Gravel transport, gravel harvesting, and channel-bed degradation in rivers draining the southern Olympic Mountains, Washington, USA

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Gravel Transport, Gravel Harvesting, and Channel-Bed Degradation in Rivers Draining the Southern Olympic Mountains, Washington, U.S.A.

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ABSTRACT / The potential for gravel extraction to adversely affect anadromous fish habitat in three gravel-bed rivers of southwestern Washington, U.S.A., prompted the need to determine sustainable rates of gravel removal. This was accomplished by evaluating the components of a long-term sediment mass balance for the three rivers. Average annual gravel transport was determined by three independent methods. The closely agreeing results indicate that annual bedload supply decreases downstream through deposition and storage in response to declining gradient and from attrition during transport, as confirmed by laboratory experiments. A survey of gravel-bar harvesting operations indicates that the annual replenishment rate has been exceeded for up to three decades, often by more than tenfold. Analysis of data from nine stream gauging stations over a 55-yr period indicates degradation of about 0.03 m/yr in these reaches and suggests that bed degradation has produced the difference between the replenishment rates and the volumes of gravel harvested from the river beds and bars.

Introduction

Gravel is extracted from the low-water beds or bars of many perennial rivers, although it is seldom done in a planned manner that takes into account the potential, inadvertent effects of extraction on river morphology or sediment transport. Where regulated at all, restrictions commonly address the season and style of removal, but seldom the quantity. One reason that river-basin planners seldom take into account the potential adverse effects associated with gravel harvesting may be because the effects are not well documented in the published literature. These effects, recently reviewed by Collins and Dunne (1987), include: changes to bed elevations and morphology, which affect aquatic habitat, in-channel structures, floodplain land uses, and riparian habitat; and changes to river banks and channel patterns. Another reason may be that many environmental scientists and planners believe that evaluations of potential changes must necessarily be expensive and take many years to complete. However, in many, if not most, cases the necessary information can be developed rapidly and inexpensively, making use of basic principles of fluvial geomorphology, existing data, and judicious collection of additional data (Collins and Dunne 1987).

Typical of rivers draining the mountainous Pacific Northwest, the Humptulips, Wynoochee, and Satsop rivers of Washington state enter zones of rapidly declining gradient and widespread deposition of gravel bars as the rivers emerge from the southern Olympic Mountains (Fig. 1). Such depositional zones are characterized by rapid bar formation and channel shifting (Dunne 1988) and, in the rivers studied, are sites of gravel extraction and also provide habitat for anadromous fish. The possibility that this habitat could be depleted by gravel harvesting brought about the need to determine the rate at which gravel could be harvested without diminishing the long-term availability of gravel for spawning redds. It was necessary to determine the long-term flux of gravel rapidly and inexpensively.

The purpose of this article is to report the results of a study that makes use of widely applicable methods to determine the approximate, long-term bed material flux for specific reaches of the three rivers. The article also contributes to the small body of literature on gravel harvesting effects. Bed degradation associated with gravel extraction has been documented in one perennial river (Page and Heerdegen 1985), and in several arid-land, intermittent sand-bedded channels (Bull and Scott 1974). Several additional unpublished case histories are reviewed by Collins and Dunne (1987).

Approach of the Study

Sediment entering a reach is either transported through the reach, deposited and stored for some period of interest, broken down to smaller particles during storage or transport, or is removed by gravel harvesting. To account for these different components of the long-term bedload mass balance, the following

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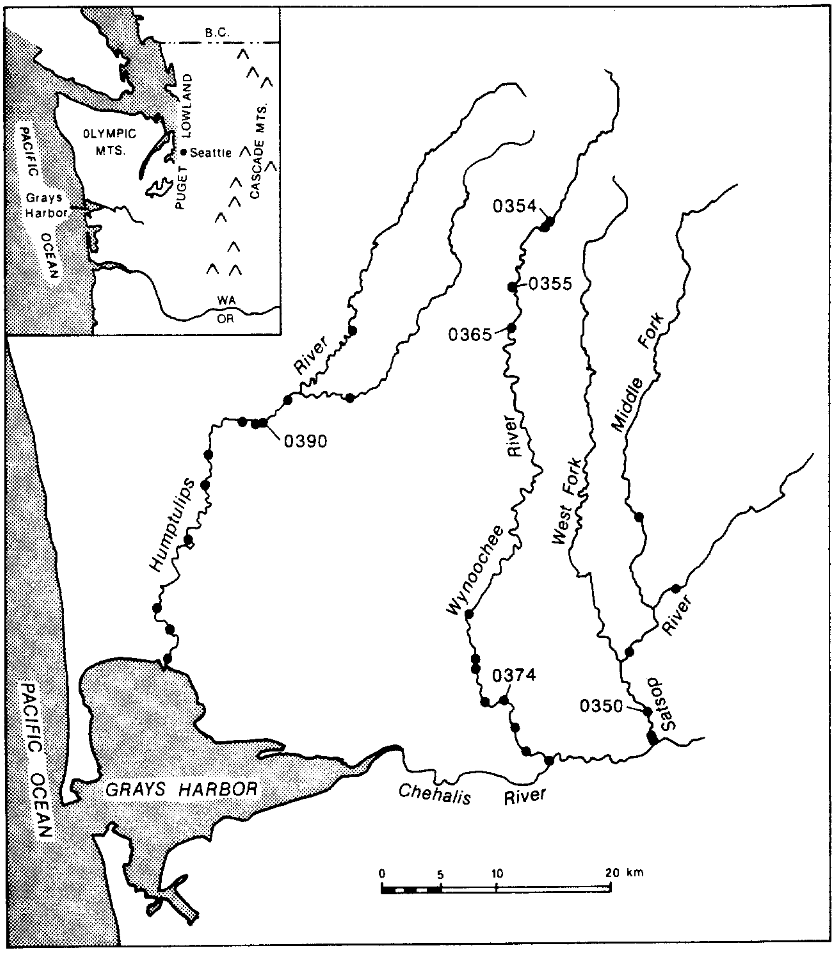

