual gravel yield is performed as follows. Consider the ith reach at the jth discharge range of its flow duration curve, i.e. at discharge Q_{ij}. Width at this discharge is calculated from Equation 14 and depth from Equation 3. The only exception is that for which Q_{ij} exceeds Q_{bi}, the bankfull discharge. In this case, I made the facile assumption of infinite floodplain storage, so that "effective" depth and width are never allowed to exceed their bankfull values. Volumetric bedload per unit width of bed gravel $(q_B)_{ij}$ is calculated from Equation 15. The total annual mass yield M_i is then obtained from an appropriate summation in j:

$$M_i = 8.36 \times 10^7 \, B_{Gi} \sum_j (qB)_{ij} P_{ij} \tag{17}$$

(The factor 3.15×10^7 converts seconds to years; a specific gravity of 2.65 is assumed for the gravel.)

Annual yields calculated in this fashion before zeroing are shown in Table 6. It is seen therein that

$$M_{N2} - (M_{N1} + M_{N4} + M_{N3}) = 97.0 \text{ tons/year}$$

providing a measure of the deviation from Equation 16. Trial-and-error adjustment of the bankfull width of either Reach 1 or Reach 2 could be performed in order to insure that the terms on the left-hand-side of Equation 16 equal zero. However, it was obvious to me that any adjustment should be done on Reach 1; the value of B_b for it was synthesized, whereas the value for Reach 2 was measured.

The results of such an adjustment for Reach 1 are B_b = 97 m and H_b = 2.26 m (calculated via Equation 3); this amounts to a ten percent reduction in bankfull width. The zeroed value of M_{N1} is shown in Table 6.

Table 6. Annual yields calculated before and after zeroing.

REACH	M_{Ni} (metric tons/year)
1 before zeroing	107.2
1 after zeroing	206.2
2	372.3
3	75.2
4	92.9

Equation 16 is seen to be satisfied within one percent. The low yields of Table 6 are, in my experience, not unusual for gravel-bed streams with self-formed gravel banks.

SHORT-TERM WATER AND GRAVEL ROUTING FOR PROJECT CONDITIONS IGNORING TRIBUTARY DEGRADATION

Water depths and gravel yields may now similarly be calculated for project conditions using the flow duration curves developed in Section 5 and the zeroed values of B_b, H_b, and B_G for Reach 1. Herein this is done under the hypothesis (later found to be wrong) that gravel yields as well as water yields remain unaltered in the tributaries. That is, project yields M_{P3} and M_{P4} are assumed to equal, respectively, M_{N3} and M_{N4}.

Project gravel yields are shown in Table 7.

Table 7. Project gravel yields.

REACH	M_{P_i} (metric tons/year)	Percent of Natural Value
1	26.5	13
2	104.9	51
3	75.2	100
4	92.9	100

The predicted values apply for the short term (first few years).

It is seen that the effect of the dam on Reach 1 is profound; annual gravel yield which was not large under natural conditions has been reduced to only a small fraction of that. Although a detailed calculation using the method of Parker and Klingeman (1980) was not performed, the values of ϕ associated with project conditions in Equation 15 are small enough to indicate that the gravel load consists mostly of the finer grains available in the pavement, so that the pavement coarsens into an armor, and Reach 1 tends toward static equilibrium.

The coarsened surficial layer acts to protect the substrate from modification. Thus no immediate change in subpavement structure should occur. Indeed, the only long-term modification likely to occur is the collection of fine material and organic debris from local sources in the substrate pores, as flows adequate to "flush" the bed are not likely to occur.

In Table 7, Reach 2 is also seen to have a lowered ability to move sediment under project conditions. The effect of the project is not so great due to the unaltered water supplies from the tributaries. On the other hand, the tributaries are feeding in sediment at an unaltered rate. The result is deposition of sediment at the upstream end of Reach 2 as the main stem is unable to move the contributions from the tributaries. The deposition rate is

$$M_{P1} + M_{P4} + M_{P3} - M_{P2} = 89.7 \text{ tons/year} \quad (18)$$

Initially this should occur as a deltaic deposit at the mouths of the tributaries. Later, it is shown that this value vastly underestimates the short-term deposition in Reach 2. However, it is seen that gravel continues to move through Reach 2 fairly actively. Except in the immediate vicinity of deltaic deposits, where fines may be trapped, both gravel payment and subpavement should remain relatively unmodified in structure, implying a healthy substrate for fish.

Short-term degradation and aggradation rates can be estimated by the equation of conservation of bed sediment, where p is bed porosity, z is bed elevation, t is time, and x is a down-channel parameter,

$$\frac{\partial z}{\partial t} = \frac{1}{1-p} \frac{\partial q_B}{\partial x} \tag{19}$$

Cast in a discrete form appropriate for the present calculation, it takes the form

$$\Delta\bar{z} = \frac{1}{(1-p)B_G L} (M_{IN} - M_{OUT}) \frac{1}{2.65} \tag{20}$$

where Δz denotes the change in mean bed elevation on a reach in meters in one year and M_{IN} and M_{OUT} are annual gravel transport rates into and out of the reach in tons.

The computed values of Δz for Reaches 1 and 2 are exceedingly small, being -2.5×10^{-2} mm for the former and $+8.7 \times 10^{-2}$ mm for the latter (the minus sign indicates degradation); a value of p of 0.35 has been assumed. Part of the reason for the smallness of the values may be the long extent of the reaches over which they are computed; i.e. the grid may be too coarse. However, even if the degradation rate in Reach 1 is actually one hundred times larger, the implication is unaltered; flows are reduced so much in this reach that it very quickly reaches a state hardly removed from static stability. The short-term potential for degradation here is exceedingly small.

The small aggradation rate predicted in Reach 2 is, however, probably very erroneous. The source of the error is in the assumption $M_{P3} = M_{N3}$ and $M_{P4} = M_{N4}$ for the tributaries. Controlled discharge releases from the dam imply lower water surface elevation in Reach 2 during floods. This implies an immediately lowered flood baseline for both of the tributaries as soon as the project is put into operation. The only way the tributaries can respond to this is by degrading their bed. Degradation should work its way upstream; gravel delivery rates to the main stem should temporarily (several years or more) increase, and much more deposition should occur in Reach 2 than that indicated by Equation 18.

The lowered baseline is illustrated in Figure 5 in terms of a probability of exceedance of given depth values (based on the flow duration curve) for natural and project conditions.

It is perhaps of value to note that the qualitative predictions that I have made herein are in agreement with the field observations of Kellerhals and Gill (1973) on the Peace River and its tributaries downstream of the W.A.C. Bennett Dam, British Columbia.

THE SHORT-TERM EFFECT OF TRIBUTARY DEGRADATION

While it is not difficult to reach the conclusion that Dry Creek and Little Dry Creek will be subject to degradation due to lowered baseline during flood, prediction of the degradation and the associated yields of gravel is a different matter.

I have attempted to obtain simple results by means of a crude numerical model along the following lines.

a. A "dominant discharge" Q_d was evaluated for each tributary; it is defined such that if continued constantly for the portion of the year for which $\phi \geq 0.95$ (i.e., gravel load is not vanishing), it would transport the natural annual gravel load. The fraction of the year for which $\phi \geq 0.95$ is 0.0031 for both tributaries. A value $Q_d = 59.7$ cumecs was found for Reach 3, and 28.8 cumecs for Reach 4. These correspond to discharges of 373 and 369 cumecs, respectively, in Reach 1 at the same exceedance probability of the flow duration curve, via Equation 10. A good average, then, is 371 cumecs on Reach 1, or via Equation 10, 459 cumecs on Reach 2. These discharges have an annual probability of exceedance of 0.000547, which is essentially identical to that of the dominant discharges in the tributaries. The concept of a yield-defined dominant discharge is introduced so that a degradation calculation can be performed under steady flow conditions that are in some way equivalent to a typical yearly hydrograph.

b. The depth in Reach 2 with a natural probability of exceedance of 0.000547 (i.e., the depth at 459 cumecs) is 1.90 m. The depth with the same probability of exceedance in the same reach under project conditions is 1.74 m (at a discharge of 386 cumecs). Thus a drop in baseline at "dominant" conditions of 0.16 m is realized.

c. This drop is realized in the short term in terms of a drop in main-stem water surface level at the tributary mouth. A proper calculation of degradation thus requires backwater curves at each step. To avoid this in a simple calculation, I replaced decreased water surface elevation at the mouth with a step on the bed consisting of an initial drop of 0.16 m spread over 20 m from the tributary mouth upstream. I then assumed that normal depth calculated from Equation 3 is realized everywhere and at all times in the tributaries.

d. Each tributary was assumed to have the constant bankfull geometries listed in Table 3 from mouth (except for the step)

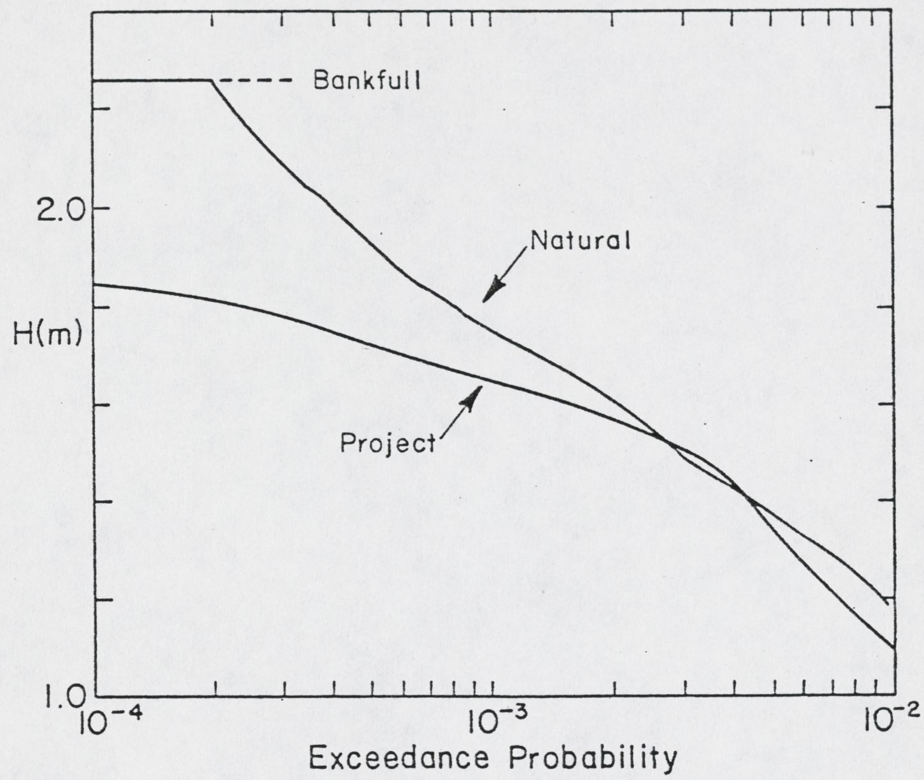

Figure 5. Depth exceedance curves, Reach 2.

to a point 2500 m upstream which was assumed to be far enough upstream not to be affected by degradation in the short term. Initial bed profiles are shown in Figure 6. "Dominant discharge" was then imposed continuously on each tributary, and degradation was calculated by means of a numerical solution to Equation 19, with the aid of Equations 3, 14, and 15. One year of real time was assumed to pass for each period of 0.0031 years for which the numerical calculation was performed. Programming was done with the aid of the University of Alberta Amdahl computer.

The bed profiles of the tributaries after two years are shown in Figure 6. It can be seen that 16 cm is gradually working its way upstream, and that considerable potential for degradation remains after two years.

In Figure 7 the cumulative sediment yield from each tributary is plotted versus time. After one year Little Dry Creek is seen to put 2550 tons of gravel into Reach 2, and Dry Creek yields 1670 tons. These values are, respectively, 34 and 18 times the annual natural yields.

These values may represent overestimations in that any tendency to armor and stabilize is not accounted for. On the other hand, the implicit assumption of perfect phasing tends to underestimate the baseline drop, and thus the degradation and sediment yields.

The aggradation rate for Reach 2 for the first year of project conditions can be computed from Equation 20 and these new gravel infeeds. The calculated value of Δz is +4.0 mm/year, or about 46 times the value obtained by ignoring tributary degradation. However, this represents only an average aggradation rate over the entire reach. Initially this aggradation should take the form of large, rapidly-building bars localized downstream of the mouths of the tributaries. It is these bars that have the most potential to capture fines, and thus become unsuitable for spawning. Downstream of these bars, the aggradation should be gradual, so that fines can be washed out; thus most of Reach 2 would likely remain suitable for spawning.

It should be noted that the tributary degradation calculations have been performed under the unverified assumption that no controls such as bedrock outcrops exist in the reaches under question.

LONG-TERM CHANGES IN CHANNEL GEOMETRY

The long-term modification of Poplar Creek as it attempts to find a new equilibrium can be surmised in terms of a stable Reach 1 and tributary degradation that has run its course.

Since flood discharges have been lowered in Reaches 1 and 2, it makes sense to assume that the channel will respond by narrowing and losing capacity via vegetation growth and collection of fine material from local sources. This reduction in width can be estimated from Equation 1a if some kind of "surrogate" bankfull discharge for project

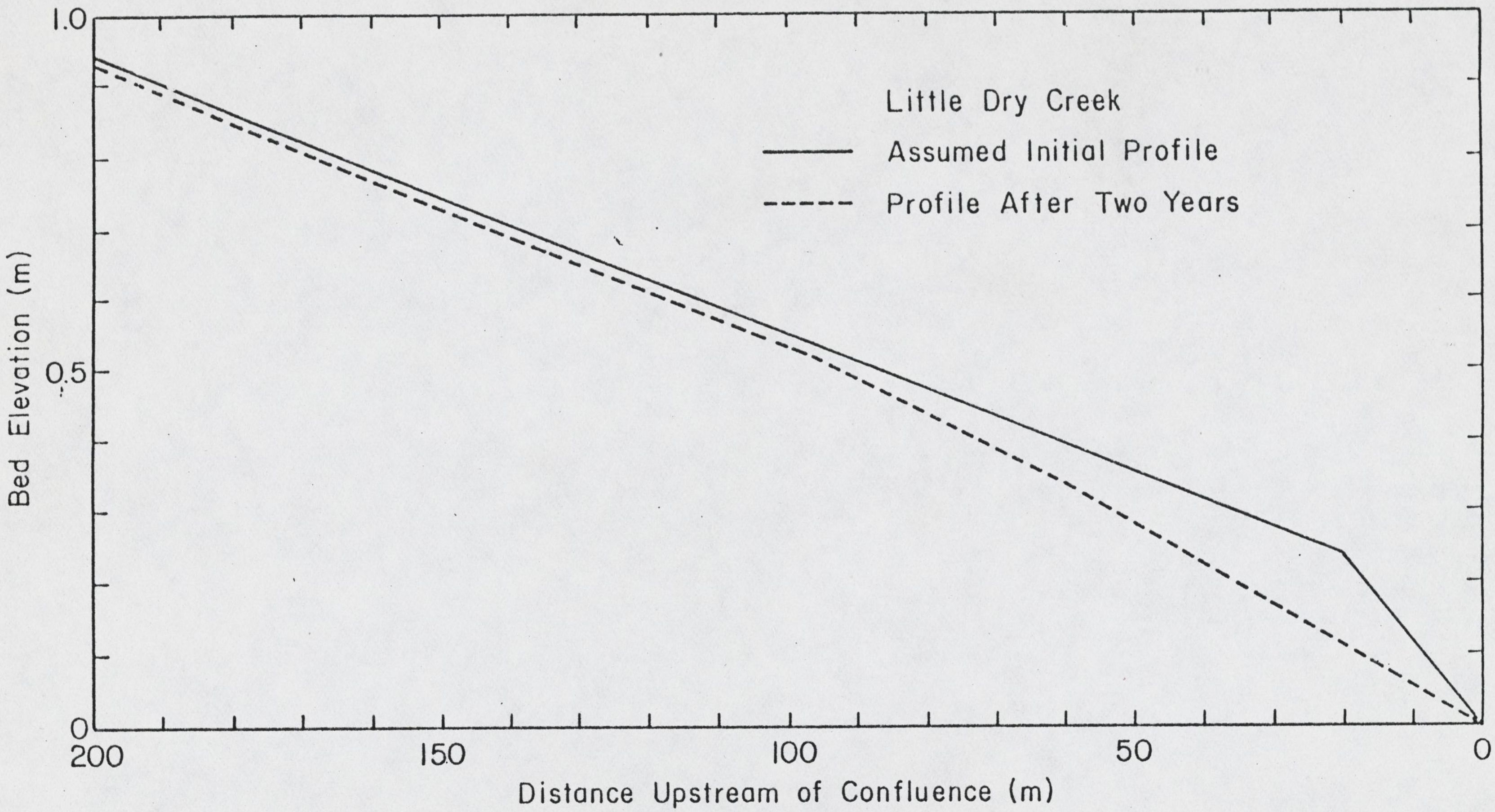

Figure 6a. Initial bed profiles.

