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A RENEWABLE RESOURCE IN
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SALMON-SPAWNING GRAVEL CONFERENCE

GEOLOGIC AND GEOMORPHIC IMPLICATIONS FOR GRAVEL SUPPLY

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ABSTRACT

There are important disparities between regions of western Washington regarding the volume and quality of gravel resources. The three major types of resource: Pleistocene meltwater deposits; recent alluvial deposits; and river channel bars, differ in their location, texture and sorting, extractable volume, and the environmental consequences of their exploitation. Evaluation of the first two types of resource requires the use of established geologic procedures for mapping, sampling, and textural and lithologic analysis. Decisions on whether to exploit river channel bars should be based in part of knowledge of availability of the first two resources. Channel bars constitute a renewable resource that can be harvested along some reaches without disrupting the channel morphology. However, the chance that careless harvesting will damage fish habitat, esthetic values, or channel stability is sufficiently great that considerable forethought and careful operation are necessary. We have proposed four steps be taken before a gravel mining permit is granted: (1) define the historical activity of the river at proposed site; (2) estimate bedload transport rate through reach; (3) evaluate probable impact of bar scalping on channel stability; and (4) require explicit information on proposed mining procedure.

KEYWORDS: Gravel mining, channel stability, gravel supply.

STATEMENT OF THE PROBLEM

Useful resources of sand and gravel are widespread, but in some places they are of small volume and are replenished slowly or not at all. The prodigious demands of modern industrial and residential construction frequently overtax the supply. In Japan, for example, the sand and gravel has been entirely removed from many river channels (1) and supplies must be imported from Taiwan. Even in less extreme situations, the excavation of sand and gravel may conflict with other resource values such as fisheries, esthetic and recreational values, or with the need for stable river channels in areas prone to flooding and channel shifting.

In the Pacific Northwest there are important regional differences in the availability and quality of sand and gravel and in the types of sources from which these materials can be obtained. This conference is particularly concerned with gravel in stream channels, but the pressure for harvesting construction materials from channels and the potential for reducing this pressure need to be discussed in the broader context of the various sources of sand and gravel (including rivers) and of the processes by which sand and gravel become available for harvesting within channels. In this paper we review the geologic and geomorphic constraints on the supply of sand and gravel in river channels and in alternative sources. We consider the possibility of estimating the quantity of the resource, and suggest some investigations that need to be directed toward this end. We also review the geomorphic consequences of exploiting each type of source.

IMPORTANT CHARACTERISTICS OF A GRAVEL RESOURCE

The location and accessibility of sand and gravel supplies determine the feasibility and cost of transport to the site of consumption. Thus, many deposits may be unused because they lie in valleys of the Cascade Range and Olympic Mountains, too distant from construction sites or roads. In some cases a trade-off may be necessary between the high cost of transport from distant sources and the environmental disturbance that may result from gravel operations at more accessible locations. At present, more than three quarters of the sand and gravel used in King County is produced in the western half of the county. Many of these sources will soon be exhausted, and others have already been rendered inaccessible by past and present urbanization.

The harvestable volume is another important resource characteristic but a distinction must be made between the total volume and the replenishment rate. In some rivers, large gravel bars may simply indicate long-term deposition rather than a rapid supply rate. If they are used for intensive extraction the bars will diminish, and channel realignment or other untoward consequences may result. In these cases it is necessary to assess the replenishment rate and the abstraction rate that will not disrupt the site or the channel downstream. Ancient terrace deposits may be very large but are not replenished at all. The constraint here may be the volume that can be mined without increasing the chance of stream-channel diversion, alteration of groundwater flow, or esthetic degradation.

Size distribution strongly affects the usefulness of a gravel resource. If the material is to be used for concrete, a wide range of size mixtures can be specified and often must be mixed to order, but the two most commonly-used size ranges are: "fine aggregate" containing particles between

1/50-inch (size 40 sieve) and 1/4-inch (size 4 sieve), and "coarse aggregate" composed mainly of gravel between 1/4-inch and 1 and 1/2-inch. Silt (smaller than a size 200 sieve) and particles larger than about 1 and 1/2-inches are usually removed by grading the natural mixture. The latter may be reduced by crushing which increases the cost of exploitation.

Coatings of fine sediment, oxides, or organic materials are particularly deleterious for concrete manufacture. Standards for artificial fills are less stringent but require a minimum of silt (usually less than about 5 percent) and an absence of organic material in order to assure high permeability and density of the fill. For surfacing rural roads, especially the extensive logging roads of the Pacific Northwest, a mixture of hard gravel and coarse sand is desirable but often impossible to obtain because of the cost of transportation over large distances in mountainous terrain.

A useful sand and gravel deposit should also be free of lenses of fine sediment. If fine-grained layers occur as an overburden, as in most of the lower Green and Stillaguamish valleys, removal increases the cost of exploitation and usually precludes mining if the overburden depth exceeds about 20 feet. However, if the overburden consists of sand, it may be mixed with the gravel according to specification for aggregate.

Finally, the lithologic and mineralogic properties of gravel are important constraints upon use, for they determine the durability of the gravel against crushing and weathering. In western Washington, granite, diorites, gabbros, quartzites, andesites and some basalts are the most durable lithologies found as gravel, while the weakest rocks include slightly indurated sediments derived from volcanic rocks, easily cleaved schists and phyllites, mudstones, and some intensely weathered basalts. The use of mechanically weak rock on logging roads in areas such as the Olympic Mountains may be particularly deleterious to fisheries. In that region the most durable sandstone and siltstone gravel is found in major stream channels. When spread onto logging roads this gravel lasts for one to several years, depending on the intensity of traffic. The rapid rate of breakdown requires frequent harvesting of gravel from streambeds, and erosion of the products of the breakdown yields fine sand and silt which infiltrate streambed gravels and reduce the spawning success of anadromous fish (Cederholm, this volume).

Some rock types are unsuitable for concrete because they react with mortar. Andesite, which constitutes from 10 to 30 percent of gravel in deltas of King County and is common in river valleys draining the Cascade volcanoes, reacts with alkali mortar and expands (2). The rock minerals should be relatively resistant to weathering so that they do not release sulfides or iron oxides. Thus glassy rocks and those containing cryptocrystalline minerals are not suitable. A significant proportion of the sand and gravel in the White River valley and in other valleys draining the recently active Cascade volcanoes is less than ideal for concrete aggregate for these lithologic reasons.

GEOLOGIC BACKGROUND OF GRAVEL SUPPLY

The distribution of desirable sand and gravel in western Washington is determined by the major geologic subdivisions of the area and by the extent of glaciation (2). Figure 1 is a generalized map of the major types of lithology to be considered. The North Cascade Mountains and southern

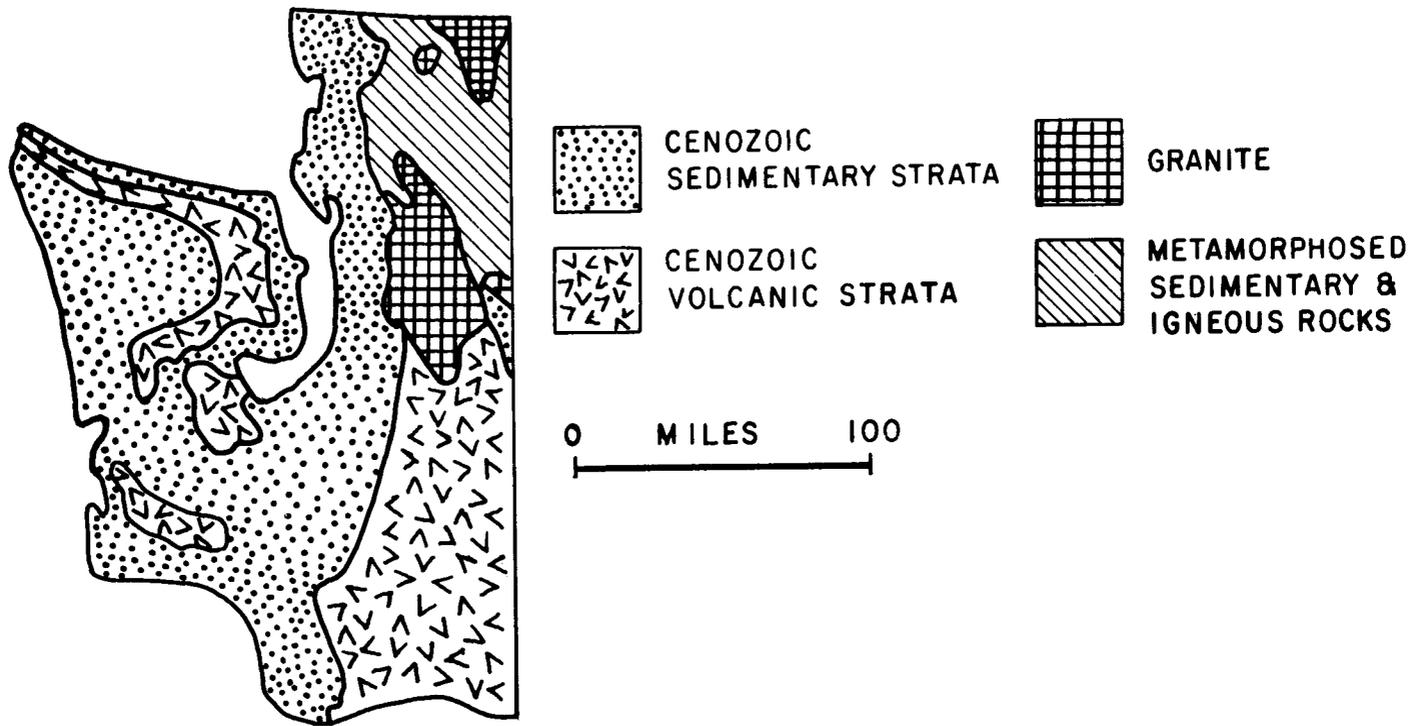


Figure 1. Generalized geological map of western Washington.
Source: McKee (15).