Figure 1. Locations of the Humptulips, Wynoochee, and Satsop rivers and of U.S. Geological Survey gauges and sample sites referred to in the text.

steps were taken. Annual volumes of bedload transport were determined by three independent methods: (1) by using the Meyer-Peter and Parker bedload transport formulae; (2) by estimating bedload transport as a percentage of suspended load, measured previously by the U.S. Geological Survey on the Wynoochee and Satsop rivers; and (3) by measuring rates of bed-material accretion at individual bars on six sets of aerial photographs taken between 1941 and 1985. Changes in channel storage were determined by analysis of bed-elevation trends from six U.S. Geological Survey stream gauges maintained during the last 55 yr; changes in channel width were evaluated from the aerial photographs. Approximate rates of attrition of bed material during transport were determined by laboratory experiment. Finally, minimum gravel harvesting quantities were provided by gravel harvesters.

Influences on Sediment Production and Transport

Hydrology and Geology

The three basins receive 3,300–3,800 mm of annual precipitation (Williams and Pearson 1985), concentrated between October and May when peak flows are generated by rainstorms and rain and snow-melt events.

The three rivers head in the steep southern Olympic Mountains, from which sediment reaches them by mass wasting of the basaltic colluvium (for details of geology, see: Tabor and Cady 1978; Rau 1967, 1986; Gower and Pease 1965). The middle portions of the Humptulips and Wynoochee basins and the West Fork of the Satsop basin have extensive deposits of deeply weathered, gravelly alpine glacial outwash, which enters tributary streams and the main rivers by bank erosion and represents the most significant source of sediment. Most of the basins of the East Fork and portions of that of the Middle and West forks of the Satsop River are underlain by gravelly outwash from meltwater streams that drained the continental ice sheet within the Puget Lowland; these deposits are a major source of gravel for the Satsop River. The relative durability of these materials is variable, as shown by attrition experiments described later. However, we were able to induce significant breakdown of each deposit during simulated river transport. The middle portion of the Satsop and the lower portion of the Wynoochee river basins are formed in friable sandstones, siltstones, and mudstone, which weather to sand and silt and are not significant sources of gravel.

The longitudinal profile of each river reflects the topography and geology of the river basin. The Humptulips River flows along a gently sloping outwash plain and has the lowest gradient of the three rivers. Between the tributary forks at river kilometer (Rkm) 45 and the mouth, the gradient declines from about 0.0023 to 0.0004 (Fig. 2). Most of this change occurs within several reaches of declining gradient and transport capacity in which the coarse load is intermittently transported through a series of large bars. The gradient of the steeper Wynoochee River (Fig. 2) drops only within the lowest 16 km from about 0.0017 to 0.0005, causing the greatest rates of bar growth and channel migration to occur. The gradient of the short (10-km-long) main stem of the Satsop River (0.0015; Fig. 2) remains relatively constant to its confluence with the Chehalis River, but it is less than that in the tributary forks, which causes significant deposition of gravel bars and channel shifting throughout the main stem.

History of Channel Use

Beginning in the 1880s, timber companies and the U.S. Army Corps of Engineers undertook extensive projects to enhance navigation and to facilitate log driving in rivers of the area, including the removal of boulders, debris, and major debris jams (Sedell and Luchessa 1981). This effort and the establishment of agriculture also brought about the ditching and draining of marshy floodplains and the blocking of side channels, reducing the storage of floodwaters in the floodplains. Numerous splash dams associated with logging operations were operated on tributaries of the three rivers, the majority of which were built between 1900 and 1920 and subsequently removed in the 1930s and 1940s (Wendler and Deschamps 1955). According to Sedell and Luchessa (1981), one effect of the outbursts of water and logs from these dams may have been the scouring of river channels. Maps of the rivers made in the mid-19th century show that river channels were generally wider and less sinuous than on maps made in the 1930s and more recently (Collins and Dunne 1986), suggesting the transition from braided rivers to meandering rivers with less gravel transport.

A dam constructed in 1972 at Rkm 83 on the Wynoochee River subsequently trapped all coarse sediment from the uppermost 106 km^2 (20 percent) of the Wynoochee River basin. The response of a gravel river bed to the effects of an upstream impoundment depends on the severity of modifications to flood hydrology and on the presence or absence of downstream sources of gravel (Milhous 1982). On the Wynoochee River, the size of floods has been reduced moderately, while the overall reduction in supply of gravel has been relatively small, because most of the gravel supplied to the river originates from the alpine outwash deposits that are located downstream. It is not expected that the channel of the Wynoochee River should degrade as a result of the dam; while there are insufficient data to allow a check of such a prediction, it is possible that portions of the channel could aggrade due to the reduction in transport capacity.