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145

Parker 22

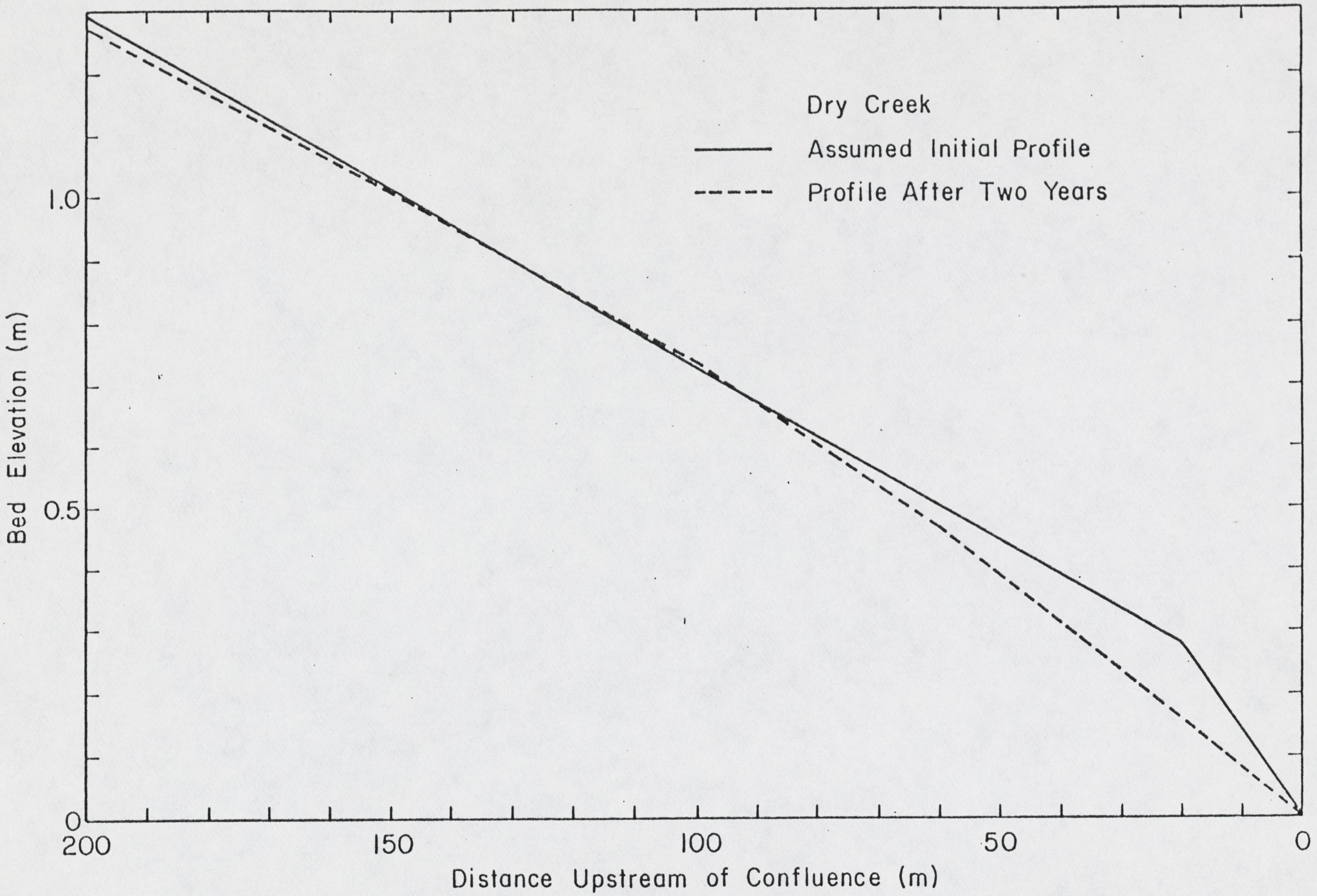

Figure 6b. Bed profiles after two years.

conditions can be estimated. I did this by calculating discharges which under project conditions have the same exceedance probability as bankfull discharge into a true bankfull discharge. Before this happens, width at the "surrogate" bankfull discharge can be estimated from Equation 14, yielding values of 90 m for Reach 1 and 112 m for Reach 2.

After the adjustment takes place, the eventual bankfull width can be estimated from Equation 1a cast in the form

$$\frac{B_{bf}}{B_{bi}} = \left(\frac{Q_{bf}}{Q_{bi}}\right)^{0.441}$$

where i denotes initial (preproject) and f denotes final values. The values so predicted are 79 m for Reach 1 and 102 m for Reach 2. Thus, a noticeable contraction in bankfull width is predicted. A contraction of this order will likely occur in Reach 2 eventually, as it will still be morphologically active in the long term. A contraction is also likely to occur in Reach 1 due to debris deposits and vegetation encroachment. Whether it can be predicted accurately from Equation 1a, however, is problematic in that asymptotically the reach should be rendered morphologically dead. Indeed, if width maintenance is heavily dependent on the availability of fines for deposition, channel widening can actually occur downstream of a dam (Einstein 1972). However, this is not likely in the case of Poplar Creek, with its gravelly banks.

Reach 1 should reach stability very slowly by a combination of coarsening and degradation; channel narrowing should abet this process somewhat. Parker (e.g., 1980a) has observed degradation and transition from pavement to stable armor in the laboratory; preliminary results suggest that final armor median size might be about 1.3 times the natural pavement D_{p50}, or about 65 mm. Assuming that armor D_{90} is twice the armor D_{50} and roughness height k is twice the armor D_{90}, and employing the Neill criterion for stability, Equation 3, and an assumed value of bankfull width of 79 m, a final stable slope of 0.00153 can be calculated for Reach 1.

In treating Reach 2, I assumed that eventually tributary degradation would run its coarse, and annual tributary gravel yields would return to their natural values in Table 7. With no gravel contributed from the stable Reach 1, then, Reach 2 must convey 168.1 metric tons per year through a channel with an estimated bankfull width of 102 m. A routing using the project flow histogram indicates that channel slope must be equal to 0.00189 for this to happen, assuming no change in gravel composition.

The implication here is that the short-term aggradation of Reach 2 will be followed by a slow, long-term degradation driven by a return of tributary yields to their former values and channel narrowing. The final channel of Reach 2 will still be active and fit for spawning.

Unless corrective measures are taken to clear debris from Reach 1 by, for example, the release of appropriately high flows from the dam, it may eventually become unfit for spawning.

MEANDERING AND THE POOL-AND-RIFFLE STRUCTURE

Kinoshita (1957) has classified free meander patterns according to their sinuousity. Low-sinuosity channels usually have two pools, bars, and riffles per bend wavelength; that is, meander bend wavelength corresponds with the wavelength of the pool-and-riffle pattern. Tortuous channels may have as many as six pools per bend.

Typical meandering gravel-bed streams, including Poplar Creek, are of low sinuosity. Where the meander pattern is free, then, coincidence of the meander pattern and the pool-and-riffle pattern may be assumed.

In much of Reach 1, Poplar Creek impinges on a steep cliff, and cannot be said to be completely free. However, the upstream half of Reach 2 shows a well-defined succession of five alternate bars about which the channel displays meandering of low sinuosity. Typical meandering gravel-bed streams, including Poplar Creek, are of low sinuosity. I determined an average linear meander wavelength of 1410 m in this portion.

I compared this value with the predictions from two formulas, the Anderson formula and the second form of the modified Anderson formula (Parker and Anderson, 1976). They take the forms

$$\lambda_A = 72F^{\frac{1}{2}} \sqrt{BH} \qquad (21a)$$

$$\lambda_{MA} = \frac{1}{a} 2\sqrt{\pi}\ F\ S^{-\frac{1}{2}}\ \sqrt{BH} \qquad (21b)$$

respectively; lambda denotes wavelength, and $a = 0.707$ in the modified Anderson formula based on data. Both of these formulas appear to work well for both laboratory alternate bars and field bars and bends of low sinuousity. This is illustrated for the modified Anderson formula in Figure 8. I employed Equation 21 in conjunction with bankfull parameters. Predicted wavelengths under natural conditions are summarized in Table 8; λ_{OBS} denotes the observed value.

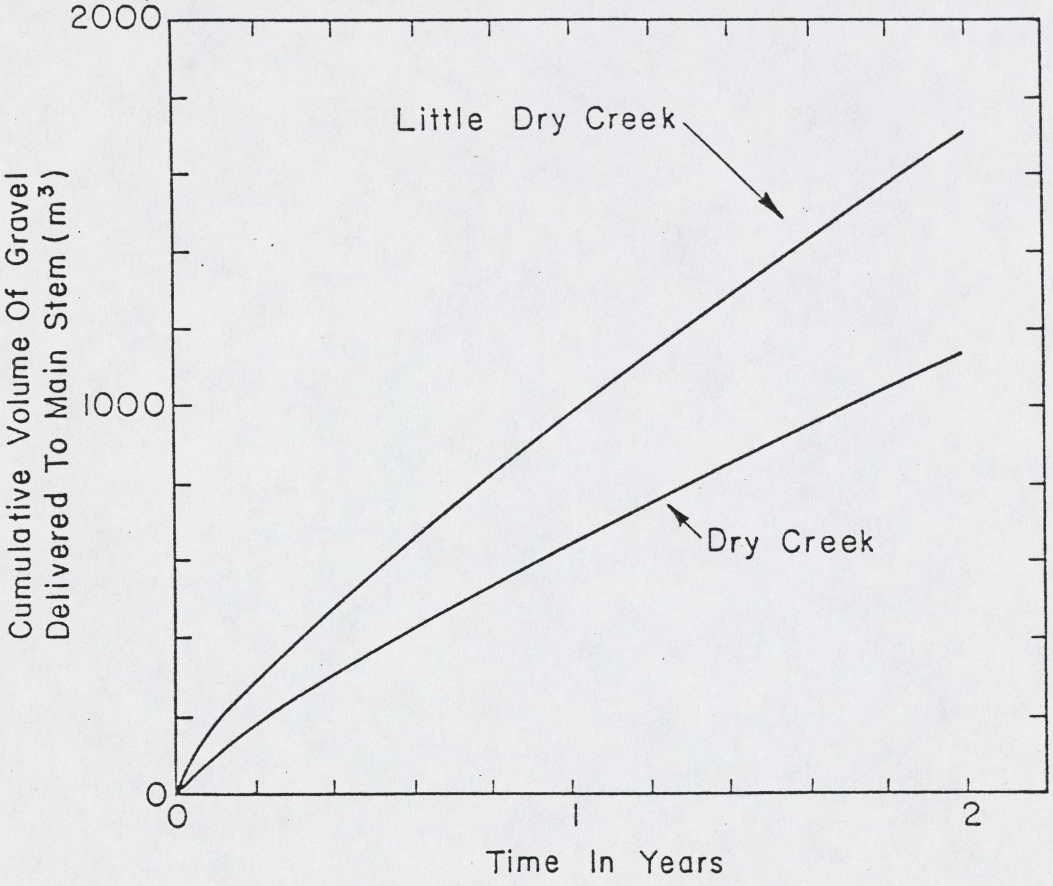

Figure 7. Gravel supply from tributaries.

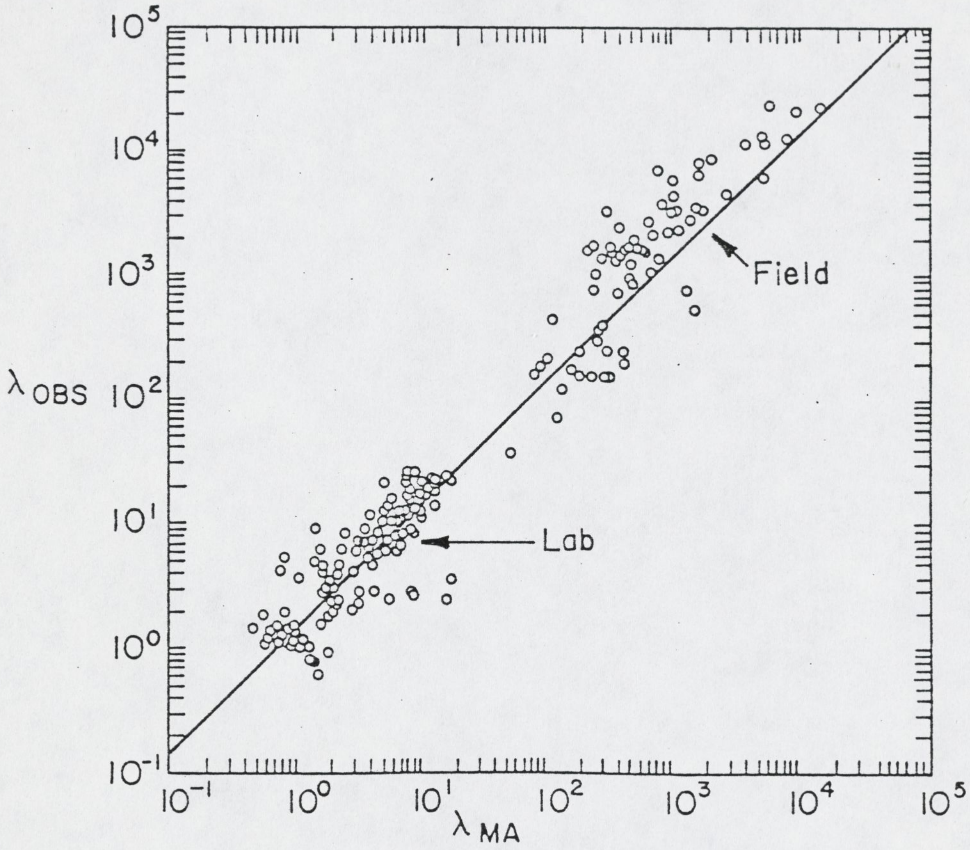

Figure 8. Relation for meander wavelength.

Table 8. Predicted wavelengths under natural conditions.

	REACH 1	REACH 2
λ_{OBS} (m)	-	1410
λ_{A} (m)	758	844
λ_{MA} (m)	884	977

The values predicted from either Equation 21a or 21b are on the small side in the case of Reach 2, but not reasonably so. Equation 21b is a little better, predicting a value that is 31 percent lower than the observed value.

I then used Equation 21 to predict meander wavelength to which the stream will tend for short-term project conditions immediately after the dam is put in operation, using the "surrogate" bankfull discharges defined previously and the assumption that channel contraction had not yet occurred. In addition, a calculation was performed for the long-term channel geometry in Reach 2 after contraction has occurred. This was not done for Reach 1, as a long-term state of zero mobility is incapable of determining its own meander pattern. Percent changes about the predicted values under natural conditions are also shown below in Table 9.

Table 9. Percent changes about the predicted values under normal natural conditions.

	λ_{A}	Percent Reduction	λ_{MA}	Percent Reduction
Reach 1 short-term	637	16	726	18
Reach 2 short-term	739	12	843	14
Reach 2 long-term	729	14	830	15

The results indicate that both Reaches 1 and 2 will initially begin to reduce their meander lengths. The process is unlikely to be very effective in the case of Reach 1 due to the near-vanishing transport rate and the control exerted by the cliffs on the south bank. Reach 2 should be able to maintain, in its final state, a meander pattern that is perhaps fifteen percent shorter in wavelength than that observed presently.

The adjustment in Reach 2 should take at least five to ten years, and would likely be disrupted at the upstream end by bars building out from the tributaries. However, the amount of adjustment is not large enough to suggest massive instabilities throughout the entire reach during adjustment.

SUMMARY OF PREDICTIONS FOR "POPLAR" CREEK AND ITS TRIBUTARIES.

The reach of Poplar Creek from the dam to just upstream of Dry Creek (Reach 1) will be almost immediately rendered incapable of moving much gravel by the project. It has negliglbe water and gravel infeed from tributaries. The gravel that moves is likely to be on the fine side. The low transport rates of gravel (gradually declining from about one tenth of the natural rate) imply extremely slow degradation, with a gradual coarsening of the pavement. After a very long time the bed slope might decrease by a maximum of fifteen percent, accompanied by perhaps a thirty percent coarsening of the surficial material. The maximum potential for degradation is roughly two meters for the reach, but it may take hundreds of years to realize this, and it may never be realized at all if the width in the reach does not contract.

A conventional formula for hydraulic geometry of active gravel streams suggests that if the reach is able to contract and form a new, smaller bankfull channel, bankfull width would be reduced by roughly twenty percent. Some reduction in width can be expected even for this essentially inactive channel (after control) due to vegetation encroachment.

The near-vanishing transport rates also suggest that the substrate will be locked into place. It will suffer only very minor modification due to bedload transport, as most of the coarsening will occur on the surface. However, locally-derived fine sand, silt, clay, and organic debris will likely collect in the substrate in increasing quantities under the proposed project flow duration curve, as no mechanism would exist to clean it.

Some cementing of the substrate is also possible. These effects could be avoided or mitigated by modifying the dam operation to allow for occasional short, large releases.

In any event, these processes which act to degrade the substrate of Reach 1 are slow, so that if it is presently suitable for spawning, it should remain so for at least the first few years after commencement of dam operation.

The reach of Poplar Creek from just upstream of Dry Creek to a point upstream of the confluence with the South Fork (Reach 2) presents a different situation. Lowered project discharges should roughly have the capacity of this reach to move gravel. The implied lowered baseline due to flow control should also induce degradation in Dry and Little Dry Creeks, with consequent rapid deltaic deposition at the upstream end of the reach, and initial slower aggradation of the reach as a whole.

Computed gravel infeed rates from the tributaries as they degrade for the first year or two are on the order of 25 times their natural feed rates. The resulting local bars at the upstream end of the reach may thus initially incorporate considerable sand (if it is available) and have substrates unsuitable for spawning. As the aggradation slowly spreads over the entire reach, it is likely that excess fines would be washed out. Most of the reach should maintain a substrate suitble for spawning during this process.

On the order of 10 to 15 cm of degradation should work its way up the tributaries. The amount will be more if tributaries and main stem are far out of phase under project conditions. The tributaries may respond by initially coarsening their bed surfaces; if they are used for spawning this may have a deleterious effect.

In the long-term tributary degradation will eventually run its course. Tributary bed structure, gravel load, and gravel content are likely to gradually return to values typical of preproject conditions.

Thus, in the long term the main stem in Reach 2, which was initially oversteepened by transient high tributary gravel inputs, should slowly degrade back to a situation where it can transport near-natural (previous to the project) gravel inputs from the tributaries, with no input of gravel from the main stem upstream.

At the same time as this degradation occurs, the main-stem channel should narrow to adjust for the reduced flood flows. I estimate this narrowing to be in the neighborhood of 15%. I also estimate that after this reach goes through its cycle of short-term aggradation and long-term degradation, it will reach a graded slope very nearly equal to the present value.

Both short-term and long-term tendencies indicate a reduction in meander wavelength by about 15%. This would probably be accomplished slowly, without an excess of disruption of the channel except at the upstream end of Reach 2 in the deltaic deposits. Here, severe local channel instability may occur.