British Columbia are underlain by hard, crystalline, igneous and metamorphic rocks. Not all of the metamorphosed and sedimentary rocks of the region are durable, but this northeastern zone is the source of the most useful gravel in the state. Sand and gravel were carried from the North Cascades by glaciers and meltwater streams and were deposited in the Puget Sound lowland during the most recent glaciation (approximately 15,000 years ago). Deposits from preceding glaciations (more than 50,000 years ago) are buried by later deposits, or have been eroded, or are too weathered or too indurated to be useful as sources for sand and gravel. The southern Cascade Range consist of weaker volcanic lavas and breccias, mainly andesites and some (more durable) basalts. The Olympic Mountains contain particularly weak sandstones and siltstones, with slightly more durable volcanic rocks in the north and east. Bedrock in southwestern Washington is dominated by intensely weathered, mechanically weak, sedimentary and basaltic volcanic rocks.

As the most recent glacier entered the Puget Sound lowland it probably encountered terrain similar to the present one, with uplands and river valleys. The ice advance blocked the northward drainage to the Strait of Juan de Fuca, forming a large lake in the central portion of the Puget Sound lowland. Streams draining into this lake from the ice sheet and from the mountains to the east and west produced widespread deposits of silt and sand; however, much of this material was subsequently either scoured out by the advancing ice or covered with glacial till: a non-sorted, non-stratified mixture of sand, silt, and clay deposited beneath the glacial ice.

As the ice withdrew, it uncovered a glacially-sculpted landscape of uplands and intervening valleys. Because the ice still blocked the northward drainage of the Puget Sound lowland, the valleys were again occupied by lakes. It was during the retreat of the glacial ice that most of western Washington's sand and gravel were deposited. The deposits generally originated in one of three forms: as meltwater channel deposits which were left behind by the glacial outwash streams that coursed across the uplands, as kame deposits which were left behind by streams flowing between the remaining ice and the adjacent valley walls, and as glacial outwash deltas that were deposited where the meltwater streams entered the proglacial lakes. Of these three types of deposits, the glacial outwash deltas are the most important gravel resource because of their volume and composition of well-sorted, clean gravels with only minor silty lenses. Meltwater channel deposits have poorer sorting and frequently contain deleterious quantities of silt, while the kames are generally of intermediate character. The kame and delta deposits form prominent benches at elevations up to about 100 m along the sides of major valleys within the glaciated region. Meltwater channel deposits are present both within the glaciated area and also along valleys, such as the Chehalis, which lay immediately south of the ice boundary and received meltwater from it.

After the ice retreated, the streams draining the Cascades and the Olympics began to fill the glacially-sculpted valleys and inlets of the Puget Sound lowland. This recent alluvium consists of material deposited within the channels of the ivers and also overbank deposits left on the valley floors during floods. The channel deposits generally consist of gravel and sand, while the overbank deposits generally consist of fine sand and silt. In some places these sediments constitute the present floodplain, while in others they form terraces a few meters or a few tens of

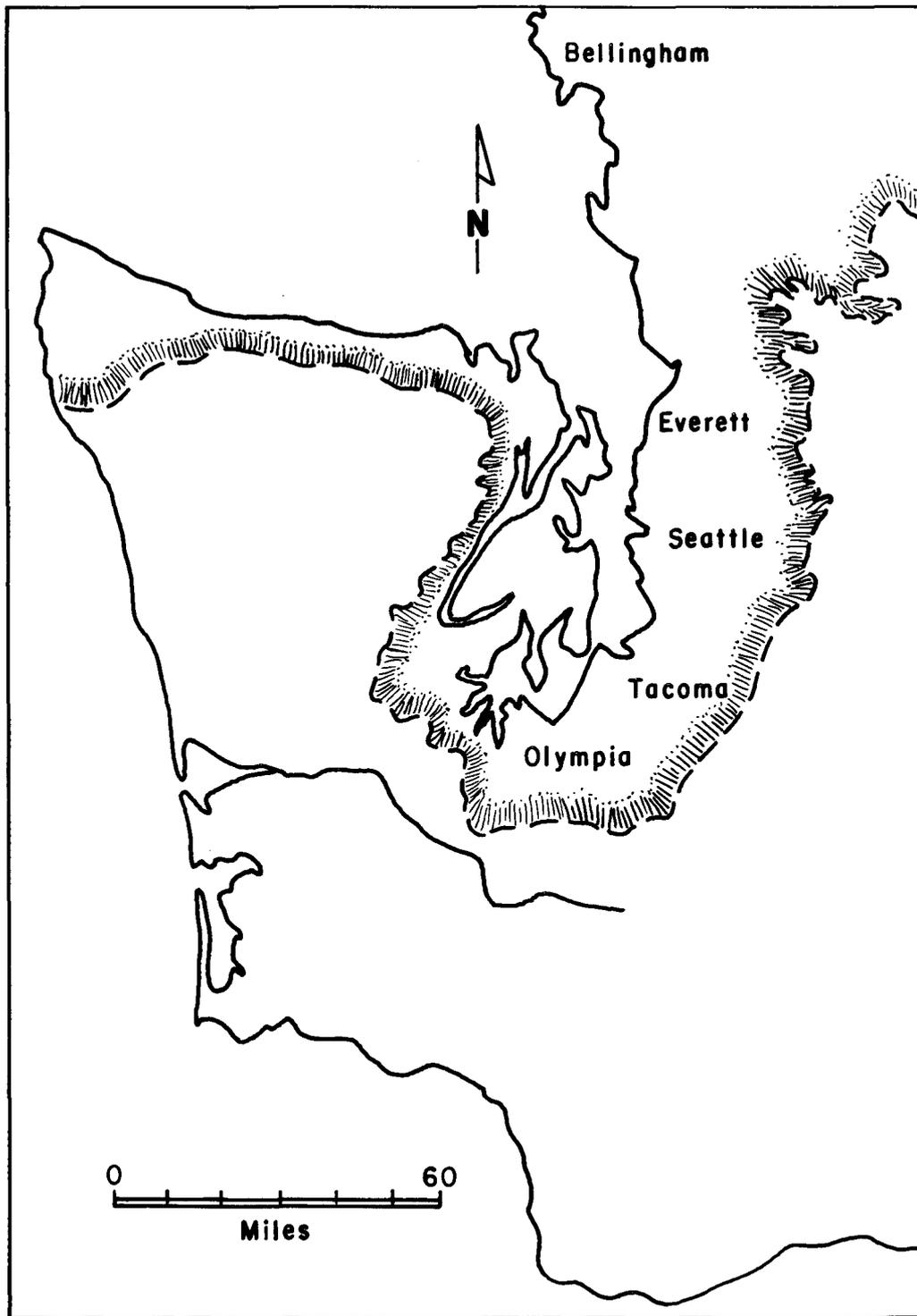


Figure 2. Extent of Fraser glacialation.
Source: McKee (15).

meters above the present river channel. Locally, such as in the Cowlitz valley above Toledo, the recent alluvium can be an important sand and gravel resource.

Today the streams of western Washington continue to transport sediment toward the Puget Sound lowland and the Pacific Ocean. The material being transported by these streams includes sediment deposited temporarily as sand and gravel bars on the inside of river bends or in mid-channel. Over the long term, the channels in western Washington are not sources of sand and gravel, but only conveyors and temporary storage places for sand and gravel that is in transit downriver. The sediment originates from a variety of sources. Soil that has crept slowly downhill over thousands of years eventually reaches a streambank from which it is scoured by high flow. Occasional landslides inject large slugs of material into channels, from which the stream picks up sediment for many years. Other sediment is eroded by the river as it undermines glacial meltwater deposits and recent alluvium.

The finest fractions (silt and fine sand) of the sediment from these sources are washed rapidly downstream as suspended load and are deposited in the lower reaches of the major rivers or are filtered from overbank flows by vegetation and contribute to the vertical accretion of floodplains. The larger particles move by rolling and sliding along the river bed and travel only short distances in most years. Measurements and calculations in other regions suggest that the average annual distance of movement of this bed load ranges from almost zero for boulders to several hundred meters in exceptional floods. Thus, it would take hundreds or thousands of years for gravel to negotiate the length of the Skykomish or White Rivers. Coarse sand moves as suspended load along some reaches during large floods in the region, and as bed load in other places and events; it generally travels distances of a few hundred meters to a few kilometers in a year.