The early history of gravel harvesting in the three rivers is not well known but is thought by local residents to have occurred in certain locations since early in the century. Gravel harvest has been most extensive on the Humptulips River, with at least two dozen bars from near the mouth to the forks at Rkm 45 having been harvested at some time. Large-scale harvesting of gravel from the Wynoochee River is thought to have been confined to about 12 bars within the lowest 24 km of the river. Significant quantities of gravel have been removed from the Satsop River on only four bars along the main stem. Gravel extraction quantities are given later in this paper.

Downstream Sorting of Bed Material

At a number of bars (Fig. 1) along each river, sample sites were selected near the edge of low water, halfway between the upstream and downstream ends of the bar. The top several grain diameters of bed material were scraped away, and 20–40 kg of bed material were collected and sieved, giving a representation of the grain-size distribution of the active bedload of the river (Klingeman and Emmett 1982; Parker and others 1982).

Both the Humptulips and Wynoochee rivers show a general downstream reduction in grain size (Fig. 2), reflecting the general decline in gradient. The decline in grain size also reflects the attrition of gravel in transit along the rivers and the absence of gravel influx from tributaries in the lower reaches. Relatively little change in the grain size occurs along the Satsop River, reflecting in part the maintenance of a relatively constant slope to the confluence with the Chehalis River and a shorter distance of transport compared to the other two rivers. The relative coarseness of the Satsop River gravels also reflects the river's shortness and steepness.

To assess the relative importance of attrition in bringing about the downstream decline in grain size, we conducted a series of experiments in which por-

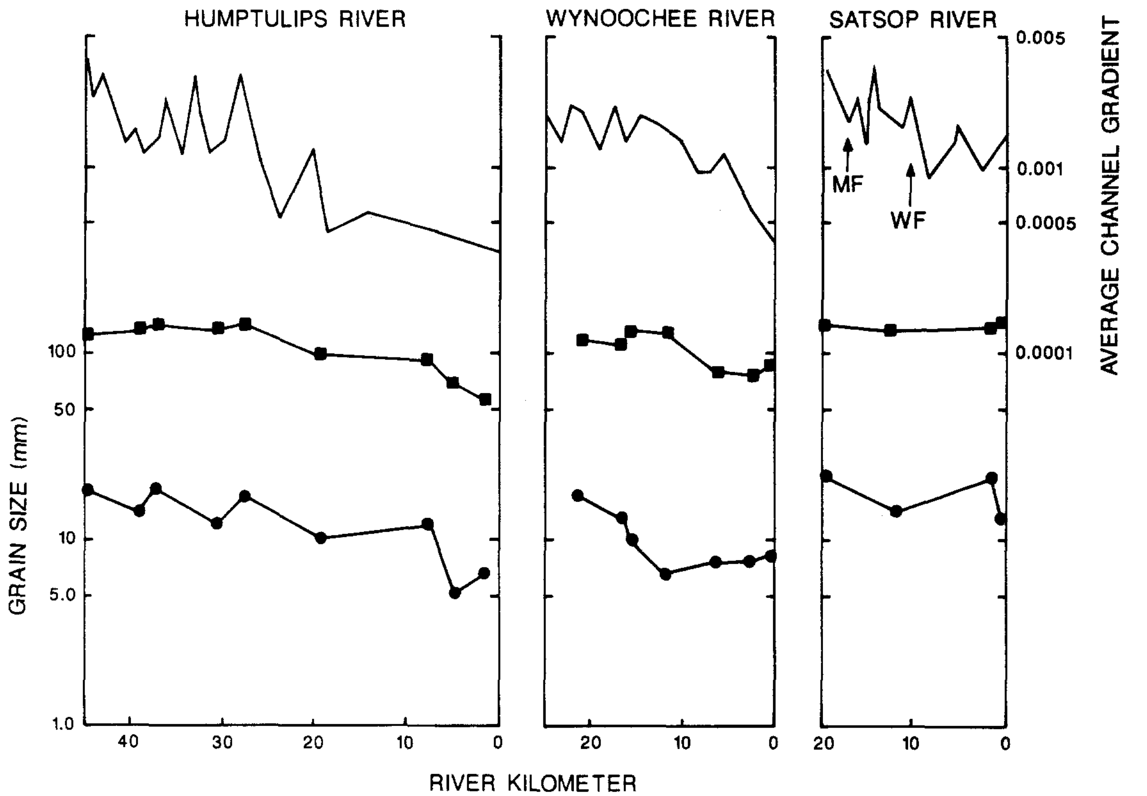

Figure 2. Variation along the three rivers of the average channel gradient, d_{50} (circles) of river bed material, and of the average of the diameters of the six largest particles undergoing frequent transport (squares), as indicated by their positions, orientations, clean surfaces, and relation to flotsam and other particles. MF and WF on the channel-gradient graph indicate the confluences of the Middle and West Forks of the Satsop River.

tions of seven of our samples of hillslope materials and of river bar gravels, each weighing about 20 kg, were placed in a tumbling mill that was then filled with water and rotated at 30 revolutions per minute. Each sample was removed, dried, sieved, and weighed at intervals of time, and returned to the mill. In this way we could determine the reduction in grain size with time and, by converting the time spent in the mill to an approximate distance of travel inside the mill, with distance of simulated river transport.