In brief, Reach 1 should be healthy for spawning in the short term, but should eventually become morphologically dead, with deleterious effects on spawning. Reach 2 should undergo rather severe aggradation, with possible incorporation of fines, at the upstream end in the short term. The rest of the reach should not be too unstable in the short term. The long-term prognosis is for a narrower, smaller, but still active Reach 2, that is otherwise not much different from natural conditions, and in that sense, morphologically and biologically healthy.

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EFFECT OF A DAM ON THE MORPHOLOGY OF POPLAR CREEK

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INTRODUCTION

Poplar Creek rises in the coastal mountains, flows eastward and joins the main valley river. A dam is proposed on the main stem of the creek about 17 miles from the mouth. The south fork of the creek enters the main stem approximately 10 miles downstream of the dam site. Two tributaries join the main stream between the dam site and the south fork. One of these, Dry Creek, enters from the north approximately 4 miles from the dam and the other, Little Dry Creek, enters from the south approximately 5 miles from the dam site.

The present paper discusses the effect of the proposed dam on the morphology of the reach of Poplar Creek between the dam site and the confluence with the south fork of Poplar Creek.

GAGING STATIONS

Table 1 lists the gaging stations at which data pertinent to the problem have been collected. The sediment yield for Station 1, which is near the dam site is not given.

In the text that follows, the gaging stations will be referred to by number as follows.

Station 1. Poplar Creek near dam site (No. 11-575810).
Station 2. Poplar Creek near mouth (No. 11-376000).
Station 3. South Fork Poplar Creek near Olinda (No. 11-375870).
Station 4. South Fork Poplar Creek near Poplar (No. 11-375820).
Station 5. Middle Fork Poplar Creek (No. 11-3744).

SIZE DISTRIBUTION OF SEDIMENTS

Data on size distribution of suspended load for several discharges is available for gaging stations 1, 2, and 3. These data are shown in Table 2. The suspended sediment near the dam site (Table 2) is from a few percent to in excess of 50% sand. Small amounts of particles as coarse as 1 mm are found in suspension. The percent of sand in suspension at Stations 2 and 3 are about the same as at Station 1.

As shown by Table 3 the bed load varies from medium sand to fine gravel and tends to be finer than the bed sediment (Table 4). Table 4 gives size distribution of samples taken from the surface of the bed and from samples of material in the upper one foot of the bed. The latter samples are seen to be very coarse and contain particles which will tend to armor the bed. The 3% size (the size for which 3 percent of the

Table 1. Gaging stations in Poplar Creek.

Assigned No.	Station No.	Elev. ft	Watershed area Sq. mi.	Mean discharge cfs/mi^2	Mean Sed. yield T/mi^2 yr	Period of record: water	Period of record: sed.
	1. Main Stem, Poplar Creek						
1	11-575810*	515	395	1.14		7 yrs.	2 yrs.
2	11-376000**	364	927	0.902	853	37 yrs.	11 yrs.
	2. South Fork, Poplar Creek						
3	11-375870	540	371			21 mos.	21 mos.
4	11-375820	525	217	0.982		15 yrs.	
	3. Middle Fork, Poplar Creek						
5	11-3744		249	0.915	1040		

* dam site
**4.7 mi. from mouth

Table 2. Size distribution of suspended load.

Date	Discharge ft³/sec	Susp. Sed. disch. T/da	Percent finer size, mm 0.062	0.125	0.25	0.5)
Station 1. Poplar Ceek near Dam Site						
3/01/77	135	31				
17/03/77	239	119				
16/03/77	375	1,150	99	99	100	
16/03/77	380	313	99	99	100	
16/03/77	410	982	100			
23/11/77	410	452	99	100		
16/03/77	454	391	99	99	100	
16/03/77	478	1,550	100			
7/04/78	1,600	497	52	56	70	93
14/12/77	2,810	14,900	56	90	93	96
8/02/78	3,180	4,970	47	54	66	90
9/03/78	5,050	12,200	58	69	82	94
19/01/78	5,280	15,400	54	65	81	96
14/01/78	6,030	22,800	69	79	87	96
9/01/78	7,570	56,000	76	84	92	97
16/01/78	12,900	67,900	98	100		
Station 3. South Fork Poplar Creek						
2/02/77	12					
1/06/77	22	5	94			
8/09/78	26	61	100			
1/12/77	52	4	98	100		
11/05/77	56	12	90			
22/03/77	60	17				
16/03/77	101	62	99	100		
3/01/77	109	111	99	100		
17/03/77	189	389	100			
20/12/77	293	126	100			
23/11/77	352	1,740	100			
16/03/77	372	3,430	96	99	100	
7/04/78	710	196	86	90	94	100
14/12/77	753	5,920	97	98	99	100
3/03/78	980	606	68	78	91	100

Table 2. (Concluded).

Date	Discharge ft³/sec	Susp. Sed. disch. T/da	Percent finer size, mm 0.062	0.125	0.25	0.5)
Station 3. South Fork Poplar Creek (continued)						
23/12/77	1,860	15,900	92	96	98	100
15/12/77	2,020	18,400	96	98	99	100
10/01/78	2,300	10,900	78	87	94	99
9/03/78	2,320	4,770	67	77	90	99
9/01/78	8,830	201,000	77	88	98	100
14/01/78	9,180	25,200	74	94	100	
Station 2. Poplar Creek near Mouth						
7/09/76	62	2	76			
3/03/77	74	3	83			
1/06/77	77	8	85			
21/09/76	95	33	99	99	100	
1/06/77	101	8	92			
22/03/77	152	18	99	100		
8/04/77	154	18	99	100		
20/09/76	293	709	100			
3/01/77	330	225	99	100		
12/05/77	339	62	95			
28/11/77	359	42	98	100		
17/03/77	627	1,780	99	100		
20/12/77	850	207	96	98	100	
23/01/78	2,980	2,060	55	67	83	97
6/03/78	4,920	10,700	54	65	85	95
15/12/77	5,460	50,300	92	93	95	97
19/01/78	6,460	21,600	59	74	90	98
10/03/78	6,780	12,700	47	58	78	95
8/02/78	7,400	18,000	54	65	85	95
8/03/78	17,400	99,600	50	66	84	95
8/03/78	19,100	122,000	58	75	90	96

Table 3. Size distribution of bed load.

Date	Disch. ft³/sec	Bedload disch. T/da	Sediment Size (mm) d_3	d_{16}	d_{50}	d_{84}	d_{95}
Station 1. Poplar Creek near Dam							
14/13/77	2800	534		0.5	4.3	14.8	18.5
17/03/77	247	1		0.74	1.3	2.0	2.8
Station 2. Poplar Creek near Mouth							
17/03/77	607	8	0.15	0.22	0.40	0.72	1.13
22/03/77	152	3	0.18	0.33	0.62	1.30	4.0
23/01/78	2920	87	0.18	0.34	0.90	3.65	8.0
Station 3. South Fork Poplar Creek							
16/03/77	151		0.20	0.086	0.32	1.13	2.0
17/03/77	198	1	0.25	0.61	1.80	8.0	13.5
6/06/78	204	4		0.56	1.88	4.4	7.3
23/11/77	338	3	0.20	0.46	1.65	14.0	
16/03/77	461	4	0.092	0.32	0.82	4.0	8.0
2/03/78	524	45		0.32	0.45	1.15	3.4
26/01/78	561	323	0.56	1.07	3.15	6.2	9.5
8/02/78	2150	134	0.19	0.68	6.10	16.0	

Table 4. Size distribution of bed sediment.

Sample No.	Distance to dam ft	Size, mm d_3	d_{16}	d_{50}	d_{84}	d_{95}	Notes
Station 1. Poplar Creek near Dam Site							
	1,300	0.36	1.13	4.8	17.7	36	Q = 3670 cfs[a]
	1,300	0.29	0.44	0.88	3.1	8.6	Q = 1520 cfs[b]
Poplar Creek, Dam Site to South Fork							
2-F-78-1	500	0.2	0.34	1.5	9.6	28	Dutch Gulch
2-F-78-6	1,000	0.1	2.0	41	130		
2-F-78-10	29,000	0.2	2.0	30	79	94	Little Dry Creek
2-F-78-12	30,000	0.5	9.4	75	120	150	
2-F-78-14	52,000	0.2	1.2	18	43	62	Near S. Fork
Tributaries to Poplar Creek							
71097	23,000	0.6	1.9	20	59	80	Dry Creek[b]
71101	29,000	0.27	0.88	10	58	100	Little Dry Creek[b]
2-F-78-16	52,000	0.1	0.78	8	27	40	South Fork
Station 2. Poplar Creek near Mouth							
		0.29	0.78	5.3	17.6	20	Q = 7310[a]
		0.19	0.72	6.2	17.3	20	Q = 2960[a]
		0.21	0.52	1.9	12.0	19	Q = 17600[a]
Station 3. South Fork Poplar Creek near Poplar							
		0.27	0.50	4.3	14.8	18.5	Q = 2180[a]
		0.29	0.88	9.6	33	35	Q = 2270[a]

[a] Surface samples

[b] Samples from top 1 ft. of bed

sediment is finer) of the bed sediment at Station 1 is approximately 0.3 mm. Material finer than this size can be considered to be wash load. From this, one can judge that sediment in this size range is carried easily by the flows without appreciable deposition on the bed (material coarser than the wash load is bed sediment load). The three percent size of bed sediment of Poplar Creek near the mouth (Station 2) is from 0.2 mm to 0.3 mm indicating that sand in this size range is carried through the river system without appreciable deposition.

DISCHARGE OF BED SEDIMENT NEAR DAM SITE (STATION 1)

The sediment yield for Station 1 is not given. However, it can be estimated from measurements at Stations 2 and 3. The sediment yield for Stations 2 and 3 are respectively 853 T per square mile and 1040 T per square mile. It will be assumed that the sediment yield for Station 1 is 1000 T/Mi^2. Data for 1977-78 (Water Resources Data, 1977-78) at Station 1 indicate that the bed load discharge was about 6 percent of the total yield. Based on this percentage the bed load yield is estimated to be 60 T/mi^2 and the suspended load yield is 940 T/mi^2.

To estimate the bed sediment yield we first assume that sediment finer than 0.25 mm is wash load. Data from Station 1 in Table 2 indicates that in 1977-78 no sediment of this size was in suspension until the discharge exceeded 1000 ft^3/sec. For the higher discharges the suspended load contained from 7% to 34% of sediment coarser than 0.25 mm. Based on these percentages the bed sediment yield in the suspended sediment is from 66 T/mi^2 to 320 T/mi^2. The latter yield seems excessive.

The total bed sediment yield is taken as the sum of the yield of suspended sand and the total bed load yield. Assuming the above quantities the total bed sediment yield is from 126 T/mi^2 per year to 380 T/mi^2 per year.

Once the dam is built it is assumed that all the suspended load coarser than 0.25 mm and all the bed load will be deposited in the reservoir. The water discharged from the reservoir will be free of bed sediment and will tend to degrade the channel downstream from the dam.

CHANNEL ARMORING

To investigate armoring, estimates of the bed shear stress for flows in Poplar Creek with several return periods are made. To do this, river slopes will be assumed to lie between .0014 and .0021 (Figure 1) and a Manning friction factor of 0.03 also will be assumed.

These calculations were made for four cross sections, two near Dry Creek and Little Dry Creek (Sections 70 and 71) (Figure 1) and two 1400 ft upstream of the confluence with the South Fork of Poplar Creek (Sections 57 and 59). The dimensionless shear stress for stable particles was taken as 0.047. The results of these calculations are given in the following Table 5.

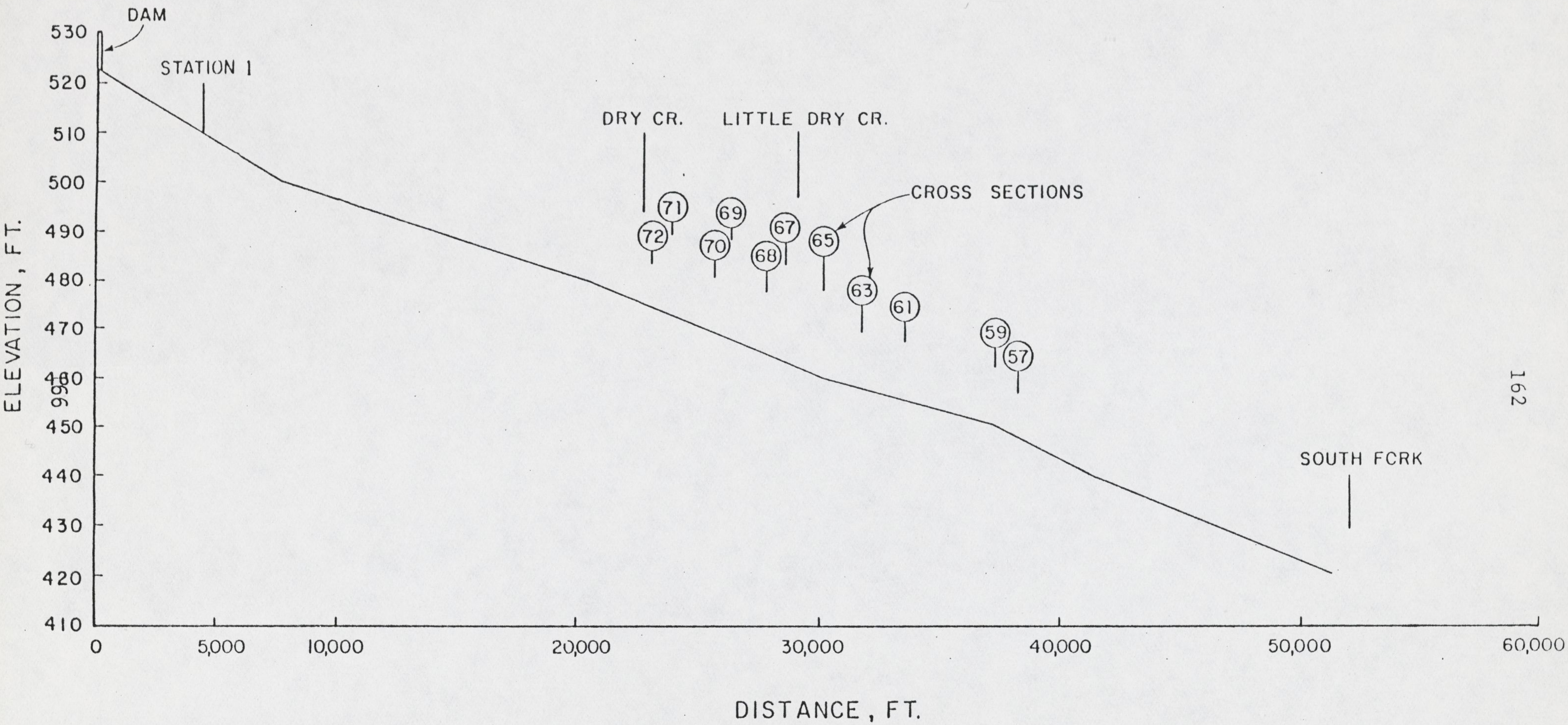

Figure 1. Profile of Poplar Creek.

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Table 5. Stable Particle Size for Flows of Various Return Periods.

Return Period	Discharge ft^3/sec	Range in Size of Stable Particles, mm Sec. 57 & 59	Sec. 70 & 71
100	4000	28-50	26-47
50	2400	24-40	21-35
20	1200	18-27	15-26

The flow rates in this table are releases from the dam for the return periods indicated. The flows at the four sections for the return periods indicated would be greater than those shown by the amount of the local runoff. However, the bed sediment downstream of the dam has ample quantities of very coarse particles which would be stable in flows considerably in excess of those listed in Table 4. For example: for a flow of 6000 cu ft per sec a 52 mm particle would be stable at Section 71 and a 59 mm particle would be stable at Section 47. As shown in Table 4 the bed of the creek between the dam and the South Fork contains particles in the 95% size that are as large as 150 mm.

Based on these rough calculations and the information on bed sediment size, it is concluded that the bed of Poplar Creek will armor after the dam is built. The bed will tend to degrade somewhat but degradation will be checked by armoring.

EFFECT OF TRIBUTARIES TO POPLAR CREEK

Dry Creek and Little Dry Creek with drainage areas of approximately 45 sq mi and 40 sq mi, respectively, are the main tributaries to the 10 mile reach of Poplar Creek between the dam site and the confluence of the South Fork. These tributaries will bring in sediment to the main stem as will other minor inflows. The total watershed area of the 10 mile reach of Poplar Creek immediately downstream of the dam, including that of the two main tributaries, is approximately 100 sq mi. Sediment contributed to the Creek from this watershed area will tend to aggrade the stream channel if the flows are incapable of transporting it.

The mean annual sediment yield of the watershed of the 10 mile reach of river downstream of the dam is estimated to be approximately 1000 tons per sq mi or approximately 100,000 tons. The sediment yield at Station 1, with a watershed area of 395 mi^2, is roughly 395,000 tons per year or almost 4 times the sediment yield of the watershed draining to the 10 mile reach of river downstream of the dam.

The proposed dam will modify the distribution of flows from what they are under natural conditions. Because the dam will regulate the flows to the creek the capacity of these flows to transport sediment will be less than that of the unregulated flows.

The mean annual sediment transporting capacity of the flows released from the dam was calculated assuming that the suspended sediment transport relation for the creek was the same as for Station 1, under natural conditions. The flow distribution was furnished. The suspended sediment transport curve was obtained by fitting a curve by eye to data for Station 1 from March 1977 to June 1978. For water discharges less than 2000 cu ft per sec, this relation is (Figure 2)

$$G_{ss} = 63 \times 10^{-6} Q^{2.36} \quad (1)$$

in which G_{ss} = suspended sediment discharge in tons per day and Q = water discharge in cu ft per sec. Applying the relation shown in Figure 2 to the distribution of releases from the dam gave a suspended sediment yield of 1027 T/da or 375,000 T/yr. Adding 6% to this for the bed load yield gives 397,000 T/yr as the estimated sediment transporting capacity of the flows released from the dam. This is almost four times the contribution of sediment from the dam to the South Fork. The actual transporting capacity should exceed the above amount because the flows will exceed those released by the amount of the local runoff.