For the harvesting of sand and gravel, the bedload is the most important fraction of the sediment load and it travels almost exclusively at high flow. The sediment does not travel uniformly over the whole width of the channel; most of it follows a sinuous path between and over bars on alternating sides of the channel, as shown schematically in Figure 3. It is this migration over bars that replenishes extraction sites in favorable locations. As each flood declines, a poorly-sorted mixture of sand and gravel bedload settles out on the bed and bars of the channel. Sand particles are winnowed out of the surface layer by the declining floodwaters, leaving a coarse lag or "armor" layer. In order to observe the distribution of sediment sizes that constitute most of the bar, it is necessary to shovel away the upper layer of gravel. In each flood, the upper few decimeters of the bar are scoured away and replaced by a more-or-less equal layer of sediment transported from upstream.

The ability of a river to transport sediment of various sizes may change along the channel. An index of this transporting ability may be obtained from the computed total boundary shear stress, or average intensity of fluid drag per unit area of the bed. This measure is obtained from the product of the specific weight of water, the flow depth and the water surface slope. In most rivers there is a general increase in flow depth as discharge increases downstream, and a less regular decrease in

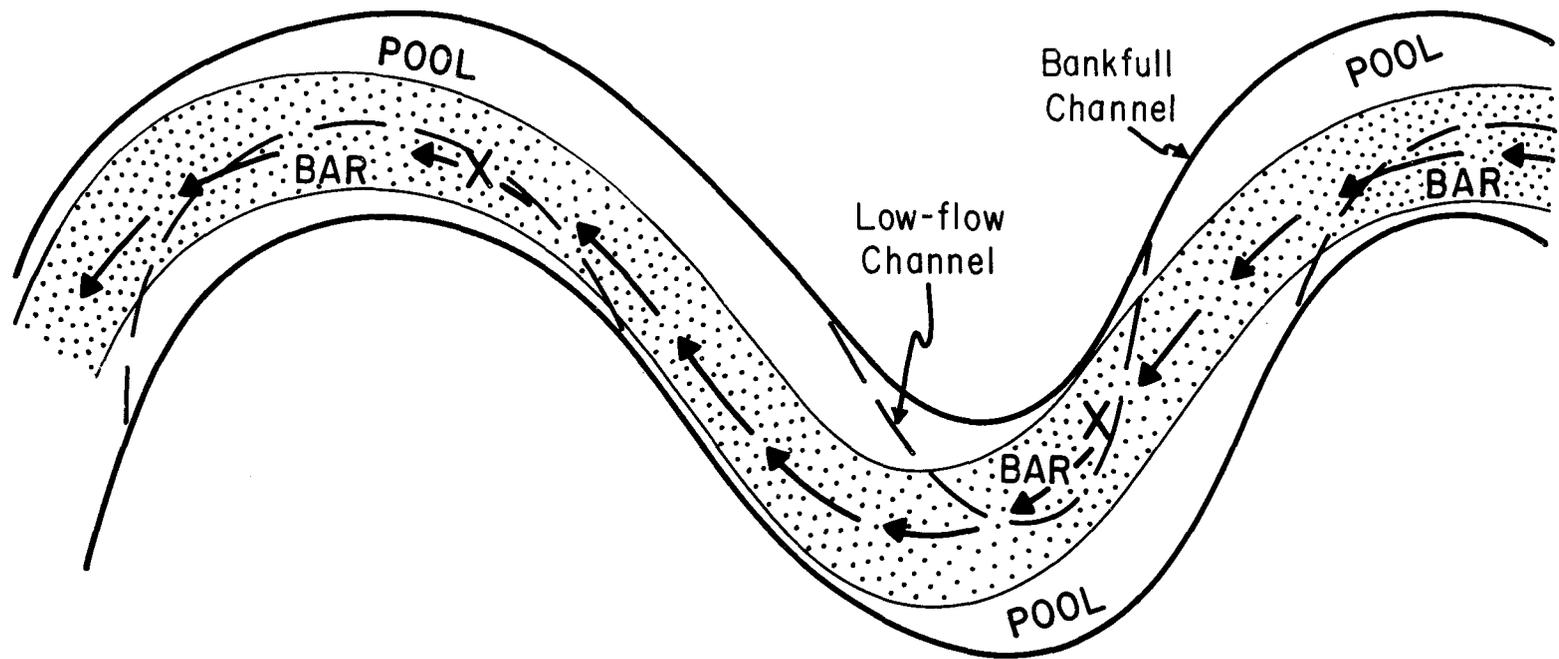


Figure 3. Schematic diagram of the path of most intense bedload transport (shaded areas) in relation to the bars and pools of river meanders.

gradient. In western Washington, the transition from mountains to lowlands imposes on the river a particularly sharp decrease in gradient and shear stress, although the change is not necessarily monotonic, as shown by the example in Figure 4. The downstream decrease in the river's ability to transport sediment leads to deposition in the reaches of sharpest decline. The larger particles are deposited in the upstream reaches of higher shear stress, while finer gravel and sand are carried downstream until they encounter a zone in which they can no longer be transported. This selective transport and sorting of bedload usually causes a general downstream decrease in the size of particles deposited on the channel bed and bars, as indicated in Figures 4(a) and 5. Such graphs are a useful part of any reconnaissance for gravel, because they allow one to choose reaches with the most favorable particle-size distribution for gravel mining or other uses.

A second result of changes in shear stress along a stream can be observed along reaches of the Green River where the river's ability to transport sediment declines most rapidly. Figure 4a indicates that in two reaches: between the Green River Gorge (River Mile 42) and Auburn (River Mile 28) and between the Black River (River Mile 10) and the Duwamish estuary sharp decreases in gradient cause a sharp drop in the size of particles on the channel bars. Each of these zones is also characterized by net accumulation of sediment, rapid bar formation and relatively intense channel shifting (Figure 4b). Such a reach offers the best opportunities for gravel harvesting without diminishing the size of gravel bars.

A similar zone of net gravel accumulation occurs in the Skykomish River immediately above its confluence with the Snoqualmie. In this case the lower Skykomish River and the Snohomish River below the confluence do not exert sufficient shear stress on the channel bed to transport the gravel bedload supplied by the steeper upstream reach of the Skykomish. A small amount of coarse sand and fine gravel, some of it suspended load while in the Skykomish, settles out as bedload in the Snohomish River and constitutes the gravel bars there. The bedload of the Snoqualmie River, which consists of fine and medium sand immediately above the confluence, becomes suspended load in the deeper and steeper Snohomish channel. When assessing the potential for gravel mining in channels or the possibility of some disturbance of a fluvial sediment transport system, it is often necessary to recognize such interdependencies. For example, if one were to assign gravel harvesting permits for neighboring bars in the Skykomish River it would be necessary to consider that the harvesting operations would be competitive in the sense of exploiting the same resource, namely the bedload of the Skykomish. However, bar scalping in the Snohomish River below the confluence would involve only the coarsest fraction of the suspended load from the Skykomish and a small proportion of its finer bedload. Hence, there would be little competition between a scalping operation on the lower Skykomish and the upper Snohomish reaches.

ESTIMATING THE RESOURCE

At present only rough estimates can be made of the harvestable volume of sand and gravel in western Washington. Different concepts and procedures are necessary for estimating the harvestable volume in each type of source. Meltwater channel deposits, kames, deltas, and recent alluvium have fixed volumes that are not being replenished. Their