Table 1 indicates that the rate of weight loss for all samples declines with time. The overall rate of attrition is nearly identical for two samples of alpine glacial outwash and for material sampled from a bar in the Humptulips River at Rkm 39, which was derived from these materials. Each shows that after 31 h of simulated transport, approximately equivalent to 26 km of river transport, the three samples experienced on average a 41 percent reduction in the weight proportion of particles coarser than 0.5 mm, the approximate lower boundary of size classes contained within the bed. The breakdown rate was less for the one sample of continental glacier outwash, which experienced a 29 percent reduction by weight in material coarser than 0.5 mm, reflecting the difference between mechanically weak basaltic rocks of the Olympic Mountains composing the alpine outwash and the more durable plutonic and metamorphic rocks from Canada and the northern Cascade Range, which are the dominant constituents of outwash from the Puget Lobe of the continental ice sheet.

Table 1 also shows significantly lower rates of breakdown for two samples from rivers bars at downstream locations on the Humptulips and Wynoochee rivers. After about 26 km (31 hr) of simulated transport, samples from Rkm 21 on the Wynoochee and Rkm 5 on the Humptulips rivers, respectively, experienced only a 19 percent and 14 percent reduction in weight of coarse material. This slower rate of breakdown of the downstream bar materials reflects the fact that only the more durable gravel has survived transport along the channel, whereas the weaker particles have been converted to suspended load through attrition.

We subjected a single sample of outwash from the Humptulips River (Rkm 39) to 100 h of tumbling (80 km of transport), which induced a 60 percent reduction in weight proportion of coarser material. This

Table 1. Sediment attrition rates.[a]

Sample	P_0	k	P at $t = 31$
Alpine outwash, Wynoochee Basin	0.905	−0.0143	0.60
Alpine outwash, Humptulips Basin	0.972	−0.0168	0.59
Continental outwash, Satsop Basin	0.951	−0.0097	0.71
Basaltic colluvium, Satsop Basin	0.930	−0.0171	0.56
Humptulips bar Rkm 39	0.929	−0.0162	0.57
Humptulips bar Rkm 5	0.988	−0.0046	0.86
Wynoochee bar Rkm 21	0.928	−0.0064	0.81

[a]Coefficients for regression equation: $P = P_0 \exp^{(kt)}$ where P is the proportional reduction in the weight of sediment coarser than 0.5 mm [$P = w(t)/w(t = 0)$, w = weight > 0.5 mm] subject to attrition experiments, t is elapsed time (h) of experimental run, and P_0 and k are regression parameters. Also given is the measured value of P at $t = 31$ h. One hour of experimental run is approximately equivalent to 0.8 km of river transport. In a river this time would be intermittent.

and all other values from our experiments reflect a minimum rate, compared to conditions in the river, because the laboratory simulation could not incorporate the effects of weathering on material stored temporarily in the floodplain and channel bars, which enhances susceptibility to attrition during subsequent transport. The importance of this factor is suggested by the abundance of rocks on bar surfaces that had shattered during the several weeks or months since their deposition.

Methods Used to Estimate Gravel Transport Rates

Bedload Transport Formulae

The first of two transport formulae used, the Meyer-Peter formula (discussed in Raudkivi 1976), is generally considered to give accurate results when applied to channel reaches not complicated by large-scale roughness elements such as gravel bars or bends, and so its application was restricted to gauge sites where this condition is well satisfied. The second formula used is that of Parker and others (1982), an empirical relation developed from field data on five gravel-bed rivers in the U.S. and Canada. We restricted our use of the Parker relation to the Humptulips River gauge, the only one at which flow conditions fell within the range of experimental data from which the relation was derived.

These two formulae were used at the three stations in Table 2 (Fig. 1). Values of average channel slope were read from river-profile maps with 5-ft (1.5-m) contour intervals and were assumed to approximate the average water-surface gradient. Required sediment-size parameters were obtained from our bed material samples, described in the previous section. Values of stream width and depth were obtained from hydraulic geometry relations constructed from current-meter records provided by the U.S. Geological Survey for these sites.

Computed bedload rating curves were then used in conjunction with daily flow records for the most recent 10-yr period of discharge record at each station to compute the annual flux of bedload for each year. The results are given in Table 2. For the Humptulips gauge the most recent 10-yr record is for 1970–1979; elsewhere the annual rates are given for water years 1976–1985. At the Wynoochee River above Black Creek station, 74 km downstream of the Wynoochee Dam, we also made computations for a 10-yr period (1959–1968) prior to the construction (1969–1972) and operation of the dam, which indicated that there has been little if any change in transport rates within the past three decades (Table 2).