Based on the above analysis it is concluded that the reach of Poplar Creek from the dam site to the South Fork will not tend to aggrade. On the contrary the sediment entering the creek downstream from the dam will be carried through the reach and some degradation will take place. As indicated in Section 5 of this report the degradation will be limited by armoring of the bed.

CHANNEL CHANGES

From the analysis above it appears that the flows downstream from the dam have more than enough capacity to move all the sediment reaching the stream in the reach of interest to this study. This means that the stream will tend to degrade the channel. Because the bed sediment is coarse the bed will armor after very little degradation has occurred. As degradation is taking place and especially after it has occurred the stream will erode its banks. This will tend to increase the width of the meanders and the sinuosity of the stream.

The changes in the stream are not expected to change appreciably the system of pools and riffles.

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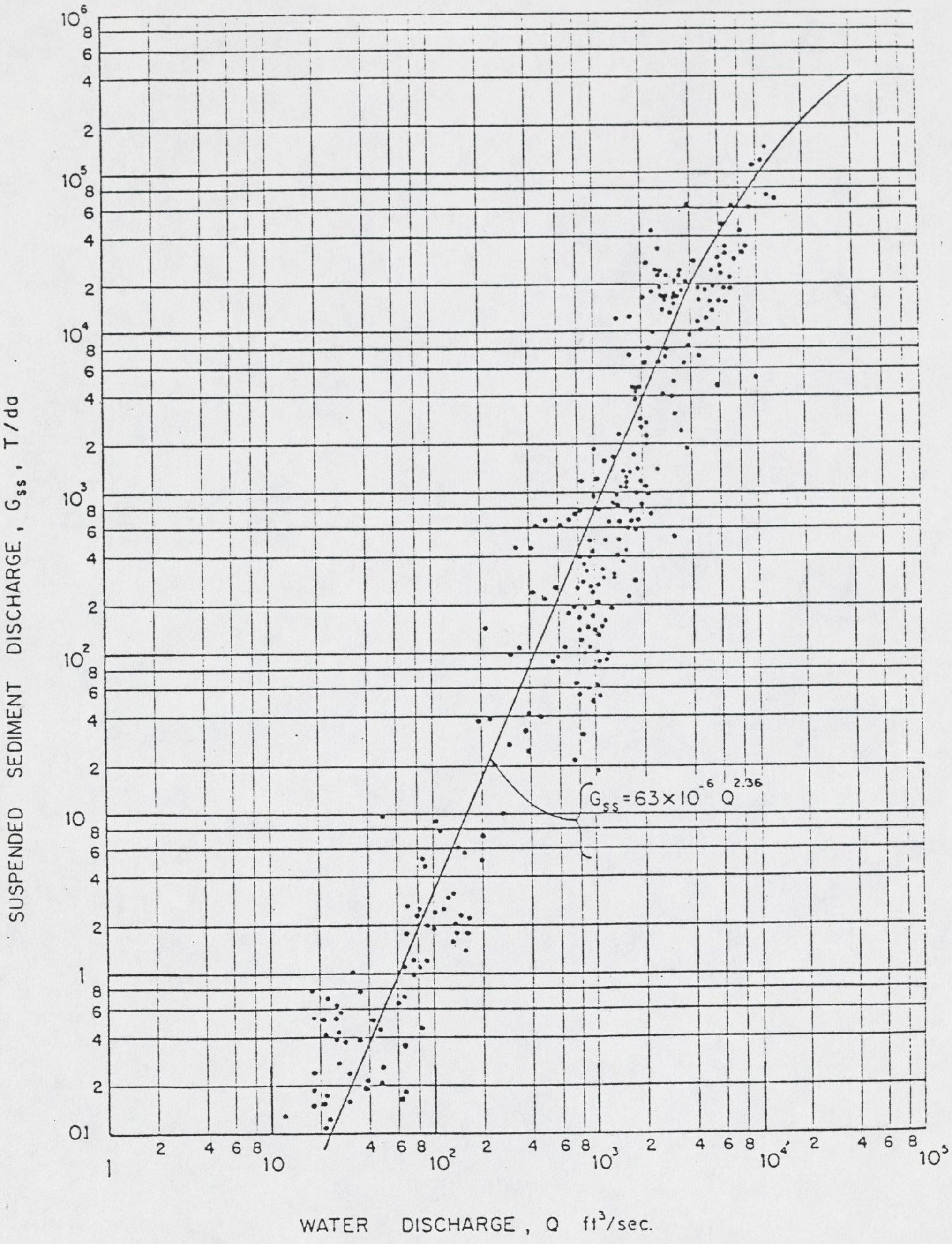

Figure 2. Suspended sediment transport curves for Station 1 near dam site.

ASSESSMENT OF CHANNEL MORPHOLOGY
ON POPLAR CREEK, CALIFORNIA

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PROBLEM

A set of data has been given to several engineers with knowledge of alluvial rivers. Each was asked to examine only the furnished data and not gather any additional information on the project nor to visit the site. Specifically we were asked: "What will happen to the morphology of the stream's channel as a result of the changes in streamflows and sediment discharge caused by the construction of a reservoir upstream of a reach of stream?" Specifically, for both a short and a long time after construction of the reservoir:

1. What will be the meander pattern?
2. What will be the configuration of the channel?
3. What will be the substrata material? and
4. What will be the pool-riffle sequence?

METHOD OF ANALYSIS

In the final analysis of this type of engineering problem there are two methods that can be used.

1. A quantitative analysis based on hydraulic data.
2. A mathematical model of channel and watershed process.

Irregardless of the quantity and type of data available, before either of the above techniques can be effective in determining present conditions and in predicting future trends, a geomorphic analysis is an absolute requirement. Even if there are only minor hydraulic data available for the quantitative or the math model approach, the geomorphic assessment will allow engineers, economists and environmentalists to make a good qualitative analysis of the drainage basin.

The initial base of a geomorphic study should be a thorough on-site examination of the drainage basin, followed by a research of available climatic, hydrologic, hydraulic, and geologic data. Next, compile a complete history of man's activities in the basin. This should include both land and water uses as well as all engineering projects that would affect the movement of the water and of the sediments. No matter what future engineering analysis is anticipated, this initial geomorphic look is of prime importance, and without it any future engineering interpretation is at best only temporarily factual.

A full scale text book would be necessary to present the geomorphic approach, but the author thought it to be appropriate to include a condensed model of the relationship of all the variables operating on and within the drainage basin.

GEOMORPHIC MODEL

Geomorphology is the science of land forms, the Earth's shape resulting from the forces acting on the landforms and their development through time. Fluvial geomorphology is the study of the action of water in changing the Earth's landforms as well as the water's influence on man's use of the land.

Schumm (1977) states that, "Development of an understanding of any part of a river system depends to a large extent on the appreciation of both upstream and downstream controls; therefore, the fluvial system must be considered as a whole ... an attempt (must be made) to consider the fluvial system and its components in such a way that the interaction of the components and the resulting degree of inherent instability of the system can be comprehended and related to some concerns of the economic geologist, geomorphologist, stratigraphor, land manager, conservationist, and civil engineer." Allen (1970) indicates that a drainage basin with its arrangement of streams is a dynamic system in which the intrinsic as well as the extrinsic variables express their behavioral changes both in time and in space. Additionally, the general shape of a drainage basin and the physical properties of the sediment are a function not only of space and time but also of the basin's geologic history. All the variables that influence the discharge and the sediment load of a drainage basin are the result of the basin's geologic history. This includes the type and depth of suballuvial formatons, the gradation of bed and bank material, the valley slope, and the hydrologic regime. These combine to produce the hydraulic characteristics of the basins and rivers. Lowdermilk (1953) shows how, over the past 7,000 years, man has had a strong influence on the Earth's drainage basin characteristics, and how man has in many basins grossly mismanaged the use of the land and the water.

One of the most difficult tasks for political, engineering, and environmental groups to understand is that nature is constantly changing. Some of the changes are catastrophic in the form of an earthquake, volcano, flood, or forest fire. Others are slow and almost unnoticeable in engineering time, such as the forces of water in changing the shape of the land and the characteristics of rivers. The term "Dynamic Equilibrium" is often used. This does not mean that all forces and reactions are cycling around some norm, but that whenever there is a catastrophic or a slow change, nature will respond and return to an equilibrium condition. This response can be fast but is usually slow and the new equilibrium state is often not the same as it was originally. We as engineers are conditioned to think in engineering time frames and to consider the data we collect, in designing any project, as being static or cyclic around an average or frequency of return of an event that will always follow the same timely pattern. This concept can be and usually is wrong. As soon as we build any engineering project, we alter nature's mode of operation and the dynamics of nature will respond and produce a new and often very different state of "Dynamic Equilibrium." In particular, variables of the fluvial system are very responsive to man's activities and engineering efforts.

Often nature has problems, because it is responding to some unbalancing event and is in a transition state, attempting to return to a balanced equilibrium. The data we collect is often taken from a transitory unbalanced system and therefore the response of the altered system can be very costly to maintain. Also, we as engineers must recognize that when dealing with the forces of nature we can never design the perfect end product. In river engineering endeavors, only by completely understanding the system, can we hope to construct projects with the least number of problems and with the least costs of maintenance.

Before design or modification of any project on any drainage basin, a geomorphic analysis must be made of that basin. The fluvial system within any drainage basin is extremely complicated and, as the following explanation will exemplify, can be in a fast or a slow response trend in a wide variety of conditions. Determining this condition and the trend of the basin's natural response is necessary in order to predict the response of the drainage system to the engineering efforts. Thornbury (1969) lists 10 concepts relevant to geomorphology and to fluvial systems. Schumm (1977) narrows these 10 concepts to 3. The first is uniformity, which means simply that the laws of Newtonian physics and chemistry controlled the operation of past erosional and depositional processes as they do today; the second principle is that within the constraints of geology (structure) there is a determinable sequence of landscape evolution through time (stage); and the third principle, which is obviously in conflict with the second, is that both landscape history and Earth history are complex. This complexity is related to the external influences of climatic change and the evolutionary alterations of the Earth's surface. Schumm (1973) offers an additional concept which states that geomorphic systems can be strongly influenced by thresholds. That is, abrupt changes may occur during landscape evolution, as threshold values of stress are exceeded. The reader can gain a more complete understanding of these concepts by reading the indicated references.

Schumm (1977) shows that any drainage system at any point in time could be cyclic, steady, progressively changing, or graded. He developed the model shown in Figure 1 of an erosional landscape over varying periods of time and places a possible time frame for each identifiable phase. Schumm states that dynamic, steady-state, and static equilibrium define the type of land-form behavior assumed for cyclic, graded, and steady time spans...but metastable and dynamic metastable equilibria may also be needed to be included because they reflect the influences of thresholds that can cause abrupt episodes of system adjustment. Thresholds result from a gradual increase of external or internal stress, or both, that eventually produces a dramatic response of the system.

Many types of variables have an influence on the characteristics of a drainage basin and their basic interrelationship is extremely complicated. Figure 2 is a qualitative model of these interrelationships.

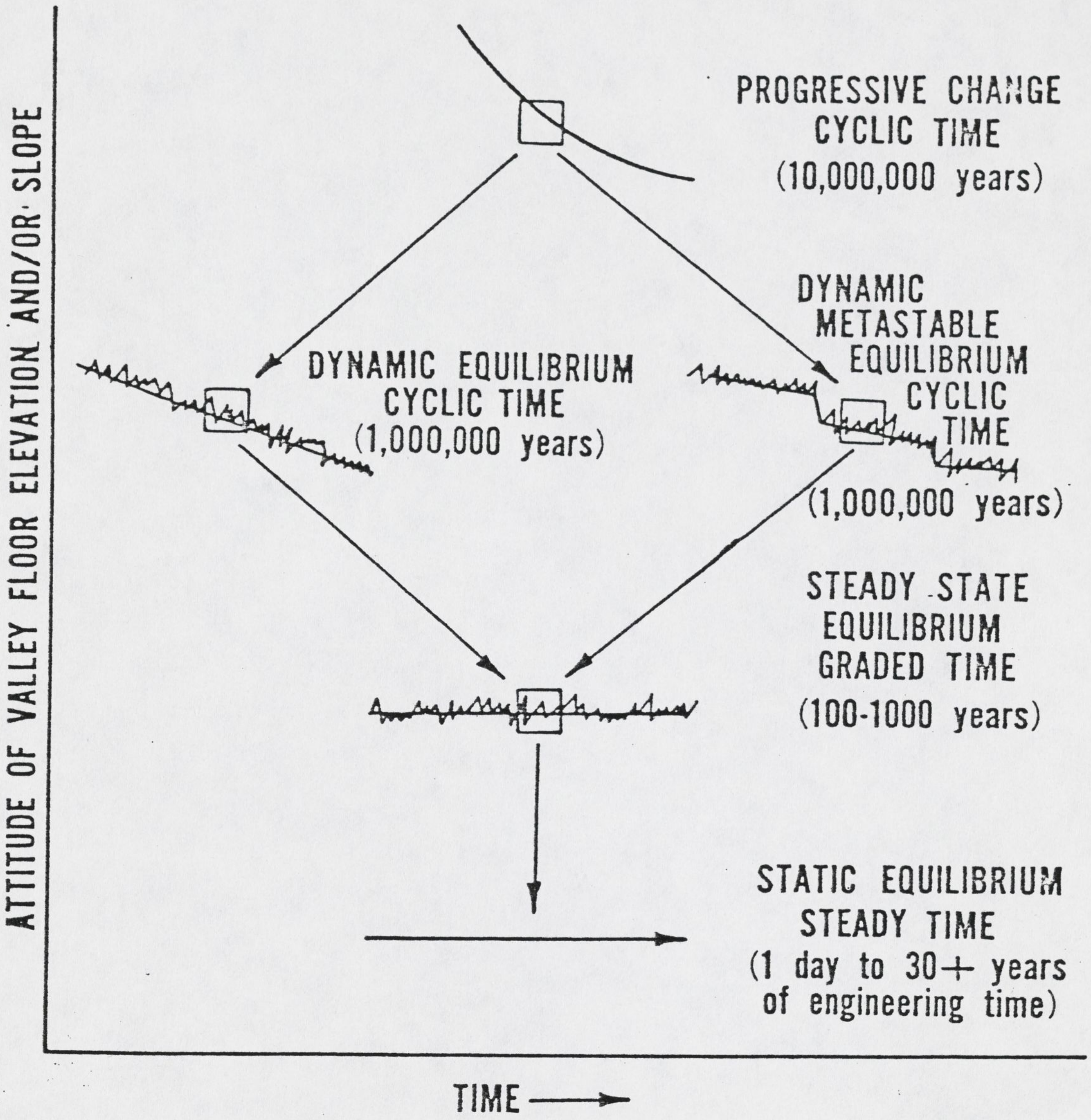

Figure 1. Model of landscape erosional evolution (adapted from Schumm, 1977).

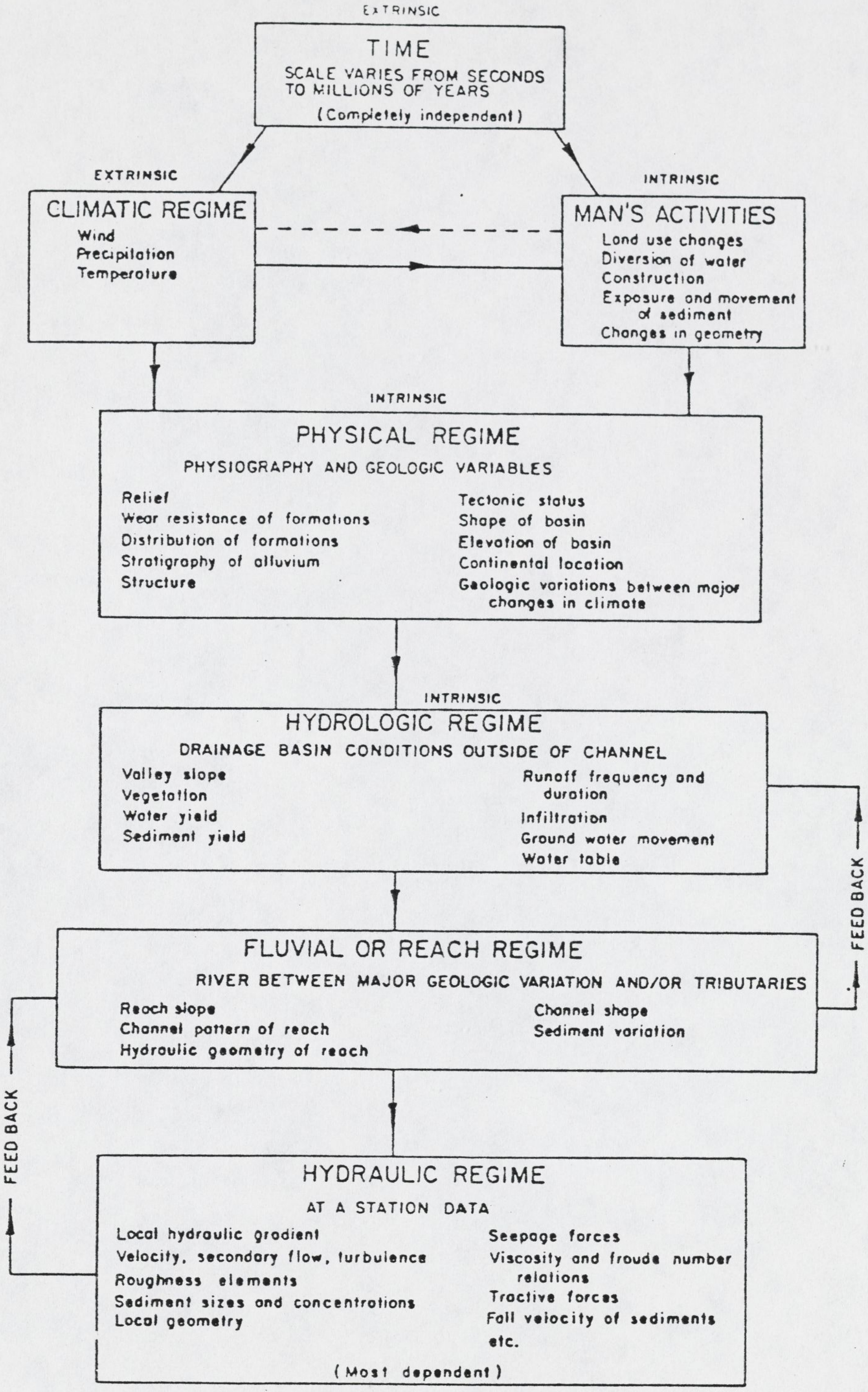

Figure 2. Geomorphic model of a drainage basin.