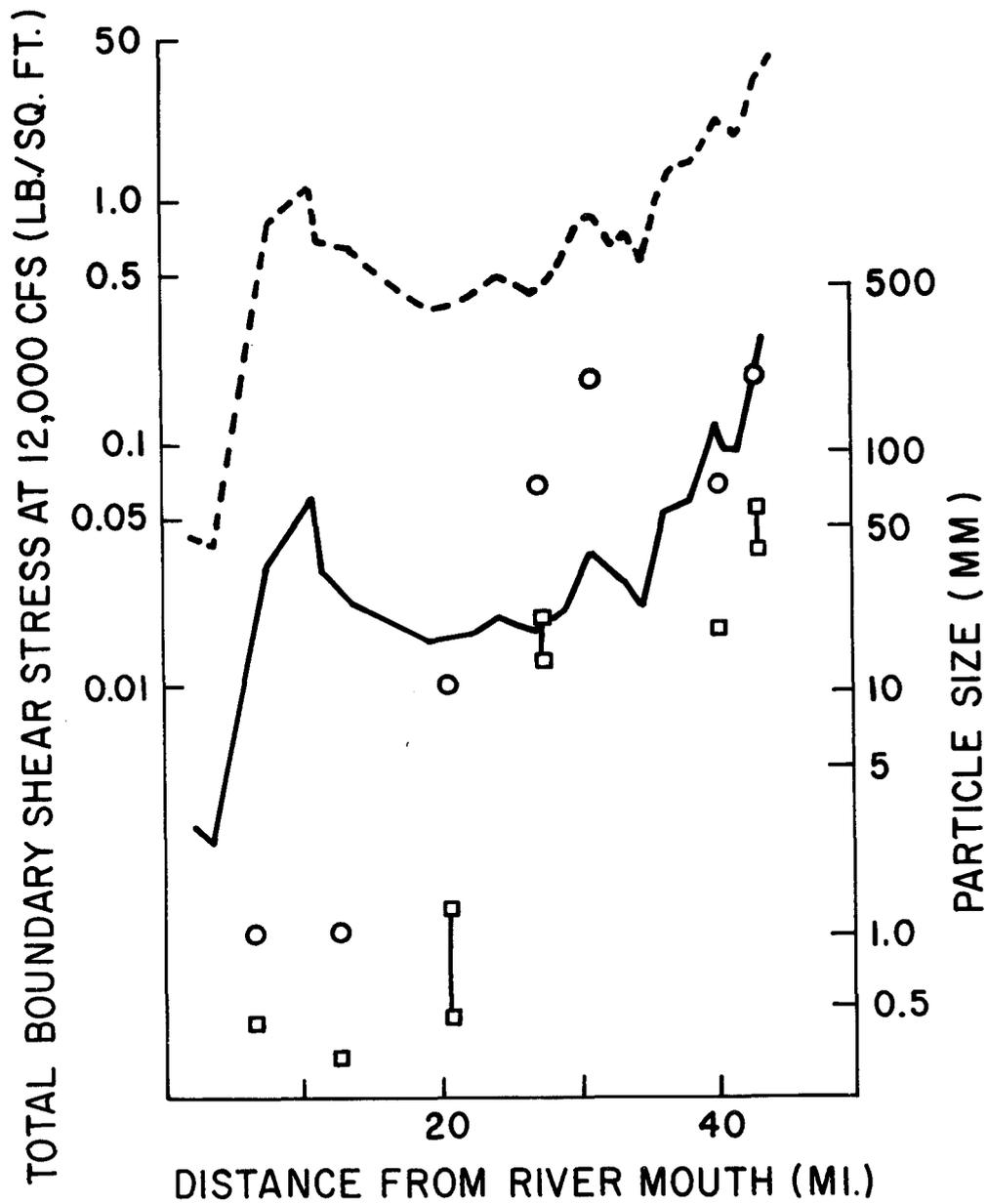


Figure 4a. Variation of total boundary shear stress (dashed line), maximum particle size that can be transported (solid line), and maximum (circles) and median (squares) particle size found on channel bars along the Green River, Washington, at a discharge of 12,000 cfs.

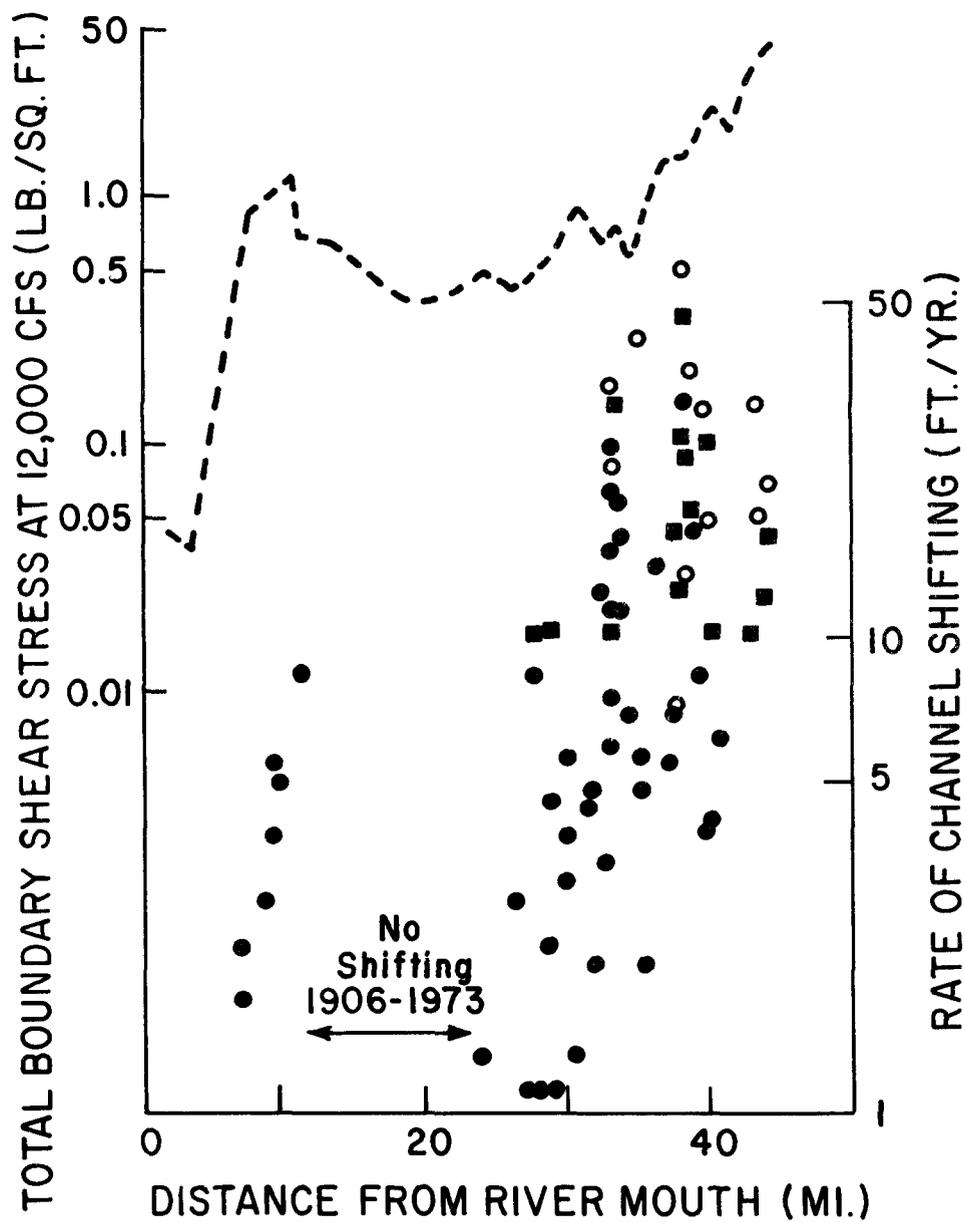


Figure 4b. Variation of total boundary shear stress (dashed lines), and rates of lateral channel shifting during the periods 1893-1973 (solid circles), 1943-1973 (open circles), and 1968-1978 (solid squares).

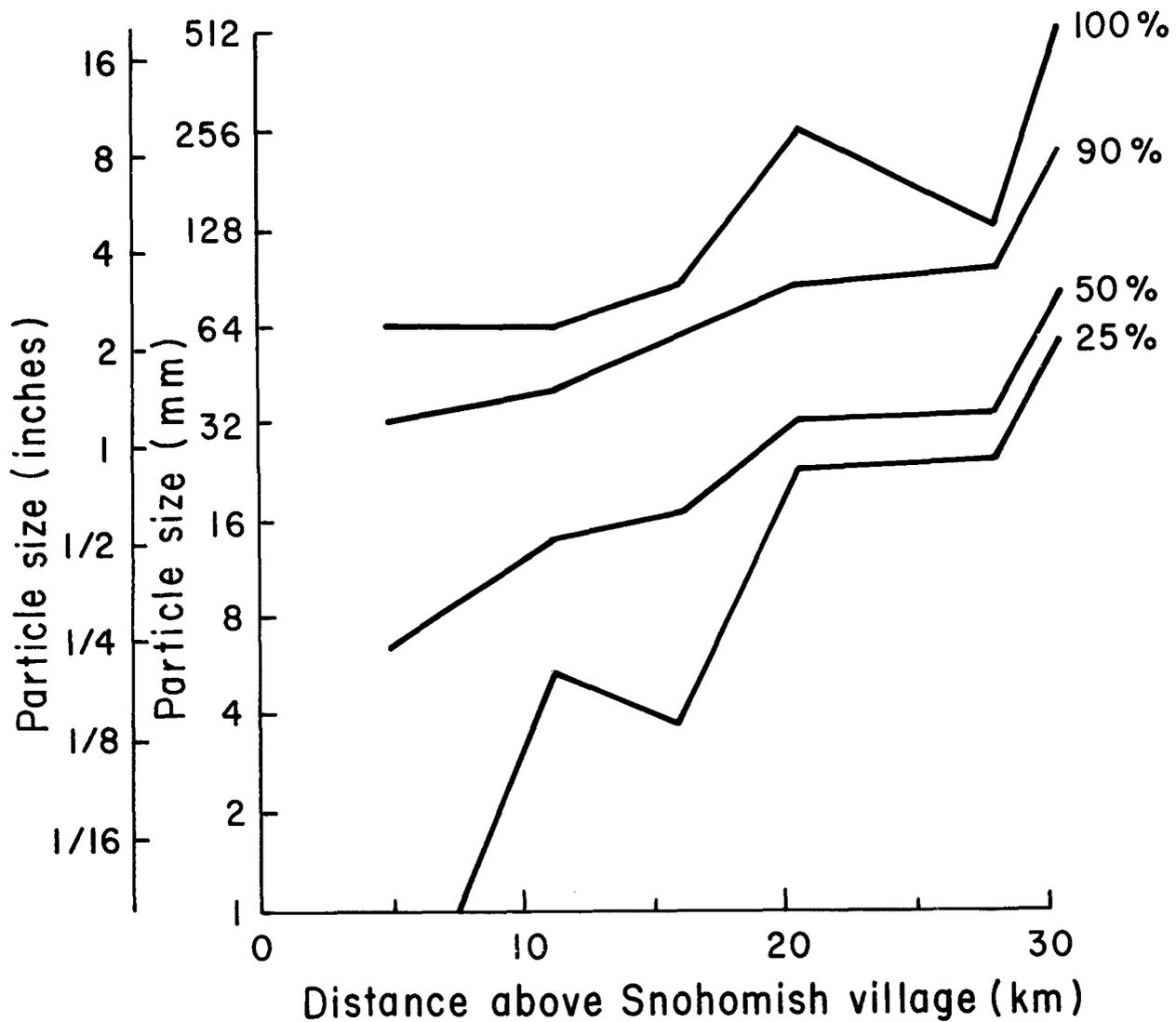


Figure 5. Downstream decrease of particle size on channel bars along the Skykomish-Snohomish River. Each line indicates a percentile on the grain-size distribution curve. Thus for a channel bar at any distance along the river, one can read the particle size which exceeds 25, 50, 90, and 100% of all gravel on the bar.

exploitation constitutes mining, whereas channel bar deposits are replenished intermittently by floods. In the latter case, estimation of the resource involves determining the rate at which sand and gravel can be removed without unacceptable damage to some other stream value such as fisheries or recreation.