Bedload as Percentage of Suspended Load

From October 1961 to October 1965, the U.S. Geological Survey measured suspended sediment at the Black Creek station on the Wynoochee River and at the Satsop River station (Glancy 1971). We used these data to estimate bedload as a percentage of suspended load. Vanoni (1975, Table 3.2) summarizes the factors that appear to determine the percentage, and indicates that for rivers similar to the Satsop, Wynoochee, and Humptulips, bedload has been found to constitute 2–8 percent of the suspended load. A value within this range is confirmed by suspended and bedload sampling undertaken from September 1976 to October 1978 by the U.S. Geological Survey in the Quillayute River basin of the western Olympic Mountains (Nelson 1982) where the geology, climate, topography, land use, and bed sediment size are similar to those in the study basins. In the two rivers where suspended and bedload samples were collected (Soleduck and Bogachiel), bedload comprised 4% of suspended load. In the Snohomish River, the other river in western Washington in which both suspended and bedload sediment sampling has been undertaken, and which is generally comparable to the study rivers, bedload is 5 percent of suspended load (Dunne and others 1981). We therefore estimated bedload in the Satsop and Wynoochee rivers as 4 percent of suspended load (Table 2).

The suspended sediment rating curves were ap-

Table 2. Average annual bedload transport.[a]

	Humptulips R. ab. Humptulips (12-039000)	Wynoochee R. ab. Black Cr (12-037400)	Satsop R. at Satsop (12-035000)
1970–1979			
Parker	2,400 ± 850		
Meyer-Peter	2,100 ± 700		
1976–1985			
Meyer-Peter		5,200 ± 1,100	2,700 ± 790
1959–1968			
Meyer-Peter		4,700 ± 800	
1961–1965			
Percent of suspended load		3,700 ± 720	5,200 ± 1,600
1976–1985			
Pecent of suspended load		5,300 ± 1,000	

[a]Transport (tonnes) and standard error of the mean, for estimates from transport formulae and percentage of suspended load, for three gauge sites.

plied to the discharge record from the Wynoochee for 1976–1985 to compare the result to that obtained from the Meyer-Peter equation for the same period. The results agree within 2 percent (Table 2). This calculation was not possible for the Satsop River, because the rating curve at this station was not well defined for discharges as high as some occurring during 1976–1985.

Measured Rates of Bank Erosion and Bar Accretion at Individual Bends

In light of the approximate nature of widely used bedload transport formulae and measured suspended loads, it is desirable to have an approximate check on long-term bedload transport rates that is field based and fully independent of hydraulic and hydrologic measurements. Neill (1983) reported one such approach used in a study on the Tanana River. He measured rates of bank erosion at individual bends, and estimated the percentage of bank material in the range of sizes transportable within the bedload. He then compared the volume of bank erosion of bed-material-sized sediment to measured rates of bedload transport into and out of the bends. His model assumed that the bedload transport into and out of a bend are approximately equal and that they equal the rate of bank erosion of bed-material-sized sediment, as well as the rate of accretion of bed material on bars. He found that the bedload transport and bank erosion rates agreed within 25 percent for a 7.5-km-long reach of three bends.

We used a related method that makes the same assumptions incorporated in Neill's model. Rather than measuring bank erosion rates, we measured the areas of gravel bars on maps made from sequential aerial photographs and converted the areas to volumes on the basis of field-measured bar heights. Comparison of bar volumes at different times gives a rate of accretion at each bar, giving a minimum measure of the flux of bedload through the channel segment in which the bar is located. The estimate is a minimum because it ignores the portions of the bedload that move along the thalweg of the channel and across the bar without depositing on the bar. Although untested, the assumption that nearly all bedload comes to rest on gravel bars is probably a good approximation for the reaches to which this method was applied, which are characterized by a decreasing grain size, partially brought about by rapid downstream decrease in sediment transport capacity, and by a series of large, actively accreting bars, which together imply the slow transport of barely transportable material, most of which is stored in bars.

To implement the method, we surveyed cross sections of 24 gravel bars in the three rivers to arrive at average bar heights. Additional cross sections were also available to us from the files of the Grays Harbor County Planning and Building Department. We also mapped the channel and banks of each river on aerial photographs taken in 1941, 1952, 1964, 1977, 1981, and 1985 at scales of 1 to 12,000 or 1 to 20,000 and converted the maps to a common scale of 1 to 6,000 to allow superimposition and to facilitate measurement of changes in area. We also measured areas of bank erosion as a means of checking our measured accretion rates, because the rate of bar accretion and bank erosion should be equal in a river not undergoing systematic widening or narrowing. In selecting bars to be studied, we avoided bends that had been stabilized by bank protection and periods of time in which individual reaches were complicated by multiple channels or in which meander cutoffs or channel avulsion occurred. We also avoided bars at which significant quantities of gravel harvesting have been documented or were suspected from air-photo interpretation. All of the photographs were taken at low water at stages within 0.15 m of one another. Rates of bar accretion and of bank erosion were equal when averaged over each river.

Areal accretion rates were converted to volumes by using an average measured bar height of 1.8 m when the channel gradient exceeded 0.001 and of 2.3 m at lower gradients. Local variation is not more than about ±0.5 m, or ±25 percent of the average value. The resulting volumetric rates of transport are discussed below, along with estimates of bedload transport derived from the methods discussed previously.