Time is the most independent of all variables but it does not operate on all parameters on the same scale. It varies from seconds of time in the hydraulic regime to millions of years in the geologic regime.

The Earth's surface is in contact with the atmosphere; this causes erosion. The atmosphere powered by the sun is in constant motion, creating the climatic variable which provides the energy and the mechanisms to shape the geologic variables. Historically, climate would be considered a very independent variable; however, in recent times, man has acquired the ability to modify the weather and possibly to create long-lasting weather alterations accidently. Man's activities are mostly intrinsic and may be either dependent or independent. He operates mostly on the physical regime and alters the normal timetable and quantity of response.

During a basin's geologic history, the climatic variables, operating on the complex physiographic and geologic variables, shape the basin and produce the sediments which determine the nature of today's rivers plus the use of the basin's land. Throughout history, man has altered many local and regional geologic processes. Man creates landforms in two ways: first, as the direct instrument of change, when he wields a spade or a bulldozer; secondly, through his diversionary influences upon other geomorphological processes, as when he channelizes and stabilizes a river and prevents its meandering or alters its flow. His direct influence may be either purposeful or incidental to other activities (Allen, 1970).

Climate, and now mankind, determine the character and the behavior of a drainage basin by operating on complex physiographic and geologic parameters. Geologic variables are not readily quantified but are predominantly the lithology, stratigraphy, general geologic structure, and tectonic status of the basin. The process is not steady but highly variable in response to ever-changing climatic input and to variation in erodibility of the basin formations. Man's exposure to any drainage basin is but a moment in time and nature may be in a transitive state, attempting to adjust to some imposed set of conditions. Therefore, nature is not always in the right condition for man's needs and can often be improved upon with a reasonable use of man's intelligence.

The action of climate and man on the physical regime produces the hydrologic regime which determines the rate and the mode of movement of the sediments and water into the basin's streams. The valley slope, i.e., the platform on which the river flows and the quantity and the type of sediment and discharge are the products of the hydrologic regime.

The interaction of the hydrologic parameters produce the fluvial regime. This is the slope and geometry of a stream reach. These interact to produce the hydraulic regime which is determined by the local hydraulic conditions. This hydrologic regime is the current or present integrated response of the entire stream basin history to that moment.

After sediment, within the stream, begins to move, conditions change so that there must be a feedback between the hydraulic regime and the fluvial regime and between the fluvial and the hydrologic regimes. These interactions set up a new group of conditions that change the fluvial and the hydraulic regimes. This is the reason that a complete geologic and historic analysis must be made of any drainage basin before imposing changes in water and sediment conditions. It is necessary to know, at least in a qualitative way, what the trends of response of the controlling physical regime are within the chain of interactions in the hydrologic, then the fluvial, and finally the hydraulic regimes.

Nearly all data collected on any river system are the variables of the hydraulic regime. These are the most dependent of all the many variables of climate, geology, soils, and hydrology of the drainage system. These hydraulic variables only occur at the time and place collected, and are constantly changing in response to the local geometry of the channel, which in turn is the result of the basin's geologic history.

Too often we attempt to analyze problems by only considering local conditions. A drainage basin should be considered a live entity. All of the many variables are integrated so that any change in one portion of the basin can in time be felt throughout the entire basin. However, these reactions and the stream's response are often arrested upstream by a geologic or manmade control and downstream by a hydraulic control. It is necessary that we understand the natural trends and responses of a drainage system so that we can better predict its reaction to any change imposed by man in order to minimize maintenance and insure more successful use of our waterways.

On this project, because of the limited data, the author has chosen to analyze the problem using a generalized geomorphic approach.

DATA AVAILABLE

Following is a list of the limited data furnished to the author.

1. Considerable discharge and sediment data over a brief period were furnished at three stations in the vicinity of the proposed project.

2. Topo maps.

a.	1958	1:250,000	100 and 200 ft contours
b.	1947/1952	1:62,500	25 and 50 ft contours
c.	1964/1965	1:24,000	10 and 20 ft contours

3. USGS Water Supply paper giving generalized information on water and sediment characteristics.

4. Location maps.

5. Limited cross sections of river over a short reach.

ADDITIONAL DATA REQUIRED FOR A MEANINGFUL INITIAL ANALYSIS

1. Aerial photos over as long a period of time as possible.

2. Boring logs to see what substrata looked like.

3. Geologic history of the basin.

4. Data on placer mining activities.

5. Land use data.

6. A visit to site. Anyone attempting to analyze a stream's characteristics or possible response, without physically visiting the site, is asking for criticism.

7. Size of the bed and bank material from the entire drainage basin.

8. U.S. Corps of Engineers (1970) report.

9. Information on response of other streams in the area with similar projects.

10. Complete set of maps instead of limited location maps as furnished.

11. Data on downstream activities that might alter the base level.

This initial analysis should point out any additional data required for complete design and regulation of the project.

INFORMATION GLEANED FROM FURNISHED DATA

<u>Climate Regime</u>

1. Average rainfall varies from 25 inches per year at the lower end of the basin to 70 inches per year at the divide. One storm in January 1974 dumped, in a 4-day period, from 4 inches of rain at the lower end of the basin to 16 inches at the divide.

2. Records indicate on average runoff of 30% but a storm this heavy during a wet period could produce over 90% runoff and move excessive sediments into the channel which subsequently reduced reservoir flows could not convey. This action could initiate aggradation and possible braiding.

3. Wet cool winters with 80% of moisture and dry hot summers. This type weather cycle is usually conducive to high sediment production under abnormal weather cycles.

Man's Activities

1. There has been considerable land clearing or loss of vegetation between the 1947 and the 1965 maps, mostly in the 1958 to 1965 period. What has happened in the past 15 years? What is the future land use to be, agricultural with more irrigated land from the reservoir water, or urban and recreational? Either would induce removal of natural vegetation and probably increase the runoff and sediment production. These changes would further aggravate tendencies to aggrade and braid the channel below the dam.

2. The 1965 maps do not extend above the damsite, but the 1:62500 scale older maps indicate considerable placer mining. Usually this activity would wash out most of the fines in the bed and leave mostly the coarse material. This might be the reason for the relative stability of channel indicated in the 20 year period covered by the furnished maps. This excessive coarse bed material would tend to armor the bed and probably prevent any future degradation below present bed elevations. The tributaries below the dam have had similar mining activity. An onsite inspection would help clarify these questions.

3. Orchards on river bank denote stream stability. These seem to be on the first terrace level and 10 ft above stream. This would suggest that flood flows are infrequent and that they do not carry large amounts of coarse material that would be harmful to agriculture.

4. Maps show irrigation ditches. How much water is removed from stream during the dry summer months and will this be increased with the reservoir? If so, increased groundwater return to the stream could activate caving. The amount of gravel shown on the maps indicates good subsurface water movement and well-drained land; therefore, an increase in irrigated water during the dry season would probably increase production of the fine sediments.

Physical Regime

1. The contours and the variation in sediment production between the upper and lower portion of the basin indicate different geologic formation with possible controls that are or could influence channel slopes and shapes.

2. Where the stream is close to a hill line below the dam, it is relatively straight. This indicates a nonerodible bed and bank and a control of the hydraulic geometry of the channel.

3. Map contours indicate a terraced topography and a possible degradation cycle. Reduced flow coupled with raising the downstream base levels could reverse this trend.

4. Terrace contours do not seem to show any signs of stream meanders. This could indicate that terraces are old, formed during a previous geologic period. This could indicate long time stability so reservoir action will probably have little effect on the channel as long as sediment production below the dam is controlled.

5. Terraces and stream banks should show intermittent lenses of sand and gravel which could effect bank stability by armoring the toe and also promote bank instability by groundwater movement leaching out sand lenses causing banks to settle.

6. Maps indicate an abundance of gravel on the bars and in the tributary flood plains. What is the size of gravel and is it only a surface armoring or is the entire bed of the stream composed of gravel to some depth?

7. What is the potential for tectonic activity in the area? Only onsite inspection, boring logs, and a study of the area's geology will answer these questions.

Hydrologic Regime

1. The USGS Water Supply Paper (1978) indicates that the bedload of the several creeks (in the report) varies from 2 to 210 tons per square mile per year and that most of this movement is during the short high stream flows which would be eliminated after the reservoir is constructed. Placer mining tailings seem to be very evident in the tributary drainage basins so this available coarse sediment will end up in the main channel during occasional high runoff from the tributaries, and the reduced flow of the main channel may not be able to move it. This would promote gradual aggradation and a tendency to braid.

2. The USGS report states that the loose soil in the hills erodes rapidly. The reservoir should trap most of this and with the apparent gradient of the stream below the dam, the fine material flushed into this reach should be transported out of the system. This could make the water more turbid and also enhance aggradation tendencies downstream.

3. In 1964, the hills were still vegetated yet the USGS report states that the hill soils are easily eroded and a larger portion of total sediment production comes from the hill area. Does this mean that tree cover is very sparse and that ground cover is virtually non-existent. If so, chances are that changes in land use may not alter present sediment production.

4. The USGS report states that the lakes of this type release only 5-30 percent of suspended material that enters from upstream. This would promote a tendency to degrade below the dam; however, excess coarse material would stop degradation, and as the stream attempts to satisfy its appetite for

sediment, it will attack the banks, convey out all fine sediment from tributaries and leave nothing but coarse material in the bed. Also, caving banks would probably armor their toe with the gravel (if it is present) in the bank, thus arresting meandering and returning the stream to stability in the reach above tributaries but promoting alternate periods of stability and then instability in the reach between Dry Creek and South Fork as the toe of banks and bars are intermittently stabilized then aggrade over the protection to a point where banks can again be attacked. This action will cause the stream to braid and aggrade until it establishes a slope that effects the tributaries. Aggradation in the tributaries will slow sediment movement and in some long period of time should again return the entire system to a more stable condition. The time for this depends on many factors that must be analyzed through further geomorphic study.

5. A more complete analysis of rainfall-runoff-area of each drainage system below the dam would give a better handle on the potential sediment production of these areas.

6. The USGS report states an increase of low flows from 5 to 32 cfs, medium flows to remain the same, and a reduction of average high flows from 6300 cfs to 5000 cfs, plus the 100-year frequency to be reduced to 40% of the 5-year flow. This suggests that river below the dam will not be able to move the coarse sediment but should continue to move all sizes of sediment below the more coarse gravel. No data is available on sizes of the coarse materials in the tributaries.

7. The USGS report states that total sediment production above the reservoir is two to four times higher than that below the reservoir. This could minimize the aggradation-braiding tendencies and indicates that the response could be very slow.

Fluvial Regime

1. All tributaries have gradients that are at least four to five times steeper than the main channel; therefore, they probably can initially transport any size sediment available, which will surcharge the main channel with coarse material it cannot move.

2. Cross sections furnished indicate, in the short reach surveyed, that both the top bank and thalweg have the same gradient with a fairly constant bank height. However, the cross section area from these surveys varies from 1800 sq. ft to 6700 sq. ft with an average of 3600 sq. ft. This wide variation in cross section area indicates potential differences in bank stability. These areas could be the location of future meander growth.

3. If the county line on the 1965 maps is a fixed boundary then the stream has not moved in a long time. If the county line

is always at stream center then this criteria is of no analytical use.

4. The stream near the town of Cottonwood is in a braided condition, but very little change is evident (from the maps) upstream of the confluence of South Fork. Is this because of slope change downstream from either sediment production and/or possible change in base level from some other engineering project or downstream aggradation tendencies? Further knowledge of the system is needed.

5. The cross section area of the surveyed section of river shows an average of 3600 sq. ft, with an average high flow of 6300 cfs. This indicates an underfit stream with velocities too slow to transport any but the fine sediments or a degrading situation which would tie in with the several terraces in the valley. But this would conflict with furnished data and indicate channel characteristics. Only field inspection and more data would be needed to resolve this inconsistency.

6. A more complete survey of the channel geometry is needed in order to identify its present hydraulic-geometry. It is also necessary to know the location of the vegetation and whether it is small and temporary or of a permanent nature. With this knowledge, present trends and future conditions could be easier to predict.

7. Several chutes on the inside of the point bars are indicated on the topographic maps. Only further knowledge and site inspection will clarify if these are permanent high water channels or developing cut-offs. There does seem to be some indication of past cut-offs in the present channel. Determining the nature of these will help determine future gradients of the channel.

8. What effect will the change in base level by the reservoir have on the channel upstream?

Hydraulic Regime

1. The only data available is from a few stations. This only tells what is happening at that point in the system and to some degree gives an indication of long time conditions (for the period of the data) of the reach between the proposed dam and the town of Cottonwood some 11 miles downstream.

2. An analysis of this sketchy, inadequate data only indicates the normal cyclic variation with stream flows and does not show any long term changes to the system that could be occurring but not evident in the short period of record.

3. Using just the hydraulic data furnished could give the designers a false security that only minor changes would be expected. At this point, the author does not believe an

analysis of the data is meaningful until after a geomorphic study.

REACTION OF THE STUDY REACH

Analysis of the data furnished indicates the following predictions.

1. The whole system is currently relatively stable but might be starting to respond to conditions of the stream below Cottonwood, California. This response could be of geologic origin or could have begun during the placer mining activities of the past century and further aggravated by recent land use changes and engineering projects in the Sacramento River Valley.

2. The reach of river between the dam site and Dry Creek will start to meander and possibly have some slight aggradation. This action will cease when the caving banks develop a toe protection composed of gravel in the present bank. From that point forward, this reach should be fairly stable in location and in time with a well armored gravel bed. The pool-riffle sequence should remain about as it is presently.

3. The reach of river between Dry Creek and South Fork will start a slow aggradation tendency and will begin to braid. Banks will be attacked until they are stabilized by the gravel in the banks forming a toe protection. This reaction will continue for a fairly long time with alternate periods and short reaches of armoring and aggradation followed by periods of bank caving as the protection is covered by the aggrading channel. When this occurs, scattered sections of bank will be eroded and the process repeated. As the river channel aggrades, this will set a new base level for both the tributaries and for the upstream reach below the dam. The reach between the dam and the aggrading reach has enough gradient that it can transport the river sediment from its banks until the entire system reaches a new stability regime. The tributaries will aggrade as a result of raising their base level and should then transport less and less of the coarser sediments. As this reach aggrades and braids, the pool-riffle sequence and number and depths of pools should vary considerably until stability is achieved. The trend of the whole system should be toward a reduction in time and magnitude of response until stability is finally reached. Present channel cross section and gradients are large enough to support this process for several cycles but eventually could incorporate the entire lowest terrace of the flood plain. If this happens, the return to stability will be much further in the future. It is also possible, with the gradually widened flood plain and gentler slopes from aggradation, for the river to revert back to a meandering stream after a long cyclic period of adjustment. Activities downstream of Cottonwood and in the Sacramento River Valley will probably be the controlling factors.

4. Alternating long periods of wet and dry climate would have an impact on the time and magnitude of these changes.

5. Increase irrigated farming will also affect the stream flow and bank stability.

6. The condition that would promote the largest and fastest changes would be a localized storm cell over the tributary basins with a resulting high runoff while the discharge from the dam is relatively low.

CONCLUSIONS AND RECOMMENDATIONS

Much more data is needed before an adequate analysis and prediction can be offered. Unfortunately, the data as presented to the author is quite often all that is analyzed prior to many of our engineering efforts. Many of the past and present problems are not so evident or obvious because maintenance dollars have "engineered" us out trouble.

After a study is made as herein suggested, downstream problems might be minimized by periodically releasing large discharges and flushing out the channel.

In the past several decades, we have learned enough about our rivers and drainage basins that no project should be built or altered without a complete fluvial geomorphic analysis.

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REPORT ON THE ELK RIVER PROBLEM SESSION PAPERS

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INTRODUCTION

The purpose of this report is to summarize the methods of approach and the predictions by the various authors of the Elk River Problem Session group. The group was composed of five authors who are recognized experts, a moderator, and a reporter.

Each of the five authors prepared papers evaluating the impacts that installing several upstream retarding structures would have on 10 miles of a downstream channel reach called the Longton reach. This reach has a total drainage area of over 390 square miles. The retarding structures control nearly 60 percent of the area.

The moderator, C. Thorne prepared a paper, subsequent to the workshop, discussing modeling and data requirements for evaluating downstream impacts. Therefore, this report will concentrate on the five experts' papers and will consider the moderator's paper to be supplemental but useful to this report.

APPROACH BY THE EXPERTS

All five experts approached the problem from the same overall viewpoint, i.e., each used experience supplemented with case histories. However, their individual approaches varied.

Three experts, H. Chang, P. Lagasse, and M. Stevens, used classic regime approaches, although each used a different set of regime equations.

Another, D. Ralston, used a geomorphical approach. He analyzed the geologic, soils, and hydrologic data and then synthesized the results to predict the stream response.

The remaining expert, E. Grissinger, used his experience gained from case studies in other geomorphological areas, together with his training as a soil scientist. He addressed the stream response entirely in terms of bank stability as related to the susceptibility of the bank toe to erosion resulting from induced prolonged low flow attack. The prolonged low flow is due to the controlled releases from the retarding structures.

ELK RIVER

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SUMMARY OF EXPERTS' PREDICTIONS

Each of the experts predicted the short- and long-term responses of the Longton reach with respect to: 1) meander pattern, 2) configuration of the channel, 3) substrate material, and 4) pool-riffle existence.