Static Sources

The locations of many large static sand and gravel bodies (meltwater channel deposits, kames, deltas, and recent alluvium) in western Washington are known approximately. Some of these are accessible enough to be used in the near future as existing sources become overtaxed. However, some of the deposits are also attractive sites for urban development. They constitute flat, well-drained building sites with spectacular views and are thus likely to be zoned for residential use, which conflicts with mining activities. Some of the largest sand-and-gravel resources could be preserved for mining if they were zoned for that purpose. This can only be done if government authorities are sure of the volume and quality of the resource, and that its exploitation will not conflict with other planning goals. Present estimates involve only educated guesses about volumes in a few areas (e.g. 2) and there has been little or no assessment of the internal constitution, size distribution, and durability of the deposits, or of the engineering, ecological, esthetic, and transportation-related aspects of their exploitation. Hence the need for a program, under the auspices of an agency such as the Washington State Division of Geology and Earth Resources, to evaluate gravel resources quantitatively.

Such a program would involve detailed mapping of the local surficial geology with the particular aim of precisely defining the boundaries of large sand and gravel bodies. Each important deposit should be examined in detail so that the depth of overburden and the thickness of unsuitable silty layers can be established and taken into consideration in analyzing tonnage and the economics of exploitation. For some deposits a program of drilling would be necessary to measure the depth of the deposits and to obtain samples from throughout the deposit for analysis of particle-size distribution and durability. Such a program requires substantial investment of funds and the involvement of some well-trained, critical field geologists, but it would assure western Washington of adequate gravel supplies for the foreseeable future.

In the absence of such a program, sand and gravel sources in western Washington can be only crudely estimated. Kroft (2) compiled an approximate list of glacial outwash deltas in western King County. He estimated the volume of available (i.e. not urbanized) delta deposits at 1.25 billion cubic yards, of which at least 22% (the data are not exactly consistent) have already been exploited. The largest remaining sources lie in the Snoqualmie Valley. An additional 890 million cubic yards were estimated to exist in meltwater channel deposits (Figure 6), two-thirds of which are in the Covington channel. Approximately another billion cubic yards of recent alluvium lie within 20 feet of the surface, mainly in the Snoqualmie Valley, but these deposits are highly variable and silty. Coarser material is available in the Skykomish Valley.

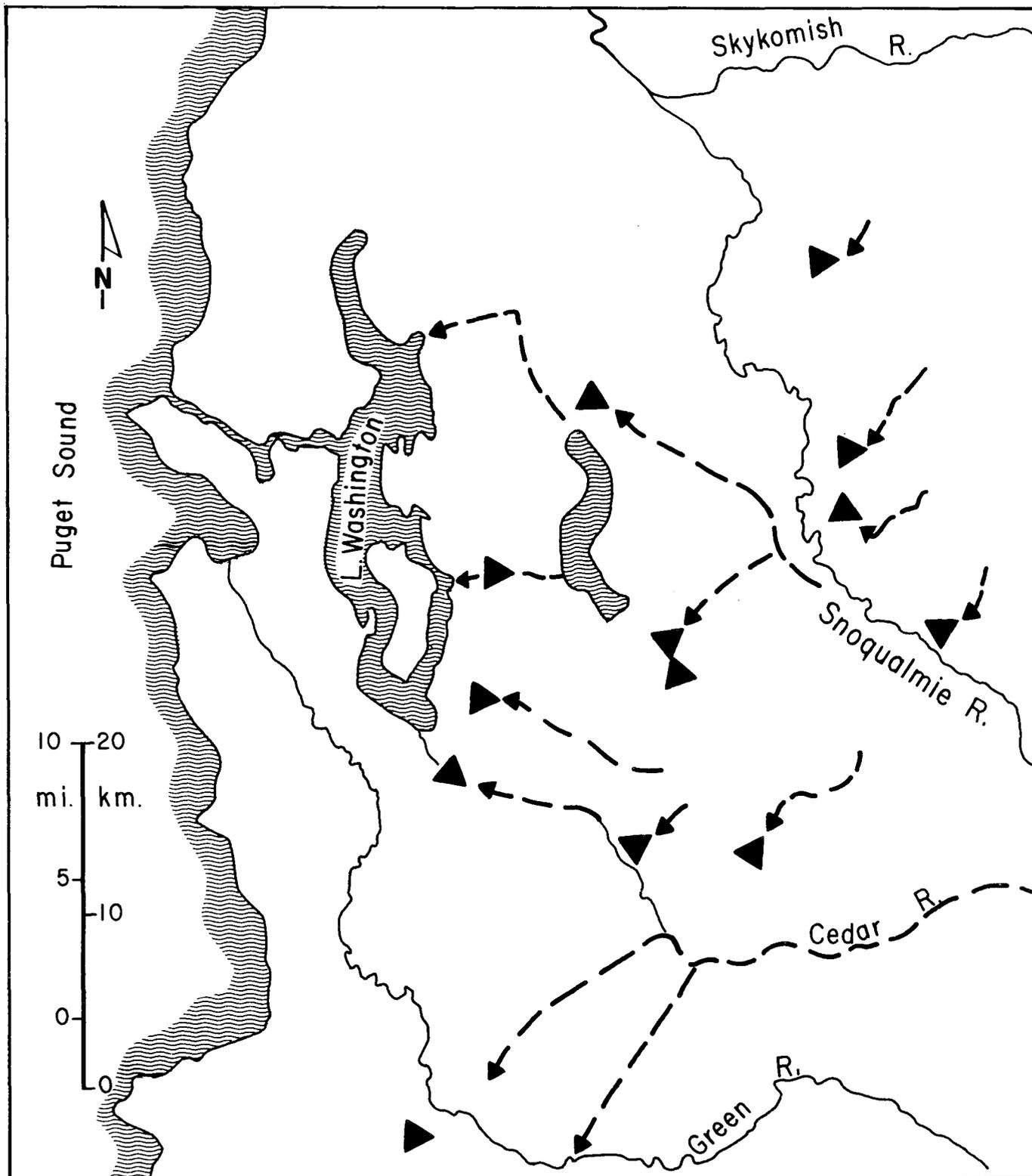


Figure 6. Distribution of glacial deltas (triangles), and major meltwater channel deposits (dashed arrows) in King County. Based on a map by Kroft (3) and our field observations.

River Channel Bars

The channel bars along some reaches of large rivers in western Washington constitute a renewable resource of sand and gravel which can be harvested without significant damage to the channel if proper care is taken. However, the maximum annual harvest that can be taken without significant alteration of the channel is small relative to that available from the static sources described above. The bars are a desirable source because they often lie close to the market in the middle reaches of rivers; they consist dominantly of the most useful sizes from medium sand up to 3 inches in diameter; and because most of the mechanically weak lithologies have been broken down and transported far downstream as suspended load. Thus the river gravels tend to be "cleaner" and harder than the mixture of sediment that enters the stream, or than some Pleistocene deposits that have been weathered.

Estimation of the harvestable amount of sand and gravel from a river channel is a complex problem, which cannot be adequately solved at this time for western Washington rivers. However, by an approximate analysis it is possible to outline the constraints on harvesting and the data needed for refining estimates.

It is necessary to know first how much sand and gravel is being transported across the channel bars at a particular river cross section, and second how much of the bar material can be removed each year without disrupting the sediment transport system enough to diminish the area of spawning gravel, or to cause channel instability or other undesirable effects. These two quantities are not equal. Channel bars are temporary storage sites through which sand and gravel pass. Most bars are in approximate equilibrium, so that the influx and downstream transport of material are equal when averaged over a number of years. If all of the sand and gravel reaching such a bar is removed, the supply to bars downstream will diminish. Since sand and gravel will continue to be transported from these downstream bars by the river, their size will decrease. Other bars, in certain recognizable reaches of the river, constitute the points of final deposition (on a human time scale) for gravel, while the sand fraction may be carried further downstream. The most favorable places for finding rapidly accumulating gravel deposits are reaches with rapidly declining shear stress, such as that between river miles 42 and 34 in Figure 4. In such zones it is common to find rapid evolution of point bars, and mid-channel bars, intense channel shifting (Figure 4b) or avulsion, and frequent burial of vegetation and other floodplain features.