Gravel Transport Rates

Rates of annual bedload transport, calculated using the various methods, are given in Figure 3 for each of the three rivers. In the Humptulips River between Stevens Creek at Rkm 36 and the confluence of the East and West forks at Rkm 45, there are few bars that met the qualifications for measurement of accretion rates due to bank protection, widespread gravel harvesting, and the scarcity of bars between about Rkm 40 and Rkm 42. Transport computed using the Meyer-Peter and Parker bedload formulae at the gauge (Rkm 40) agrees with measurements from a bar at Rkm 39 and indicates an annual transport of 1,900 m^3/yr. In the channel of Stevens Creek (drainage area 73 km^2), which enters the Humptulips River at RKm 36, there is an abundance of bed material in the bed and on mobile bars. Bar accretion rates in the Humptulips River in Figure 3 show that the rate of bedload transport increases downstream of the gravel influx from Stevens Creek to about 5,000 m^3/yr, the average of accretion rates at the two bars between Rkm 32 and Rkm 33 shown in the figure.

Downstream of this influx of gravel from Stevens Creek, transport rates decline gradually to about 2,300 m^3/yr at Rkm 24. The implication is that 2,700 m^3, or about 50 percent of the load at Rkm 32, is lost to attrition and net addition to the floodplain behind the bars in this reach. Between about Rkm 16 and Rkm 12 there are few bars, and the transport rate appears to remain approximately constant above and below this reach. This may be because of the general absence of long-term storage sites within the reach and because gravel in the lower river is more durable (Table 1) than that upstream, and hence less subject to attrition.

The flux of bedload through the lower reach of gravel bars and at the mouth of the Humptulips River is about 1,500 m^3/yr as indicated by bar accretion rates. While we were able to measure accretion rates at three bars in the lowest 1.5 miles of the channel, rates in this reach (about 400 m^3/yr) probably represent underestimates of the flux, because a significant portion of the bedload is traveling below the low-flow water level in this tidal reach of the river, and therefore is not expressed in the bars visible on the aerial photographs.

In the reach of the lower Wynoochee River, which contains the Black Creek gauge (Rkm 9), the sediment transport computations and estimates based on percentage of suspended load (Table 2) are in areement with a value of about 4,000 m^3/yr interpolated from upstream and downstream bar accretion measurements. The downstream decrease in transport is relatively small despite the absence of significant tributary influx of gravel throughout this reach. This result is explained by the gradual decrease in channel gradient and by the durability of the riverbed material at the upper end of the reach (Table 1): the bar sample from Rkm 21 underwent a 20 percent attrition after 31 h (26 km). Attrition of the Humptulips River samples after 31 h was 14 percent at Rkm 5 and 40 percent at Rkm 39. While no upstream samples of river bar material from the Wynoochee were subject to the attrition experiment, the similarity of the sediment sources in the Humptulips and Wynoochee river basins suggest that bar material undergoes a similar downstream increase in durability in the two rivers.

As indicated earlier, there is no reduction in gradient or grain size throughout the mainstem (Rkm 0 to Rkm 10) of the Satsop River. In the absence of tributary input, a reduction in grain size is associated with attrition and hence a decline in the bedload transport rate; thus Figure 3 shows no apparent decline in transport rate. Results of the three methods used to determine the bedload transport do not agree as well as on the other two rivers. The estimate from the Meyer-Peter formula is substantially less than the estimates derived from the other two approaches; it may also be less reliable than the estimate obtained on the other two rivers because the channel at the Satsop gauge has been modified by a bridge and upstream pilings. It was not possible to extend the suspended sediment data to periods other than the 1961–1965 period, for the reasons given earlier. However, on the Wynoochee River the estimate given in Table 2 for 1961–1965 is 70 percent of that for 1976–1985. Assuming this same relation between the 1961–1965 and 1976–1985 periods on the Wynoochee River is also approximately true for the Satsop River, then the transport rate on