The significance of the extensive geologic bed control forced the attention of all to the importance of bank stability and the role of the existing bank vegetation. These two factors, geologic bed control and dense bank vegetation, resulted in very similar conclusions among the experts in spite of minor specific differences.

Table 1, Summary of Responses, shows the individual predictions regarding some basic dependent variables associated with the above four items. A "0" rating means no change, "-" means decrease, "+" means an increase, and "N.C." means no comment. The ratings were extracted from each paper. They were either extracted directly or were interpreted by the reporter to be inferred. "N.C." means the reporter could not reasonably determine the author's prediction for that specific variable.

Table 1. Summary of responses.

Author	Bank Stability	Bed Material Size	Bed Elev.	Bed Slope	Sinuosity	Meander Wave Length	Riffle-Pool Spacing	Channel Shape Width	Channel Shape Depth	Channel Shape Width Depth Ration
Short Term										
Change	0	0	0	0	0	0	0	0	0	0
Grissinger[1]	0	0	0	0	0	0	0	0	0	0
Lagasse	+	-	+	+	0	0	0	0	-	0
Ralston	+	+	0	0	0	0	0	0	0	0
Stevens	+	+	0	0	0	0	0	+	0	+
Long Term										
Change	+	-	+	+	-	N.C.	-	-	-	0
Grissinger[2]	-	-	+	+	0	0	0	+	-	+
Lagasse	+	+	0	0	0	0	0	0	0	0
Stevens	+	+	0	-	-	+	0	-	-	N.C.

[1]Assumes stable banks.
[2]Assumes unstable bank toes and <u>in-site</u> cohesive bank material.

In spite of any differences between the experts for a specific variable, most authors indicated that what changes might occur would be minor in magnitude because of the geologic and vegetative controls. All authors stressed the importance of the bank vegetation on bank stability.

Grissinger presented three possible scenarios: 1) stable banks resulting in no change, 2) unstable bank toes resulting in bank failure primarily dependent upon hydraulic action, and 3) unstable bank toes resulting in large-scale gravity induced bank failure. However, he felt that he had insufficient data to predict which scenario was most likely to occur. Also, the Elk River stream system is not underlain by paleosols as were the two other case studies he presented for comparison.

SUMMARY CONCLUSION

This reporter concludes, based upon the experts predictions, that the Longton reach will not change appreciably or that any changes will occur very slowly over both the short- and long-term, except for a thinning and coarsening of the alluvium over the bedrock channel bottom, as long as the bank vegetation is properly maintained.

Future projects should be screened for potential change using similar approaches including site visits supplemented with applicable case studies. An analysis of bank stability with respect to prolonged flows attacking the bank toes should always be considered.

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MODELING AND DATA REQUIREMENTS FOR THE PREDICTION OF DOWNSTREAM RIVER CHANNEL CHANGES FROM DIVERSIONS OR RESERVOIR CONSTRUCTION

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INTRODUCTION

The development of a hydrologic basin and river system for the purposes of flood control and water resource management will almost always result in changes in the flow regime, the rate of transport and quality of sediment and consequently the cross-sectional geometry and plan shape of the channels in the system. These physical changes to the channel in turn affect the ecological habitats in the river system. These effects may or may not be beneficial. However, if design and management procedures based on a sound knowledge of natural processes are used, the effects can be optimized and environmentally undesirable and economically expensive repercussions can be avoided. For example, river training work tends to be most successful where a sinuous channel is maintained. Artificially straightened reaches often attempt to regain their sinuous form. This results in the need for almost continual dredging and bank reveting, both of which are extremely costly and environmentally undesirable (Winkley, 1980). Experience like this highlights the importance of working with, rather than against, the natural inclinations of the river.

In this respect, we may question whether the present level of knowledge of natural fluvial processes is sufficient for the purpose of predicting downstream channel changes. A second question then arises. Are the data avilable for natural river systems adequate for the latest prediction techniques to be applied outside highly instrumented experimental hydrologic basins? These very fundamental questions were addressed at this meeting.

In this short contribution, the author, as moderator of the Elk River discussion group, wishes to summarize some of the points he made in discussing these questions.

FLUVIAL PROCESSES

Mathematical modeling of fluvial processes and systems has now developed to the point where future development can concentrate on improving and refining existing models rather than developing new models from scratch in each new study (D. B. Simons, personal communication, 1980). When using mathematical models to predict downstream response to the imposition of diversions or reservoirs, it is very important to consider the whole hydrologic, sedimentary, and fluvial system. However, the evaluation of future ecological habitats in the river requires very detailed data on the variations in flow velocity, boundary shear stress and bed material size, gradation and stability between pools and riffles, and bends and cross-overs. These morphological features have repeating lengths of the order of a few times the channel width. To run a catchment wide model to produce this detailed information for the entire river system would require a huge amount of computing time and core storage. This simply would not be feasible at the moment. The best approach may be initially to use a catchment model to predict overall response and to identify both critical and typical channel reaches. Hydraulic models could then be applied to the reaches which are of particular interest to supply the type of detailed data required for habitat evaluation. This approach to catchment modeling has been adopted and developed by scientists at the U.S. Department of Agriculture Sedimentation Laboratory (Alonso et al. 1978 and Borah et al. 1980).

Perhaps the least well understood aspect of channel response is that of streambank erosion. Yet it is essential that streambank stability and erosion be considered because it has an immediate and very damaging impact on the channel, on the flood plain, and on the people who use or inhabit the river valley. This can result in highly adverse social and political repercussions as well as undesirable fluvial effects.

Bank erosion plays an extremely important role in the fluvial system as an alternative source of sediment (particularly fine-grained wash load) when the sediment input to a reach is reduced significantly by a diversion or reservoir. Bank erosion also brings into operation rapidly operating and highly complex feedback loops between the hydraulic and sedimentary regimes and channel geometry. These feedback loops operate through changes in plan shape, and particularly through changes in sinuousity, which can result in rapid channel slope adjustment (Hey 1979).

Channel degradation, aggradataion, plan shape changes, or dynamic stability in a laterally active channel can all result in bank erosion under certain circumstances. This makes it difficult to predict the extent of bank erosion which may be experienced as a result of any particular hydraulic change. Also, as almost all rivers erode their banks to a greater or lesser degree under entirely natural conditions, it becomes very difficult to separate normal bank erosion from that caused by a newly imposed artificial change to the fluvial system.

Bank retreat may be the result of a variety of processes of erosion and mechanisms of failure. These processes and mechanisms are related not only to hydraulic conditions but also to the height, slope and stratigraphy of the bank, to the properties of the bank material, and to climatic conditions especially the intensity and amount of precipitation (Thorne, 1980 and R. H. Kesel, personal communication, 1980). This makes it unlikely that a single parameter of bank material property can fully represent the susceptibility of a bank to all the various processes and mechanisms of erosion and failure. One factor common to all eroding streambanks does emerge, however. This is the importance of the balance between rates of sediment supply to the toe by bank failure and sediment removal by the flow in the channel (Thorne, 1980). If the flow is able through time to remove all the debris from bank failures and to continue attacking the intact bank, instability is maintained, failures continue, and the bank retreats rapidly. If the flow is unable through time to remove all the debris then a talus slope develops, buttressing the intact bank and protecting it from further erosion and instability. The bank tends to stabilize and it retreats less rapidly as a result. This sediment balance, described by the "state of basal endpoint control", ultimately determines the retreat rate of an eroding bank, and, in a widening channel, also determines the rate of widening and the eventual width. The concept is equally applicable to a dynamically stable channel which is laterally active. Here the rate of accumulation on the depositional bank and the rate of removal on the eroding bank are matched over time.

It might be possible to incorporate the concept of basal endpoint control into hydraulic models of downstream geometry. This would require a sediment budget for the toe area of left and right banks based on the respective rates of sediment supply and removal. The caliber and supply rate of sediment would be estimated from bank stability analyses, while detailed information on the velocity and boundary stress distributions and the local sediment input from upstream would be used to estimate sediment output. If this approach could be used to model channel width control it would represent a significant improvement over empirical techniques.

DATA COLLECTION

The papers presented at this meeting make it quite clear that the data routinely collected for most small catchments in the United States are insufficient for application of quantitative methods of prediction based on geometric or geomorphic analyses, tractive force considerations, or the minimum stream power concept. Neither could mathematical or physical models be calibrated without considerable extra data collection. Despite this insufficiency, the data collected generally by the Soil Conservation Service and the U.S. Geological Survey do allow semiquantitative estimates of the likely direction and approximate magnitude of changes that might be expected. Perhaps the greatest variation to be noted between the results obtained by workers using different semiquantitative approaches is in their predictions of the time scale over which changes will occur and stability be re-established.

Ideally the data collection network should be extended and intensified to include many more catchments and many more variables. In particular, data are usually lacking on sediment transport (especially bed load), and the size, gradation, and degree of armoring of the bed and bank material. The huge cost of collecting such data routinely for many hundreds of catchments means that it is unrealistic to propose that such a program be mounted. A more realistic alternative may be to propose that data collection should continue roughly along present lines but that at an early stage in any proposed water resource scheme a pilot study should be undertaken to identify possible problems. A semiquantitative geomorphic study like any of those reported here of the Elk River would be sufficient to do this. On the basis of the pilot study an intensive data collection program, concentrated on likely problem areas, could be executed in the period between initial planning and the period of major design and decision making some years later. At that stage, state of the art quantitative predictions could be made on the basis of at least some comprehensive data. If the pilot study suggests that serious problems would not arise, as was the case with the Elk River, then the intensive study might not be necessary.

If this strategy were to be adopted it would still be essential that the river system be monitored, though not intensively, so that if unforeseen problems did start to develop they could be detected and dealt with at an early stage. Monitoring of this type should be an integral part of any and every water resource or flood control project, because it enables scientists and engineers to check the accuracy of their predictions and the performance of the project. It could be carried out at a very small cost in the form of perhaps a semi-annual official channel inspection, augmented by cooperation and liaison with local land owners, floodplain dwellers, and anglers. Monitoring would then be stepped up immediately if channel instability were detected to allow time for remedial and preventive measures to take effect before serious destruction of the channel could occur.

There is another and equally important reason to recommend that the pre-and post-construction fluvial and sedimentary regime and the degree of channel instability be studied. This is to develop a wide range of case histories. Case histories from similar projects in other areas were cited by nearly all the participants as an important aid in predicting downstream response. The greater the variety and number of cases documented the better is the chance of finding a good analogy to the case in point, and the more reliable will be the predictions which are made.

CONCLUSIONS

The direction and approximate magnitude of overall downstream channel changes which result from diversion or reservoir construction can be predicted with a good degree of confidence, but there is a need for more research into processes of bank erosion and width adjustment. Detailed local data required for habitat evaluation cannot be obtained from catchment scale models and so a nested approach consisting of hydrologic, sedimentary, and hydraulic models applied at catchment and local scales is needed. If procedures based on natural processes and the natural inclinations of the river are used in developing a river system, many undesirable repercussions from that development can be avoided.

All the data required to apply quantitative prediction techniques to a river system are seldom available. It is unrealistic to hope that this situation will change in the near future. An alternative approach may be to use available data in a semi-quantitative geomorphic pilot study at the outset of a project. Areas of potential problems identified in this study could be the focus of a program of more intensive data collection so that at the time of major decision-making the different design and management alternatives could be evaluated quantitatively using modern techniques based on at least a few years data.

Data collection at a reduced level and river system monitoring must continue into the post-construction period so that any unforeseen problems can be detected and remedial steps taken before serious damage occurs. Such monitoring is also vital to check the accuracy of the predictions and to build up a library of case histories to aid in future schemes and predictions in analogous situations.

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EVALUATION OF DOWNSTREAM CHANGES FOR THE ELK RIVER

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INTRODUCTION

The study reach of the Elk River is near Longton, Kansas. The question relative to the river is "What will happen to the morphology of the stream channel as a result of the changes in streamflows and sediment discharge caused by the construction of a number of small flood retaining reservoirs upstream of a reach of stream?" Specifically, for both a short and long time after construction of the reservoirs, the meandering pattern, channel configuration, substrate material, and the pool-riffle sequence need to be determined.

At present, materials of the channel consist mostly of fine gravels for the bed and loamy soil for the banks. The banks are lined with trees. The study reach of the river has a channel slope of 0.000462 and a valley slope of 0.00075. The sinuosity of the river, taken as a ratio of these two slopes, is obtained as 1.62. For this flat slope, the channel is not subject to braiding or rapid increase in width.

VARIABLES

The independent variables, dependent variables, and physical constraints for this problem may be summarized below.

a. The independent variables include the water discharge and sediment inflow.

b. The dependent variables include the channel width, depth, slope, sinuosity, sediment size, pool/riffle spacing, etc.

c. The physical constraints include the bank slope, the valley slope, geology of the alluvium, vegetation, etc.

The river banks are lined with dense trees which have played a very important role in developing the present river morphology. Because of the protection and resistance provided by the trees, the river has steep banks and a very small width-depth ratio. These again affect its sinuosity, riffle-pool spacing. Therefore, a change in the tree protection alone will significantly change the river morphology.

The alluvium consists of silt, loam, and gravels. At present, the channel has a gravel bed and silty and loamy banks. Because of the limited thickness of the alluvium, the channel bed has reached the bedrock at several places as evidenced by scattered rock outcrops. For this reasons, physical constraints due to bedrock will limit channelbed degradation to local reaches, if any.

THE APPROACH

In predicting the morphological changes for the river, the regime approach will be employed. There is a never ceasing tendency for a river to attain equilibrium (regime). With the changes of the water discharge and sediment inflow, the river will undergo gradual changes to seek a new regime. These changes are limited by the physical constraints listed above and a new regime may never be attained. However, the regime approach will provide the directions of change for the river.

Regime relations developed previously generally relate the channel width to the bankfull discharge. For example, the Lacey relation for regime canals with a sand bed has the form

$$P = 2.67 \sqrt{Q} \quad (1)$$

The surface width B for gravel streams has the general form

$$B = C\, Q^{0.5} \quad (2)$$

A graphical relation for regime gravel streams developed by Chang (1980) is shown in Figure 1. This relationship was developed based upon a flow resistance formula, a sediment load formula, and the concept of minimum stream power. In this graphical relation, the channel width and depth are shown as functions of the channel slope, the bankfull discharge, and the sediment size. The bank slope plays a significant role in channel morphology. It has been found in the analytical study (Chang, 1980) that for a steeper bank slope, the channel has a smaller width and greater depth. On the other hand, a flat bank slope indicates greater width and smaller depth.

The threshold condition in Figure 1 is based upon the threshold condition for gravel movement given by the following equation

$$\frac{\tau}{g(\rho_s - \rho)d} = 0.03 \quad (3)$$

where τ = shear stress; g = gravitational acceleration; ρ_s = density of sediment; ρ = density of water; and d = sediment size.

Above this line, the channel bed is mobile. Below this line, the channel bed is not mobile although "through-put" load may still exist. Based upon Equation 3, the critical channel slope for the threshold condition may be related to the bankfull discharge and sediment size as (Chang, 1980)

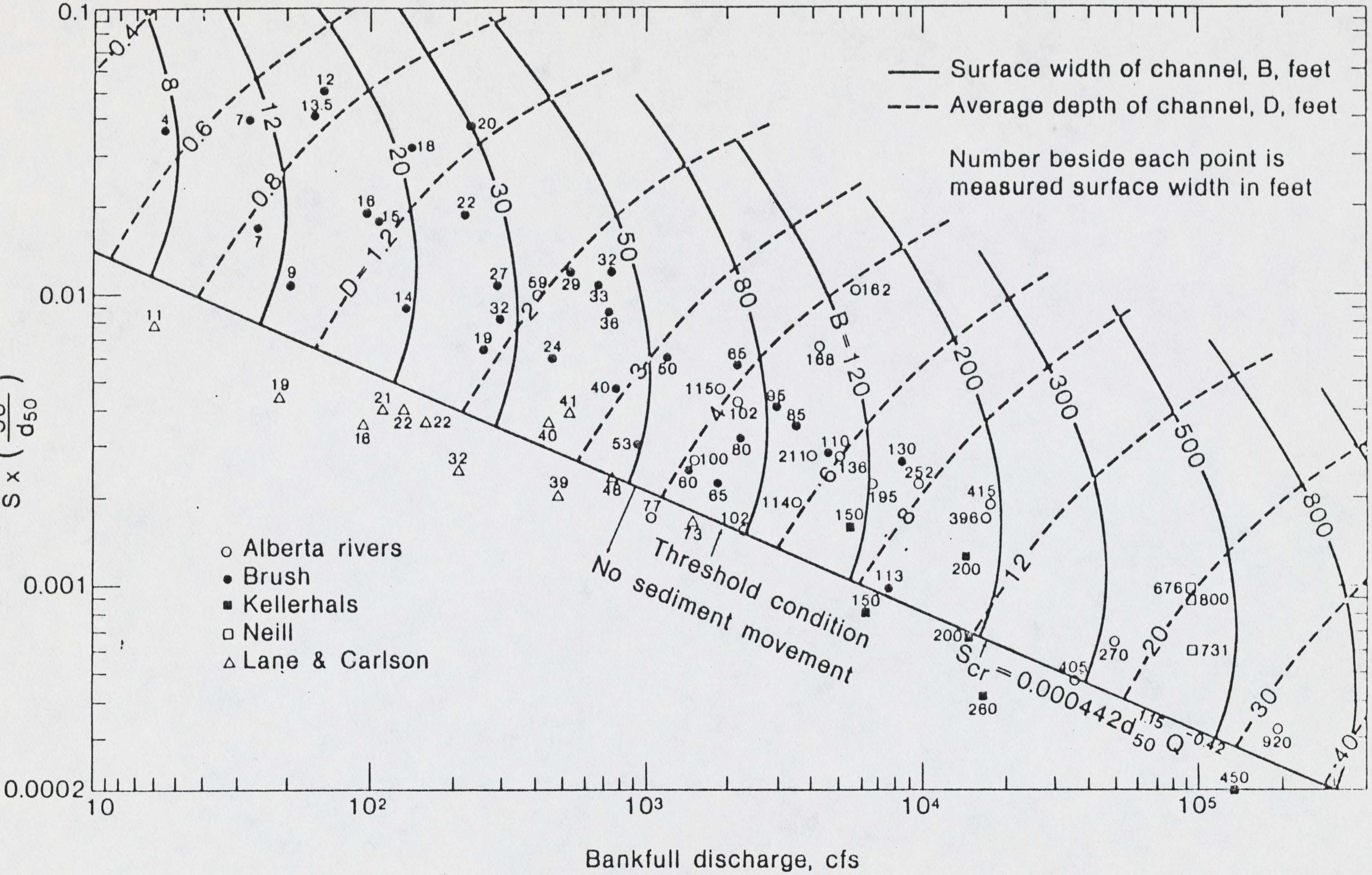

Figure 1. Relation of channel geometry with slope and bankfull discharge for regime gravel streams.

$$S_{cr} = 0.000442\ d^{1.15}\ Q^{-0.42} \quad (4)$$

For the study reach, the bankfull discharge is estimated to be 7000 cfs and the representative sediment size is estimated to be 15 mm. Substituting these values into Equation 4, one has $S_{cr} = 0.000242$. Since this slope for the threshold condition is less than the channel slope, the channel bed is mobile at the bankfull discharge. Using the bankfull discharge of 7000 cfs and $S\ (50/d^{1.15} = 0.00046\ (50/15)^{1.15} = 0.00184$ for the study reach, its position may be placed in Figure 1. The analytical channel width and depth for this point are obtained as 140 feet and 8 feet respectively, considerably less than the actual values. The major reason for the discrepancy is due to the large roughness and the steep bank slope of the study reach in comparison to most other gravel streams.