We will deal first with techniques for estimating the flux of coarse sediment across a channel bar and later with the problem of estimating the volume that can be harvested without diminishing other gravel bars in the vicinity. We will illustrate the problem with an example for the Snohomish River system (4). Unfortunately, theoretical equations for computing bed-load transport rate do not work well in the coarse-bedded rivers of the Pacific Northwest. These formulae are based on the assumption that the factor controlling sediment transport is the river's capacity for transport, and therefore the gradient and depth of velocity. In thickly-vegetated catchments the influx of sediment from the drainage basin is usually less than the river's capacity for transport, so that influx rate limits channel sediment transport. Thus, our attempts to apply the Einstein (5) and

Leopold-Emmett (6) methods yielded bedload rates many times greater than measured values (see later).

Rates of bedload transport have been measured at only one site in the Snohomish River basin: on the main channel near Snohomish village (7). The bedload measurements were collected by personnel of the U.S. Geological Survey, using a Helley-Smith bedload sampler (8). Only nine measurements were made, but they sampled the high range of flows (including the major flood of December, 1975) that transport most of the river's bedload. We have used these scanty data to construct a bedload rating curve, shown in Figure 7. The regression line is not well-defined, but it indicates that only a few hundred to a few thousand tons per day are transported along the bed. Such measurements could be augmented and extended to other sites on the river system relatively easily. We used this rating curve in combination with 10 years of daily flow records (1967-1977) from the U.S. Geological Survey to calculate the average annual rate of bedload transport past the site. The average was 26,000 tons/yr or 15,000 yd³/yr (9), but varied strongly between years.

Bedload measurements are not made routinely on most rivers. In depositional zones of some rivers, repeated surveys of channel cross-sections allows the computation of long-term average rates of accumulation (10), but such measurements are rare, and must be carried out over many years to yield useful averages. In the absence of methods for direct assessment of bedload, one must resort to very rough, indirect methods using the yields of suspended load.

Bedload typically constitutes only a small fraction of the total load of most rivers; suspended load is usually the dominant component. A survey of published values of the ratio between annual bedload and annual total load for rivers in various parts of the world (11, 12) indicates an average proportion of 3.5 - 5 percent for lowland rivers and of 10 percent for hilly to mountainous basins. Thus, if the bedload contribution is symbolized by Y(%), one can write

$$\text{Annual bedload transport} = \frac{Y}{(100-Y)} \times \text{Annual suspended load transport}$$

It should be emphasized that such a computation is very rough, and that even the suspended load transport is rarely known to within 10%. Nevertheless, the technique should yield the correct order of magnitude for the bedload yield, and it can be checked by other procedures referred to in this paper.

The annual suspended sediment transport in the Snohomish River was estimated from U.S. Geological Survey (7) measurements, shown in Figure 7, and daily flow records (also from the USGS) for the decade 1967-1977. The computed yield was 501,000 tons/year. The Snohomish River just below the Skykomish-Snoqualmie confluence is a lowland river but its bedload is strongly affected by the settling out of suspended load from the steeper Skykomish River. Therefore, a value of Y on the upper end of the range for lowland rivers seems appropriate. If Y = 5% is inserted into the equation above, one obtains a bedload yield of 26,000 tons/yr (15,000 yd³/yr). The exact agreement with the preceding calculation of bedload is fortuitous, but suggests that the indirect method should give approximately correct values.

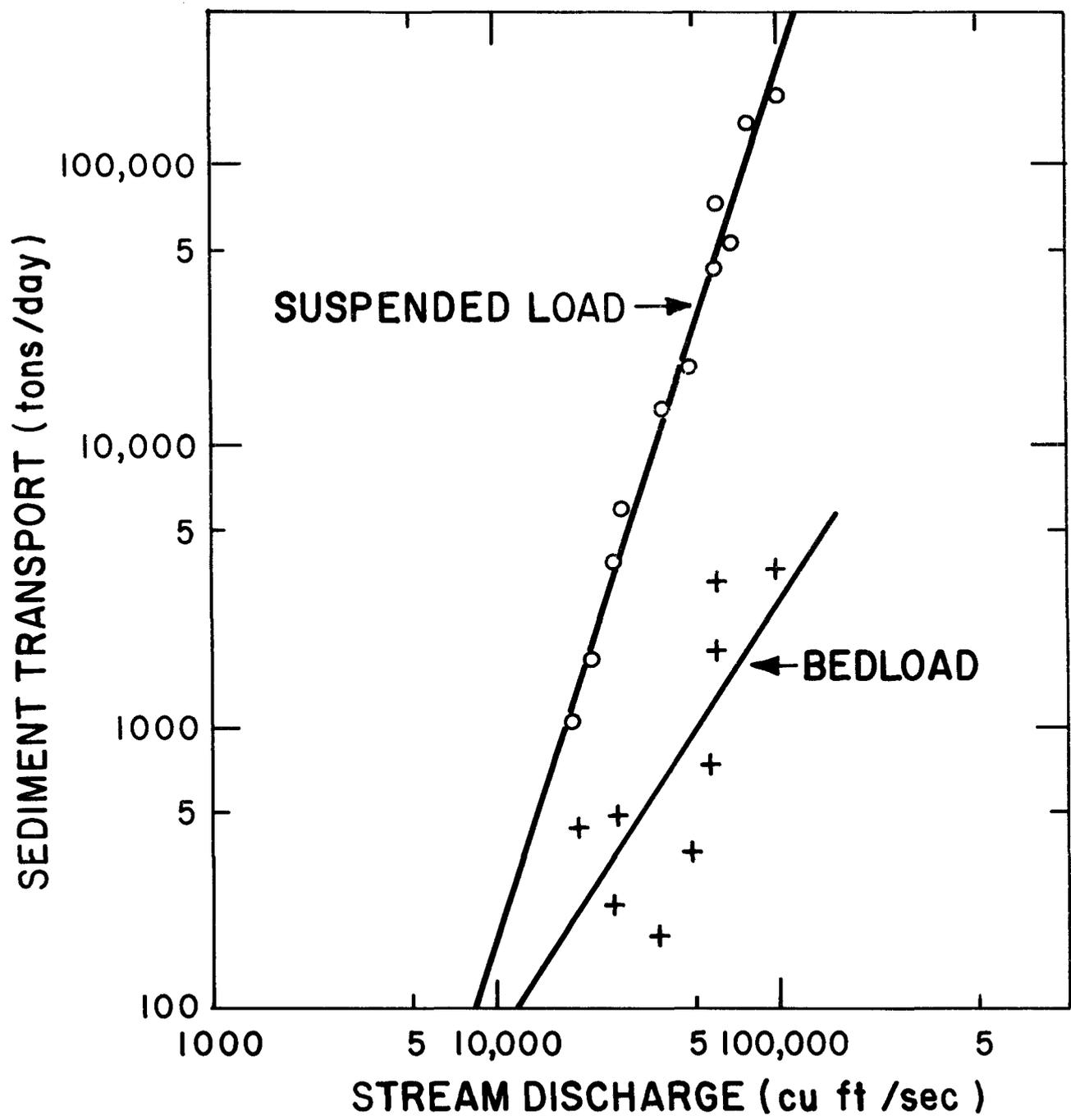


Figure 7. Suspended load and bedload rating curves for the Snohomish River at Snohomish Village. Based on Geological Survey measurements in (7).

We have made similar computations for other stations in the Snohomish basin, using the suspended sediment data of Nelson (13). Differences between bedload yields at various stations agree with our qualitative observations of the pattern of sediment accumulation along the river channels (4).

Even more indirect values for bedload transport rates can be obtained through compilation of suspended sediment yields from basins throughout the region. These data are obtainable from various U.S. Geological Survey publications and files and from a few journal articles. Within a region of relatively homogeneous physiography, climate, vegetation, and land use, it can be expected that basin sediment yields will cluster within certain definable limits. For example, Nelson's (13) data show that almost all of the annual sediment yields in the Snohomish basin lie between 100 and 700 tons/mi² of basin area, while other USGS file data indicate similar yields in other basins on the west side of the Cascades, yields of 10-100 tons/mi²/yr in the upper Columbia basin, and 500-5,000 tons/mi²/yr in the Coast Ranges of California. These are broad ranges to be sure, but in combination with the finding from many other regions that average annual bedload yields are generally of the order of a few percent of total yield, these values can be used to estimate the order of magnitude of the bedload supply. For example, one can state with some confidence that a site on the Skykomish River which receives drainage from 300 sq. mi should have a bedload transport between 5000 and 20,000 tons/yr. These are wide limits, but the point is clear that the supply is small by comparison with the industrial demands for gravel in western Washington. Although the big rivers produce desirable gravel, they can supply only a small fraction of the market demand, and because the supply varies with flow conditions it will be exceedingly small in some years. The only way to refine these estimates at present is to initiate a program of bedload transport measurements by the methods referred to above, and to refine the application of theoretical computations on the basis of these measurements so that interpolations can be made between sampling sites.