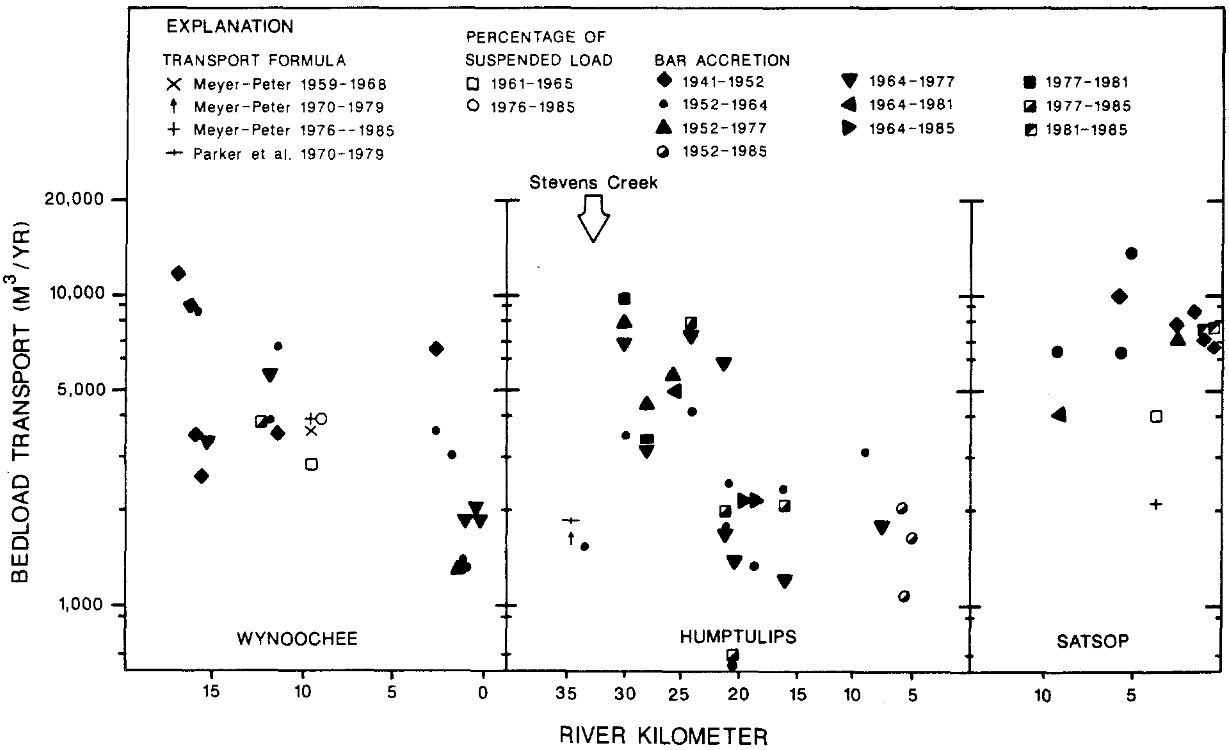

Figure 3. Variation along the three rivers of average annual volumetric bedload transport, estimated from transport formulae, percentage of suspended load, and bar accretion rates.

the Satsop River for the 1976–1985 period would be about 6,000 m^3/yr. The bar accretion measurements indicate a transport rate of about 8,000 m^3/yr. Because of the apparent agreement between the bar accretion measurements and the other two methods on the Wynoochee and Humptulips rivers, and because of questions about the validity of the Meyer-Peter and percentage-of-suspended-load estimates at the Satsop station, the best estimate of transport on the lower Satsop River has been taken to be 8,000 m^3/yr.

Gravel Harvesting Quantities

To document recent rates of gravel mining in the three rivers, we conducted a survey of gravel operations. Not all operators responded to the survey, so the survey responses indicate only minimum, documented rates of gravel removal from various reaches of each river. We then summarized unofficial estimates of removal by nonreporting operations made by the Grays Harbor County Planning Department to derive additional, higher estimates, which are presumed to lie closer to the actual removal rates. While these latter estimates may or may not accurately reflect the actual removal rate, the lower estimate is based solely on information provided by a portion of the operators, and so it is certain to represent a minimum rate. These two estimates are given in Figure 4 for the reach of each river in which gravel harvest has been most intensive.

On the Wynoochee River, most of the larger operations are thought to have been accounted for by the survey responses, and the estimated total rate is probably not greatly different from the documented rate (Fig. 4). Rates are not documented for the period before 1960, but are thought to have been less than rates since 1960. By 1965 rates of removal exceeded the annual replenishment rates estimated above. In addition, there has been an average annual harvest of about 2,600 m^3 since 1970 upstream of this reach, between Rkm 19 and Rkm 24.

On the Humptulips River, harvesting has been most intense between about Rkm 26 and Rkm 45 and has clearly exceeded the estimated replenishment for the last 35 yr. Within an additional zone of gravel removal between about Rkm 4 and Rkm 9, survey responses indicate that at least an additional 80,000 m^3 have been removed from this lower reach in the last three decades.

Gravel has been harvested from the Satsop River in relatively few locations between Rkm 2 and Rkm 6. The minimum documented rate suggests that the annual replenishment rate was not exceeded except for

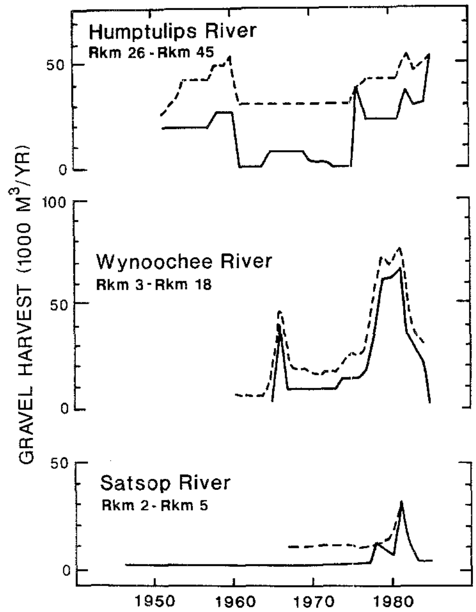

Figure 4. Volumetric annual gravel removal for particular reaches of the Humptulips, Wynoochee, and Satsop rivers. Dashed line represents estimated total rate, and solid line the minimum documented rate.

the period between 1978 and 1982, when rates ranged from 8,000 to 30,000 m^3/yr. Unofficial estimates indicate that annual harvest averaged 15,000 m^3/yr beginning in the mid-1960s.

In summary, while the harvesting quantity data are incomplete, they are adequate to make clear the location, general magnitude, and timing of the discrepancy between the replenishment and harvest rate. It is clear that there is a discrepancy of several tens of thousands of cubic meters per year between rates of harvesting and replenishment.

Reconciliation of Gravel Transport and Gravel Harvest Rates

Bed Degradation

The river channels could accommodate the imbalance between the amount of gravel harvesting and the rate of gravel replenishment during the last several decades by widening, deepening, or both. We could not define an overall change in channel width from our aerial photographic record other than the obvious, local effects of bar removal at some of the larger operations.