SHORT-TERM CHANGES

Judging from the distances to the reservoirs, short term changes will not affect the study reach. After the completion of reservoir construction, changes will start to occur in channels immediately downstream of the reservoirs and then progress downstream gradually. Being depleted of bedload sediment, the water flowing out of the reservoir will start to scour the channel bed. In the process of scour, finer materials will be removed and transported downstream first. This will result in coursening of the bed material and formation of an armored layer.

LONG-TERM CHANGES

Judging from the distances of the reservoir projects to the study reach, their impacts to the study reach will be of long term nature. The present storage of sediments in the channels leading to the study reach will continue to affect its morphology for quite a long time. With the changes in water discharge and sediment inflow caused by the reservoir projects, the study reach will feel these changes eventually. Basically, it will seek its new regime by adjusting its width, depth, slope, sediment size, and meandering pattern subject to the physical constraints. The adjustments are complicated by the fact that these variables are inter-related. In the following discussion, each individual change will be described first, then, how each change affects other changes will be investigated. The channel will be delicately adjusted in consideration of all the operative variables.

First of all, the regime channel width and depth are functions of the bankfull discharge. With the reduction in discharge, the study reach tends to adjust itself into a smaller channel with a narrower width and shallower depth.

With reductions in both water discharge and sediment inflow, the study reach tends to assume a steeper slope as analyzed below. The reservoir projects will block off 59% of the watershed area resulting in a reduction in bedload inflow to the study reach of roughly 59% in the long run. The reduction in bankfull discharge is more difficult to estimate; it is assumed to be 50% for the convenience of analysis. Now, for regime channels, the sediment discharge is roughly proportional to the square of the bankfull discharge when other variables are constant (Chang 1980), or

$$Q_s \propto Q_w^2 \tag{5}$$

Again, the square power is only a rough estimate. Despite these rough estimates, the trend of variation for the slope can be ascertained. As the bankfull discharge is reduced to half, the sediment carrying capacity is reduced to one fourth. Since the sediment inflow is reduced by roughly 59%, greater transport capacity is required and it will be achieved by a combination of slope increase and other adjustments.

The decrease in channel depth and increase in slope indicate that the study reach is subject to aggradation. The extent of aggradation is not expected to be very significant because of other inter-related adjustments. Specifically, aggradation in the main channel will raise the base levels of the tributaries. The raise will then reduce the amount of sediment inflow from a tributary and the size of the inflow sediment. These again will reduce the aggradation trend of the main channel until a delicate balance is reached.

The increase in channel slope may be achieved by the combination of aggradation and reduction in meandering sinuosity. For this reason, the study reach tends to become less sinuous.

The spacing of the riffle-pool series has been related to the channel width in previous studies (Leopold, 1964, Schumm 1977). Since the width tends to decrease, the spacing of the riffle-pool will likely decrease.

One physical constraint that plays a very important role in the present channel morphology is the vegetation on the channel banks. Because of the dense tree protection, the channel banks are steep and the width-depth ratio of the channel is small. A loss of the protection will result in reduction in the channel bank slope, an increase in width and a decrease in depth.

CONCLUSIONS

The following conclusions may be summarized:

1. The present river channel of the Elk River has an unusually large depth and small width-depth ratio. These morphological

features are related to its steep channel banks and high degree of channel roughness. The dense growth of trees has contributed significantly to the steep bank slope and roughness. For this reason, removal of the trees would cause significant changes in river morphology.

2. The study reach of the river near Longton is not subject to any significant short term changes due to the reservoir construction. Short term changes will be limited to river channels in the downstream vicinity of the dams.

3. With the changes in water discharge and sediment inflow, the study reach will experience long term changes. These changes are the result of the delicate adjustments of the channel width, depth, slope, sediment size, meandering pattern, etc. Since these morphological features are inter-related and their adjustments are subject to the given physical constraints, the extent of these adjustments is not expected to be very significant.

4. The study reach is predicted to develop into a smaller channel with narrower width and shallow depth. Its slope tends to become steeper; the channel bed tends to aggrade; its sinuousity tends to decrease; the riffle-pool spacing tends to decrease; the substrate material tends to become less coarse.

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CHANNEL CHANGE WORKSHOP PROBLEM NUMBER 3, ELK RIVER, KANSAS[1]

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ABSTRACT

The Elk River, Kansas is typical of many streams in the Mississippi drainage system. It has a deep channel incised into late-to postglacial valley-fill deposits. At present, the distribution and properties of these valleyfill deposits are undefined, and this lack of information prevents reliable prediction of channel adjustments resulting from significant watershed changes. Studies in northern Mississippi and western Iowa, which have established the significance of comparable valley-fill deposits, have been used as case examples. This case history application is based on preliminary results indicating the valley-fill units were deposited in response to paleoclimatic controls. Alternate scenarios are presented based upon vegetative or stratigraphic controls and upon hydraulic-induced or gravity-induced bank failure.

INTRODUCTION

The central theme for this workshop is "What will happen to the morphology of the stream channel as a result of the changes in streamflows and sediment discharge caused by the construction of a number of small flood retarding reservoirs upstream of a reach of stream?" The Elk River, Elk County, Kansas, a gravel-bed river, was assigned and the reach near Longton, Kansas designated for study. The specific questions to be considered are:

1. What will be the meander pattern?

2. What will be the configuration of the channel?

3. What will be the substrate material?

4. What will be the pool riffle sequence?

The following data were supplied.

1. General Plan - Elk River Watershed Joint District No. 47,

2. Soil Survey of Chautauqua County, Kansas (Chautauqua County is immediately south of Elk County),

3. Geology, Mineral Resources, and Ground-water Resources of Elk County, Kansas,

4. Plan, profile and cross section diagrams for the Longton reach of Elk River, Kansas,

5. Monthly streamflow data for Elk River basin, Kansas,

6. Elk River bed material,

7. Elk River sediment yield,

8. Frequency-runoff curve,

9. Unit discharge hydrograph curves and table of values,

10. Evaluation-discharge curves and table of values,

11. Pictures of the Elk River channel at selected locations.

Although this is a sizable data base, additional data and expertise are required to fully answer the four specific questions. Additionally, extended field observations should be made before any attempted evaluation, and such evaluation must consider the Longton reach as an integral component of the entire watershed system. The following discussion is, therefore, presented to stimulate discussion and is not intended to be definitive.

Limitations in the current state of the art for gravel-bed rivers were identified by several of the authors at the recent International Workshop on Engineering Problems in the Management of Gravel-Bed Rivers, Greganog Hall, Powys, Wales. Two major limitations pertinent to definitive solutions of the four questions for Elk River are a) the poor definition of the influence of upland watershed conditions on the movement of coarse sediment to the main channels, and b) the lack of information describing channel bed and bank material stability. Inherently, both the type and magnitude of instability must be considered for this latter influence. Moreover both influences must be evaluated as interactive components of the complete system.

Identification of failure modes and magnitudes for Elk River channel materials is critical for definitive solutions for the four questions, particularly for long-term channel reactions. Such data, however, are incomplete. Channel beds are apparently stabilized by hard-rock outcrops, and vertical (thalweg) degradation is improbable. In an attempt to generalize about the significance of bank material stability, I have a) generalized the results of our current channel stability studies in northern Mississippi, b) compared the nature of the northern Mississippi valley-fill stratigraphic units to those of Iowa, and c) noted similarities between Elk River watershed features and comparable features in Iowa and northern Mississippi.

INFLUENCE OF CHANNEL BED AND BANK MATERIAL, NORTHERN MISSISSIPPI

Four valley-fill stratigraphic units influence channel stability and morphology in northern Mississippi. The youngest of these units, termed postsettlement alluvium (PSA), was produced in historic times, resulting largely from cultural activities. It is unweathered and directly overlies either a young paleosol or an old paleosol. The PSA typically varies in thickness from several inches to several feet. The weight of this material functions as a loading term for gravity-induced failure of either of the underlying paleosols.

The next youngest of these units is the young paleosol, a relatively unweathered fluvial deposit. Typically, the basal part of this unit is composed of lateral accretion deposits and the upper part is composed of vertical accretion deposits. The unit was deposited in areas where streamflow had eroded (incised into) an older valley-fill unit. This cut-and-fill was frequently associated with lateral meandering. The young paleosol deposition and weathering commenced about 2,500 ^{14}C years Before Present (B.P.) (Figure 1d). The unit is termed a paleosol because it is buried by modern sediments and because it must be differentiated from present soil classification units. These soil units are materially influenced by the properties of the PSA. Failure of this young paleosol material results primarily from gravity stress, and such failure is accentuated by the development of vertical tension cracks parallel with the bank. This tension crack development is undoubtedly related to the relatively unweathered and, hence, isotropic nature of this silty material.

Old paleosol materials underlie the young paleosol and/or historic sediments. These materials are fluvial deposits and represent a major phase of valley aggradation. They are highly weathered and are typified by a well-developed polygonal structure which controls the mode of bank failure. The polygonal seam materials have minimum stability, and block-type failure is induced by gravity stress. In general, the old paleosol materials are more stable than the younger materials. Deposition of this old paleosol material occurred around 10,000 ^{14}C years B.P. (Figure 1d).

Gravel and/or sand deposits underlie the old paleosol. These deposits represent the initial phase of valley aggradation, starting at or immediately prior to 12,000 ^{14}C years B.P., following a major phase of valley degradation. The gravels and/or sands are usually unconsolidated but are occasionally cemented by iron, forming bed-control sills where they crop out in the channels. Exposure of the unconsolidated materials in a bank toe position, resulting from vertical degradation, typically increases rates of failure due to gravity stress.

The present-day channel morphology in northern Mississippi has been largely determined by the presence or absence of the iron-cemented bed control sills. Where such sills are absent, such as in Johnson Creek, a tributary of Peters Creek, thalweg lowering has progressed to a sufficient depth to expose the unconsolidated gravels and/or sands in a bank toe position. For this condition, gravity forces become the limiting stress for bank stability. Thalweg degradation started at least 40

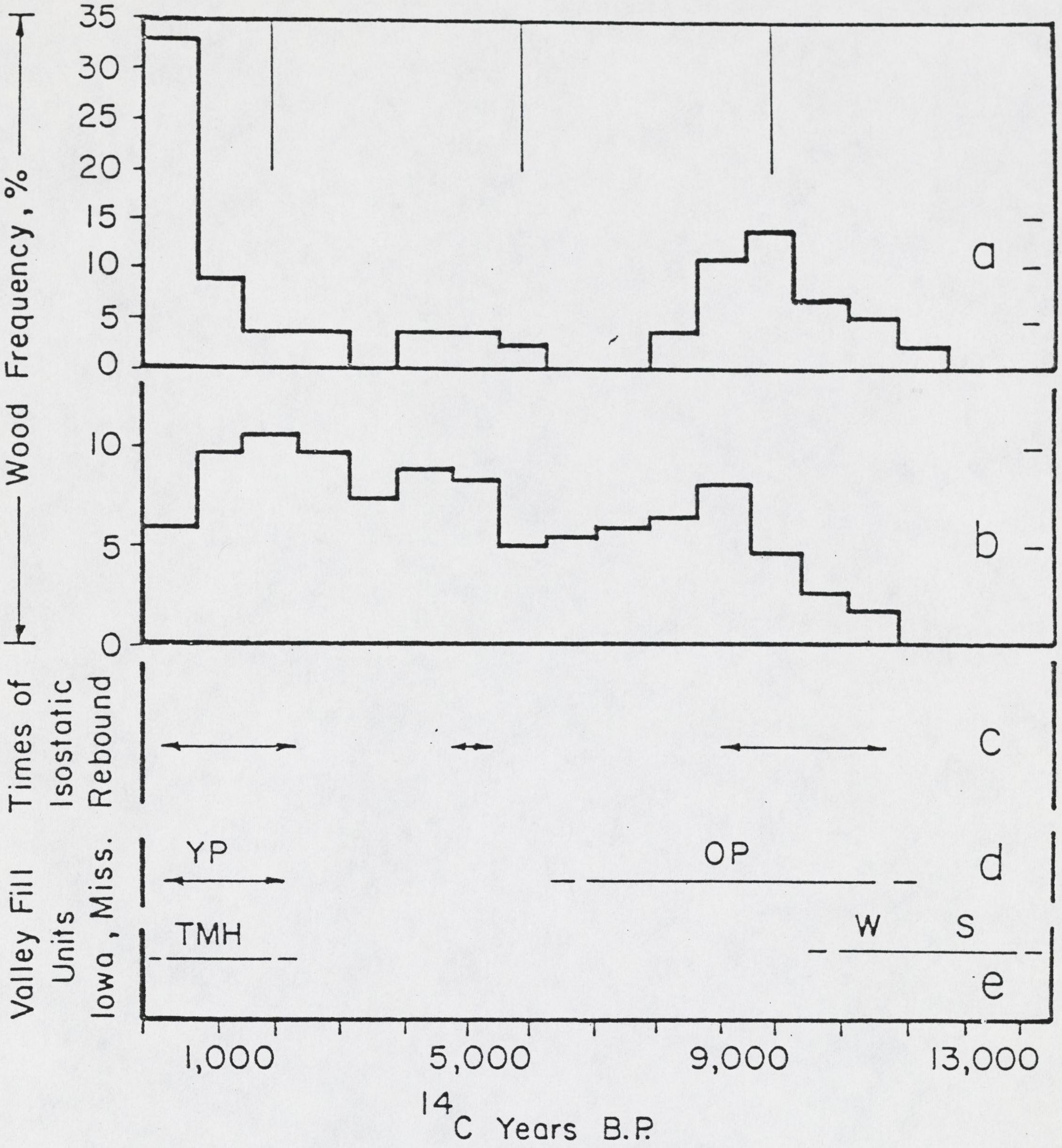

Figure 1. Valley-fill chronology. a) Frequency histogram of ^{14}C dates for 57 samples from northern Mississippi, b) Frequency histogram for 815 ^{14}C dates selected from the journal Radiocarbon (Wendland and Bryson, 1974), c) Times of paleoclimate-controlled crustal rebound in the Great Lakes area (Flint, 1957), d) Paleosol ages in northern Mississippi; YP = young paleosol, OP = old paleosol, e) Valley-fill ages in Iowa; T = Turton, M = Mullenix, H = Hatcher, W = Watkins, S = Soetmelk (Daniels and Jordan, 1966).

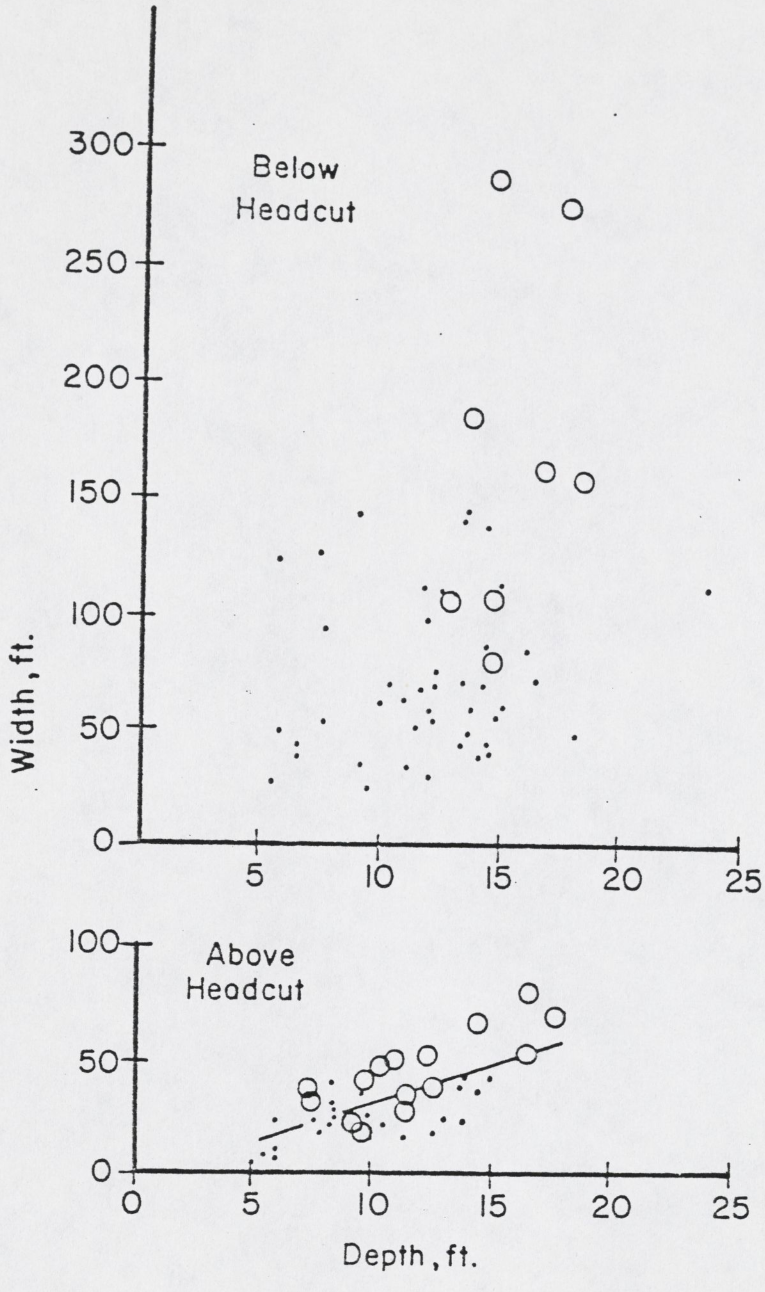

Figure 2. Width-to-depth relations for Johnson Creek, northern Mississippi, from steroscopic analysis of Agricultural Stabilization and Conservation Service aerial photographs for the years 1937, 1940, 1944, 1953, 1957, 1963 and 1968 (identified by a dot) and for the year 1975 (identified by a circle).

years ago and has progressed upstream in the form of either a diffuse or discrete headcut. Channel width-to-depth ratios are coherent upstream of the headcut where the channel bed material is either of the cohesive paleosols (Figure 2). Downstream of the headcut, however, Johnson Creek is a sand-bed channel and measured channel depths are less than scour depths. Width-to-depth ratios are random downstream of the headcut, resulting from excessive channel widening particularly in young paleosol materials (Figure 2). Where iron-cemented sills have prevented vertical degradation, such as in Goodwin Creek, a gravel-bed tributary of Peters Creek, excessive lateral channel erosion has occurred (Figure 3). This widening is not constant throughout the system but appears to be associated with local stratigraphic and/or channel morphometric conditions. Channel width-to-depth ratios are random and channel sinuosity is highly variable. Selected reaches in both channels have widened excessively since 1968.