Figure 3 indicates that not all of the bedload transport occurs over the portion of a bar that emerges from the water and can be scalped in summer. Harvesting of all or most of the bedload passing a site would interrupt the supply to downstream bars and diminish or even eliminate them. Channel banks would be undermined in new locations, the river could shift unpredictably, and damage would probably occur to structures and to spawning areas. For this reason, gravel harvesting should be conducted in such a way that a considerable fraction of the bedload arriving at a site is allowed to pass on to downstream bars.

Unfortunately, no method exists for computing how much sediment should be allowed to pass downstream to maintain the channel bars. The problem can only be addressed empirically at present by observing channel changes that result from various rates of gravel extraction. The best record of channel changes is usually that from aerial photographs. For example, we obtained air photos of gravel bars in the Skykomish and Snohomish Rivers taken in 1948, 1961, 1969 and 1976. Changes in bar area could be measured on the photographs (after adjusting for the effects of differences in water elevation), and changes in bar elevation could be estimated with the parallel bar accessory to a mirror stereoscope. Records of gravel extraction from various bars indicated that the average extraction rates for the periods

between photographs had ranged from zero to 84,000 tons/year.

For example, one bar in a six-mile zone, for which differences in sediment yields had indicated the accumulation of between 5,000 and 21,000 yd³/yr, grew by 3,000 yd³/yr between 1948 and 1961 in the absence of gravel harvesting. Between 1961 and 1968, an average extraction rate of 50,000 yd³/yr decimated the bar, and slightly diminished the adjacent bars upstream and downstream. During the period 1969-1976, when the extraction rate declined to an average of 15,000 yd³/yr, no significant changes were observed.

Although these observations are complicated by the vagaries of flow and sediment transport as well as by vague records of extraction, they suggest that 10,000 to 15,000 yd³/yr could be removed from this bar or one of its neighbors without causing a long-term erosive trend. Such a harvest could not be taken from more than one bar, although the total harvest could be divided between several sites. A reasonable policy in such a case would be to limit extraction in the reach to perhaps 12,000 yd³/yr and to monitor the results over a number of years, either by ground survey or photographically. If there are no unfavorable effects, the limit could be cautiously raised. However, doubling of the offtake would remove more gravel than enters the reach, and could not be maintained for long. Other case studies are reported elsewhere (4).

In some channel reaches, extraction limits need to be set in the absence of either aerial photographs or of earlier extraction records. In such cases, a reasonable initial policy might be to limit total offtake from the bars in a reach to one half of the estimated annual bedflow influx. The resulting channel behavior can be monitored and the limit decreased or raised cautiously if appropriate. Where sequences of aerial photographs show that the bars are diminishing even in the absence of gravel extraction, harvesting is not likely to be a wise policy.

ENVIRONMENTAL IMPACTS OF GRAVEL EXTRACTION

Exploitation of the various gravel sources referred to in this paper could have deleterious consequences that could be minimized with foresight and an understanding of the geomorphic basis of the hazard.

Pleistocene Meltwater Deposits

The most frequent consequence of exploiting these highly visible features is the creation of an obvious scar in the landscape. Also, during their active lives the quarries are unsightly, dusty, and noisy. These problems could be reduced by designing the quarry to reduce its visibility, and by regrading and revegetating the site after its exhaustion. Removal of vegetation and disturbance of slopes and dirt roads by heavy vehicles can generate an important local source of sediment that erodes into nearby streams and ditches. Various sediment control techniques, such as installation of settling ponds or design of the work are to prevent the concentration of runoff, can be used to alleviate this problem. Some meltwater deposits are aquifers, and they may consist of gravel that is too coarse to filter contaminants from water. In such cases it is prudent to ensure that oil, fuel or other pollutants do not enter the groundwater either during or after quarry operation. This is a particularly important issue

where the aquifers are shallow and close to streams.

Recent Alluvium

Floodplains and low terraces in western Washington are often cultivated or used for dairy farming. To an increasing extent they will probably also be used for parks and other facilities associated with recreation on the major rivers. The esthetic degradation associated with gravel mining on valley floors conflicts with these uses to some extent, although the conflict could be limited through careful site planning and regrading after gravel extraction. Some of the present eyesores associated with gravel mining could easily be avoided by greater sensitivity to esthetic values on the part of landowners.

Gravel extraction creates large, deep pits, the floors of which lie below flood levels in the river. The pits are usually diked to prevent invasion by the river during overbank flooding, but the dike material is commonly obtained from the pit and therefore is of a size that can be eroded by the river. Dike collapse and river inflow allows entrapment of fish, and in some cases may cause drastic channel displacement, erosion of new channels across the floodplain, and undermining of hillslopes, bridges, and other structures. The channel-diversion hazard is particularly great if gravel extraction is carried out in or near former flood channels crossing point bars in the most recently deposited portion of a floodplain.

The threat of river channel diversion is illustrated in Figure 8. Recent alluvium of the Yakima River at Union Gap, Washington, had been mined from deep pits in the valley floor. Each pit was diked, but lateral channel shifting undermined the dike of the upper gravel pit during a modest flood in 1971. The river entered this pit and flowed out of the downstream end of the pit, across the floodplain, and into a second gravel pit 4,000 feet downstream. There it breached another dike and re-entered the original main channel. This avulsion moved the channel up to 2000-3000 feet westward in a single flood, causing it to begin undermining the embankment of an interstate highway. The consequences do not end with the initial diversion because the new channel is shorter, steeper, and less sinuous than the original channel. Because the sinuosity of the main channel had not changed during the preceding 34 years for which there is an air-photo record, one might expect the river in the diverted reach to re-establish a more sinuous course by bar disposition, bank erosion, and rapid lateral shifting.

The presence of many abandoned gravel pits in the floodplains of the Yakima, Stalloguamish, and other rivers increases the chances of future diversions of this kind. Fortunately, sequences of maps and air-photos can be used in combination with field observations of floodplain microtopography and stratigraphy to predict whether a proposed or active gravel pit is likely to be invaded, as well as the course of events after breaching (4).

Channel Bars

Ill-planned and careless harvesting of sand and gravel from river channel bars can have serious impacts on stream turbidity, bar stability, channel evolution, and various other subtle aspects of river behavior. There may also be impacts on fish habitat, esthetics, and other river values as

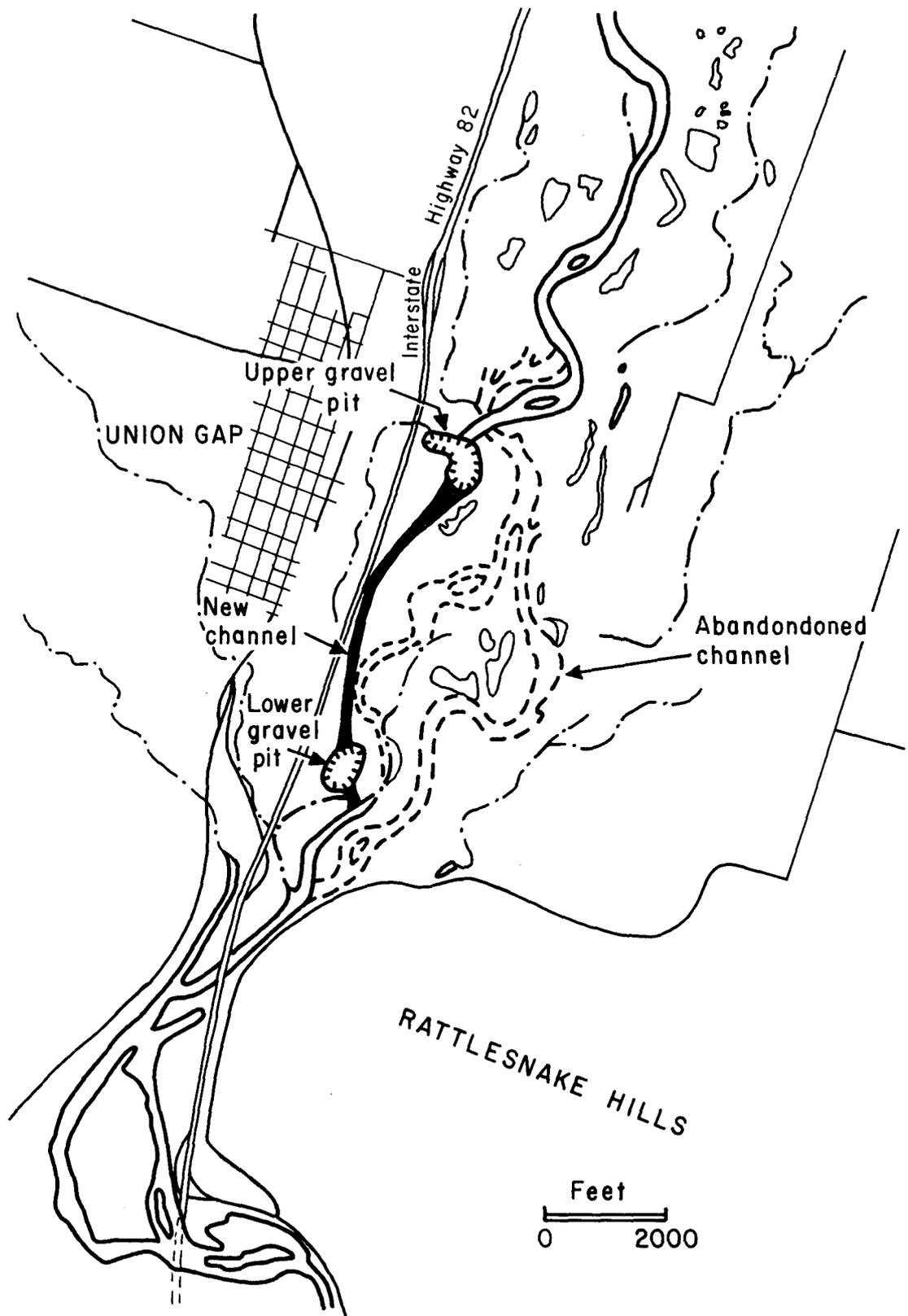


Figure 8. Channel diversion across the Yakima River floodplain at Union Gap, WA, caused by dike failure in a gravel pit. Tributaries to the river are represented by dashes separated by dots.

an indirect result of the channel disturbance.