In summary, the energy expenditure within the channels has not been uniform over relatively long channel lengths but has been concentrated in relatively short reaches of the channel. As illustrated for Johnson and Goodwin Creeks, this form of degradation is intimately associated with the nature and distribution of the valley-fill stratigraphic units of Holocene age. Channel morphology and channel morphometric changes are similarly intimately associated with these Holocene units. Gravity stresses limit bank stability for channels which are presently incised and the magnitude or rate of failure ultimately depends upon the ability of the flow to remove the slough from the bank toe position. Slough from either of the paleosols and from the postsettlement alluvium is easily removed, generating the failure process.

COMPARABILITY OF VALLEY-FILL SEQUENCES IN IOWA AND NORTHERN MISSISSIPPI

Daniels and Jordan (1966) have identified six valley-fill units in Harrison County, Iowa. These six are recent (postsettlement) deposits and five members of the DeForest formation including the Turton, Mullenix, Hatcher, Watkins, and Soetmelk members. Wood contained within the latter two members has been dated at 11,120 to 14,300 ^{14}C years B.P. The comparable ages of the Turton, Mullenix, and Hatcher members ranged from less than 250 to 2020 ^{14}C years B.P. These ages (Figure 1e) are in general agreement with ages of the two paleosols identified in northern Mississippi (Figure 1d), and are in general agreement with the periods of muck accumulation in closed systems in Iowa (Ruhe, 1969).

In addition Ruhe (1969) has identified two erosion surfaces in Iowa which, preliminary data show, may have counterparts in northern Mississippi. The Wisconsin erosion surface which developed in Iowa prior to 14,000 ^{14}C years B.P. is comparable to the observed erosion cycle in northern Mississippi which developed prior to 12,000 ^{14}C years B.P. In addition, the Iowan erosion surface formed prior to 18,300 ^{14}C years B.P. (Ruhe, 1969) and may be comparable to an erosional surface in northern Mississippi overlain by organics which are 17,000 ^{14}C years old. This surface in northern Mississippi has not been fully defined. Other similarities include the ages of older alluvial fills ranging from 37,600 ^{14}C years B.P. in Iowa (Ruhe, 1969) to 34,900 ^{14}C years B.P. in

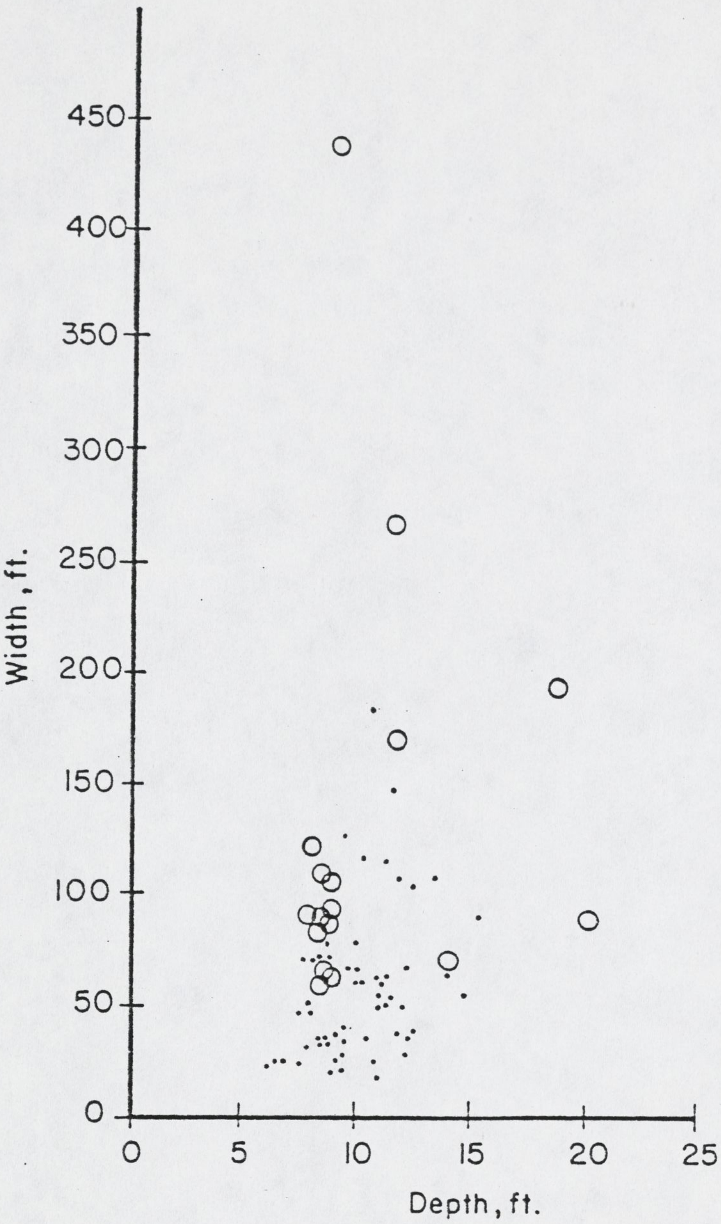

Figure 3. Width-to-depth relations for Goodwin Creek, northern Mississippi, from stereoscopic analysis of Agricultural Stabilization and Conservation Service aerial photographs for the years 1937, 1940, 1944, 1053, 1957, 1963 and 1968 (identified by a dot) and for the year 1975 (identified by a circle).

northern Mississippi (Grissinger). These dates illustrate the dynamic nature of the fluvial systems during the late Quaternary, especially during the Holocene.

More significantly, the hypothesis that paleoclimate has been the dominant control of the late-Quaternary fluvial systems and valley-fill processes is supported by the agreement among a) the (wood) age frequency for northern Mississippi (Figure 1a), b) the age frequency compiled by Wendland and Bryson (1974) for paleoclimatic interpretation (Figure 1b), c) the times of paleoclimate-controlled crustal rebound in the Great Lakes area (Figure 1c) identified by Flint (1957), and d) the ages of the valley-fill sequences (Figure 1d and 1e). Various other comparisons supporting climatic control of fluvial episodes are discussed by Knox (1975). Verification of this hypothesis together with channel bank stability studies complementary with those in northern Mississippi (but in other areas) will facilitate prediction of channel response for "uncalibrated" areas. Such stability studies have been reported by Bradford and Piest (1980) for western Iowa. Their results are comparable with ours for northern Mississippi in that a) gravity forces are the limiting stress for bank stability and b) stability is controlled by the distribution and properties of the valley-fill stratigraphic units. For the subsequent discussion, I have assumed that a) the hypothesis of paleoclimatic control is valid and b) the western Iowa and northern Mississippi studies are viable "calibrations" for Elk River channel stability problems.

ELK RIVER WATERSHED

Not enough data are available to positively relate the valley-fill sequence in Elk River watershed with the sequences in either western Iowa or northern Mississippi. Bayne (1958) reported that some of the valley-fill units may be Kansan or older whereas the valley units in surrounding counties are reported to be mixed Illinoian-Wisconsin (Jamkhindikar, 1967) or mixed Wisconsin-Recent (Holocene) (Frye and Leonard, 1952) deposits. The parent material for the Verdigris, Brewer, and Osage soils is identified as alluvium in Butler County (Soil Conservation Service, 1975) and is assumed to be Holocene in age.

The Verdigirs (Cumulic Hapludolls) soil occurs adjacent to present stream channels, is well drained, has no B horizon development and is friable (when moist) to a depth of 57 inches. These properties are comparable with those of soils formed in PSA or young paleosol materials in northern Mississippi. The Brewer (Pachic Argiustolls) and Osage (vertic Haplaquolls) soils are moderately well to poorly drained, frequently have B horizon development and are firm to very firm (when moist) at a depth of 30 to 66 inches. Similarly, these properties are comparable with those of soils developed over old paleosol materials in northern Mississippi. The sandy to gravelly basal phase of this valley fill, the presence of older fill materials preserved as terraces, together with the preceding soil similarities, all suggest that the Holocene valley-fill sequence in southeastern Kansas is similar to that in western Iowa and northern Mississippi.

Two features of the present day Elk River channel are pertinent to the (assumed) role of the valley-fill stratigraphic materials. These features are the apparent incision of the channel to a depth of bedrock control, about 30 feet, and the apparent bank stability. Most cross sections show two bank slopes, an upper, relatively low angle bank slope and a lower, steeper bank slope. I interpret this change in bank slope to indicate past thalweg lowering with a change in channel cross section shape from a relatively broad channel to a deep channel. This past thalweg lowering may have resulted from historic land use changes which either directly increased the rate and magnitude of runoff or indirectly resulted in the same change in runoff due to excessive denudation (erosion) of the upland areas. One critical area of uncertainty is the nature of the lower bank material. The present lower banks may be composed of in situ materials of sufficient cohesion to resist detachment or they may be composed of slough materials from overlying deposits which have been stabilized by vegetation. Several of the pictures show trees, estimated to be 25-35 years old, close to the channel and the aerial photograph shows more or less continuous timber bordering the channel. This vegetative cover and the lack of meander (lateral) migration indicates stability of the channel system for an extended period of time. Exceptions to this vegetative cover are between ranges 11-1 and 3-5 where the channel apparently has been relocated, and on the outside bank of the meander at range 13-2. Regardless of whether the channel system has incised into relatively resistant material, possibly similar to the northern Mississippi old paleosol materials, or has been stabilized by vegetation, it is evidently stable at present.

An additional area of uncertainty concerning the proposed watershed project is the influence of the structures upon the sediment load. The proposed structures will retard the runoff from 58.6% of the watershed area. According to the sediment yield curves, these structures will reduce the bedload yield by 60% and the suspended sediment yield by 57% for this 409 square mile watershed. I am somewhat surprised that these estimated reductions are so similar. Nevertheless, these structures will influence peak discharge and will produce sediment starvation which, individually or combined, may influence channel behavior in two ways. Channels immediately downstream of the structures may degrade depending upon the relative degree of sediment and flow reduction and upon reach conditions such as bed slope, channel roughness, bed and bank material size, etc. Such degradation, if it does occur, will probably be relatively insignificant in influencing Elk River channel behavior. An additional and more significant influence may be the accelerated degradation of, and sediment production by, tributaries not directly controlled by structures. This type of accelerated degradation of uncontrolled tributaries frequently results from main-stem stage reduction. Depending upon reach conditions, the relatively coarse sediments, produced by such a mismatch of peak stage, may be transported to the Elk River channel and deposited as tributary fans. These fans would influence secondary flow, possibly producing local problems of bank instability. Quantification of these features would require sediment routing data based on individual sediment sizes and a thorough knowledge of the distribution of these sediment sizes in the watershed.

The second set of possible influences of the proposed structures involves the direct effects on Elk River channel of peak-discharge reduction and sediment reduction. Prolonged, within-channel flows may impair the vegetative cover on the banks due to prolonged submergence. If the present bank stability is a result of vegetative cover, then any vegetative reduction could impair bank stability. Additionally, prolonged, within-channel low flows may excessively erode the bank toe materials. The Elk River channel thalweg is nonuniform and, for such channels, low-flow point shear velocities may be an order of magnitude or more greater than average shear velocities. Toe instability could result if such point velocities were imposed on bank-toe materials for long periods of time. Such toe instability would critically affect overall bank stability.

If toe instability occurs, gravity-induced failure will become the dominant mode of channel instability. This is really a two-stage process involving a) failure due to gravity stress, and b) removal of the slough material by stream flow. Prolonged within-channel sediment-deficient high flows, sufficient to remove slough material, would regenerate the failure process, leading to acute bank instability problems. The probability of this type of acute instability developing in Elk River is unknown. I assume it is possible due to a) the longer duration of within-channel flows resulting from structural control of the present flooding and b) the prevalence of gravity-induced bank failure in both western Iowa and northern Mississippi. Detailed analysis of the valley-fill stratigraphic materials must be made to better define the possibility or probability of this scenario.

WORKSHOP QUESTIONS

As stated previously, the preceding discussion is not intended to be definitive but is presented to stimulate discussion. It is tempting to directly apply regime-type equations to the subject questions, but I have refrained from this exercise since I do not consider Elk River to be a true alluvial channel. The bed is controlled and the banks are not "free to adjust" as evidenced by their past and present stability.

Based on the apparent stability of the present Elk River channel, I believe that the proposed structural control of flooding will not result in any significant channel adjustment in the short term. Minor aggradation may occur at tributary confluences but this feature should be relatively inconsequential. In the long term, bank stability will determine the changes in channel morphometric characteristics; such changes will be site specific and inherently nonregime in nature. Quantification of the possible changes will depend upon the relative significance at each site of vegetative and stratigraphic controls relative to hydrologic erosive conditions, particularly those associated with nonuniform flow. These conditions and controls are not presently defined.

Three possible scenarios are outlined for long-term stability and, for each of these cases, bank toe stability is the critical condition. These scenarios are: a) the bank toe will be stable, b) the bank toe will be unstable and bank failure will depend primarily upon hydraulic stress and c) the bank toe will be unstable and bank failure will be progressive, resulting from gravity induced failure with subsequent removal of the slough material by high-stage flow. None of these possible scenarios would result in regime-type channel changes.

Insignificant channel adjustment will result from implementation of the flood control program if the bank toe materials remain stable. More pronounced instability will occur if the toe material is unstable; the degree of bank instability will depend upon stratigraphic controls.

If the present banks are composed of in situ cohesive valley-fill materials, the channels will widen but at a relatively slow rate. Timber falls into the channel could create excessive secondary flow conditions leading to accelerated bank instability. As channel widening progressed, pool depths could become somewhat shallower and the substrate materials would become somewhat finer. The riffle-pool sequence and the sinuosity pattern would be unaffected, however. In this scenario, the vegetative cover is a result of the relatively large resistance to erosion of the stratigraphic materials. Channel width would approach a "limiting width", beyond which the imposed flow would be unable to cause detachment.

The worst possible scenario is that the present banks are composed of slough materials, residual from some past cycle of bank instability. In this scenario, the present stability is not related to stratigraphic controls, but to vegetative controls introduced in the past during a short period of atypical climatic conditions. Removal of the present toe materials resulting in exposure of weak stratigraphic materials would exceed the stability threshold and Elk River channel could "fall apart." Due to the present excessive depth of this channel, gravity forces would become the dominant bank stress, and the "limiting width" would depend upon the capacity of the flows to remove the slough materials. In this scenario, the influence of large storms would become progressively more significant. The channel would widen, possibly to the extent of forming a new floodplain at a lower elevation than the present one. If such a "rejuvenation" was allowed to reach completion, a new regime would be established. For this scenario, quantitative prediction of the channel characteristic changes is not possible since the distribution and properties of the valley-fill units are unknown. Certainly the channel width-to-depth ratio would increase (especially since the channel depth would be reduced). Meander size would probably decrease due to the reduction in within-channel peak flow and due to physical constraints by the new terraces (the present floodplain) but the change in sinuosity is unknown. Substrate material would become finer due to reduced flow velocities and the pools would fill and become shallower. The ultimate pool-riffle sequence is unknown. I must reiterate that the preceding scenario is the worst possible case. Such a scenario would be disastrous, potentially too disastrous to ignore. Channel reconnaissance should be performed periodically (every few years) to verify bank toe integrity and completeness of vegetative cover. Possibly this reconnaissance should be performed as an integral part of a case history documentation for Elk River. Such documentation would be invaluable for future planning in this or adjacent areas.

The preceding discussion of this workshop problem illustrates the significance of valley-fill stratigraphy. For predicting channel changes or general landscape reaction, we must understand the system in the field. Our detail of knowledge of these systems must be commensurate with the problems with which we are concerned. For predicting channel behavior. we must have a detailed knowledge of the distribution and properties of the valley-fill units. For this purpose, the process (formative) controls of the system must be established. Our preliminary studies have indicated that paleoclimate is the process control for the Holocene valley-fill sequence in northern Mississippi and possibly a large part of the Mississippi River drainage area. If this result can be verified, it would greatly simplify solutions to problems such as those posed to this workshop.