Some of the impacts on water quality are now controlled by law. Extraction should not be conducted below the water level in order to keep turbidity levels to a minimum, and settling ponds must be used to detain gravel-washing water long enough for settling out of fine particles. A more difficult problem to control is the leakage of oil from machinery into the stream.

The most obvious impact of gravel harvest is likely to be a reduction in the size of the gravel bar if the rate of extraction exceeds the difference between the rate of sediment influx and the rate at which sediment is transported downstream to the next bar. As a result, the volume of the gravel bar is reduced and in extreme cases the course of the river may be altered. Our air-photo analysis of channel changes during several years of intense gravel harvesting on the Skykomish and Stillaguamish Rivers (4) indicates that mining of a point bar often leads to disturbance of the next bar upstream. Lowering of the bar surface by two or three feet is small in comparison with the amplitude of depth variations between regularly-spaced pools and riffles along most large channels, and the disturbance caused by gravel mining usually does not propagate more than one bar upstream.

Downstream effects of bar scalping are much larger and potentially more serious. Between 1961 and 1969 removal of gravel from a Skykomish River bar at rates several times the replenishment rate decreased not only the size of the exploited bar, but of several bars as much as 2.5 miles downstream. However, in most cases along the Snohomish and Stillaguamish channels, where the extraction rate is closer to the supply rate, the downstream effect extends only one or two bars downstream from the extraction site.

The diminution of channel bars can have a variety of consequences for channel stability and, unfortunately, theoretical predictions are complex and require large amounts of hydraulic data that are not routinely available for gravel extraction sites. Thus, it is usually necessary to rely on qualitative or rough quantitative interpretations of channel behavior at a site and of the probable consequences of bar reduction on the mode and rate of channel shifting, the stability of flood dikes and streamside property, fish habitat, and recreational amenities. One of the most useful methods for such interpretation is the comparison of channel position and morphology on sequences of aerial photographs, and interpretation based on an understanding of flow and sediment transport in rivers. Study of the past behavior of a channel bend or a braided channel reach during periods of heavy, light, and moderate gravel harvesting can yield results which are applicable to that site in the future and, with appropriate care, to similar reaches in the same river system or region.

In some cases, such an analysis may suggest that the extraction of gravel from a point bar or a mid-channel bar would have a stabilizing effect on the channel. For example, the accumulation of sand and gravel on a point bar tends to force the main thread of the current towards the opposite bank, where this high-velocity core of the flow concentrates high shear stress on the concave bank. The resulting undermining of the outer bank, together with continued deposition on the point bar, causes the channel to shift laterally across its floodplain. In the sediment-accumulating reaches of the large rivers in western Washington, average channel-shifting

rates of up to 10-20 ft/yr are not uncommon and can pose a threat to bridges, houses, roads, and farmland. Careful scalping of the annual accumulation of sediment from the point bar may be useful in stabilizing such channels.

On the other hand, if a point bar is lowered too much by excessive harvesting, a destabilizing effect may come about. As the bar is lowered, a greater proportion of high flows follows a more direct path downstream, rather than being diverted to the longer path around the bend. The shorter path increases the water-surface slope across the bar with an increase in boundary shear stress over the downstream end of the point bar. There is a likelihood of scouring and breaching of the point bar so that the bend may be cut off as the water gradually forms a new channel, particularly if harvesting operations or access roads cause any diversion or concentration of flow. If such a cut-off occurs, a complicated sequence of events is likely to ensue which is difficult to predict in detail. The channel realignment is usually accompanied by abandonment of the loop through the pool, and by considerable local re-distribution of sediment as a result of bank erosion and the initiation of new point bars as the river re-establishes its original sinuosity. The changes would be most dramatic over a distance of one or two bends downstream of the cut-off.

On the basis of an understanding of fluvial geomorphology it is possible to develop a methodology for managing gravel extraction from bars to minimize channel disturbance. We suggest that such a methodology include the following steps which should be taken before a gravel mining permit is granted:

- (1) Analyze the recent history of channel reach, with particular emphasis on modes and rates of point-bar formation and channel shifting. Sequences of aerial photographs and maps can be used for this purpose, and the earlier channel positions superimposed on the most recent map. The task is easily and rapidly accomplished through the use of a mirror stereoscope or a zoom-transfer stereoscope. Observations of bar sediments and vegetation on the air photos and in the field provide further insights into past river behavior and probable future evolution.
- (2) Estimate how much bedload is moving past the site and accumulating on a bar or in a channel reach. Records of sediment transport provide a starting point, as indicated above, and air-photo interpretation of changes in bar form allow some extraction limits to be cautiously imposed. For example, we suggest the following guidelines be tried on an experimental basis. If the gravel bars in a reach are diminishing, withhold permits. If the bars are stable or growing, limit harvest rates to one-half of the estimated bedload transport rate. If several applicants are competing for gravel on point bars along a reach, divide the harvestable volume between them. Monitor the channel by ground survey or through the regular aerial photography that is flown in most regions, and renew permits every five years. At that time, the extraction limits can be altered to reflect channel changes that have occurred during the permit period. Our suggestions should be refined as more systematic observations become available, and in the light of legal requirements, but we offer them here to stimulate discussion.

- (3) Estimate the probable impact of bar scalping on the form of adjacent bars. This can be done in an approximate fashion by examining air-photo records of the effects of previous gravel mining on neighboring bars along similar reaches of the same river. Limit extraction rates to values below those that have caused undesirable consequences in similar situations.
- (4) Require the applicant to provide details of the mining operation, including the location of access roads and scalping, the alignment of trenches, and the disposition of pollutants. The applicant could also be furnished with advice on how to minimize the possibility of cutoffs and channel diversions on the alignment of trenches transverse to the flow to trap bedload more efficiently, and on avoidance of lowlying abandoned channels or sloughs on the floodplain.

SUMMARY

Glacial deposits, floodplain alluvium and active river channel sediment are sources of gravel in western Washington. The importance of individual gravel sources can be defined by location and accessibility, harvestable volume, size distribution, and structural and chemical strength of the material. Due to distribution of bedrock types and the past activity of glaciers, the Puget Sound area has an abundance of gravel deposits, and most gravel currently mined is from ancient deposits rather than present stream channels. Some gravel is harvested from most of the large rivers draining into the Sound but outside the Puget Sound area, river channel sediments are a principal source of gravel. However, these gravels are often derived from the mechanically weak rock types which underlie the surrounding hills. When used to surface roads, these gravels break down and contribute much fine sediment to adjacent stream channels. The total available gravel supply in western Washington is only approximately known and the environmental consequences of mining operations are not well established.

Pressure for use of gravel in accessible, ecologically sensitive, and potentially unstable river channels should be assessed in terms of full knowledge of availability of gravel in glacial deposits and valley floor alluvium in western Washington. Along specific sections of river systems where long-term deposition of gravel is occurring, gravel in bars can be harvested as a renewable resource without causing significant downstream or upstream channel instability. These sections of river channels may be recognized in the field by the presence of rapidly migrating river bends, rapidly declining channel gradient, abundant, algae-free gravel in bars, and island bars. These signs can be quantitatively defined from sequential aerial photographs over a period of years. Confirmation that there should be long-term gravel deposition can be made from simple hydraulic calculations which evaluate the rate of change in the transporting capability of the river through the section of interests. Finally quantitative estimates can be made from direct measurements of gravel transport rates and from published records of suspended load transport rates. Until more is known, as a minimum standard the harvestable volume should not exceed one-half the estimated bedload transport through those reaches showing geomorphic signs of active gravel deposition. Long-term monitoring of extraction rates, sediment transport rates, and channel stability upstream and downstream of gravel borrow area would improve this estimate. The mining of each of the

three sources of gravel in Washington have predictable environmental consequences of a nonbiologic nature which can be avoided with proper planning. Removal of glacial deposits may destroy or contaminate ground water supply to neighboring wells. Mining of valley-floor alluvium and inadequate diking of pit walls may cause catastrophic diversion of the channel. Excessive removal of gravel from bars in rivers may lead to channel diversion and reduction of upstream and downstream gravel bars. Periodic field checking of river gravel harvesting sites and recording total extraction could prevent long-term degradation of channels by controlling the extraction rates to non-destructive levels.

Before a gravel mining permit is issued at least four steps should be followed: (1) define historical activity of a river at proposed site; (2) estimate bedload transport rate through reach; (3) evaluate probable impact of bar scalping on channel stability and (4) require explicit information on proposed mining procedure.

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