In order to evaluate the possibility of bed degradation, we examined trends in river-bed elevations at gauging stations maintained by the U.S. Geological Survey. Figure 5 shows the mean annual water surface

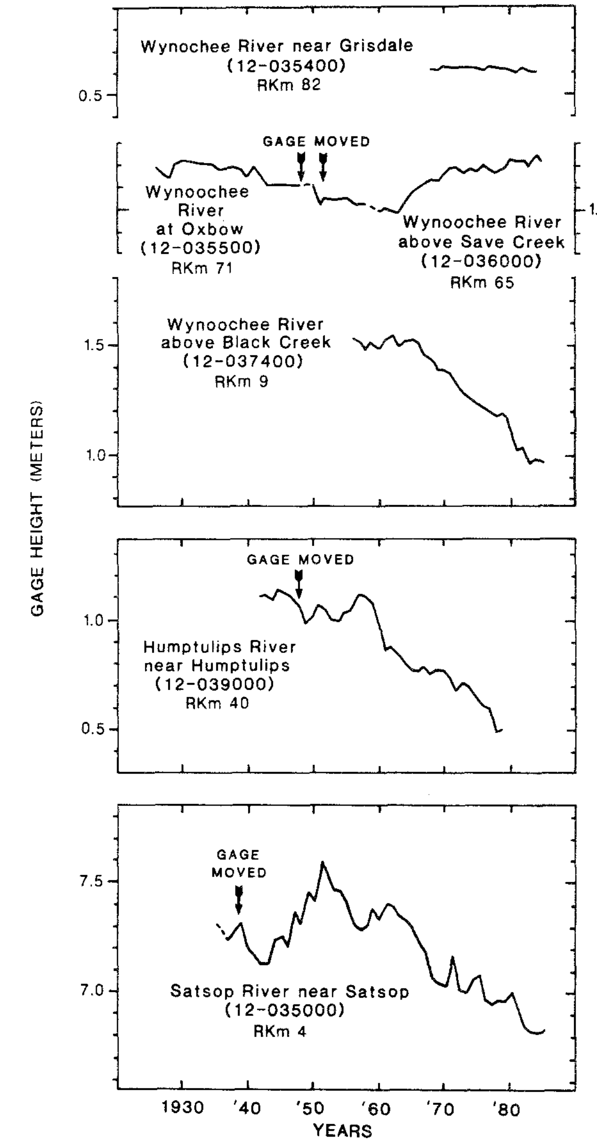

Figure 5. Mean annual water surface elevation at a flow of 14 m^3/sec for the period of record at six U.S. Geological Survey gauges.

elevation at a flow of 14 m^3/s (as a surrogate for average bed elevation) at the stations.

The record from the Wynoochee River shows that essentially no change has occurred at a gauge near Grisdale (Rkm 82) since the late 1960s, which includes the period in which the dam at Rkm 83 was closed in 1972. However, field inspection showed that the channel at the gauge and elsewhere along this stretch of the river is steep, with patches of exposed bedrock among a stable bed of cobbles and small boulders. Consequently, relatively little change in river-bed elevation would be expected here. A short distance downstream, the "At Oxbow" (Rkm 71) and "Above Save Creek" (Rkm 65) gauges have been maintained since 1926. The record at these stations, where the bed is potentially mobile, shows a total difference between highest and lowest elevations of about 0.2 m over the 60-yr period. A systematic, slow degradation occurred from the mid-1930s to the early 1960s, a trend that was slowly reversed by an approximately equal aggradation over the following decades. While land or channel uses that may have caused these slow, apparent changes during the period are not known, the bed has not degraded within the past 25 yr. This situation contrasts with that downstream, at the gauge above Black Creek, where the bed was stable between 1956 and 1966, after which time it degraded at an average rate of about 0.03 m/yr.

At the Humptulips River gauge (Rkm 40), there is no clear suggestion of a systematic degradation between 1940 and about 1959. Beginning in about 1960, the river bed was lowered by about 0.03 m/yr; the rate, duration, and constancy of change is greater than any systematic changes evident prior to this time. This rate, and that at the Black Creek gauge on the Wynoochee River, were confirmed by the measurement of similar rates from stream cross sections at downstream bridges (Collins and Dunne 1986).

Data from the Satsop River gauge are less clear because of fluctuation in river bed elevation on the time scale of 5–10 yr. There appears to be a systematic trend toward aggradation beginning in 1943 and ending in 1951, followed by a general degradation from then to the present. The present river-bed elevation is well below the apparent mean of the 50-yr record.

Variation in bed elevation may also be brought about by changes in transport capacity due to climatic fluctuations. To evaluate this influence, we examined trends in runoff over the past 50 yr. The large interannual variation in runoff obscures any systematic trends, but variation is reduced by plotting average annual discharge as a three-year running average (Fig. 6). Average runoff has fluctuated about the long-term average in systematic patterns of above- and below-average runoff occurring with periods of 5–10 yr. Most notable is a period from the mid-1930s to the mid-1940s, in which the annual runoff was less than the 55-yr average at the Satsop River gauge, with the lowest point occurring at the middle of this period (1943). The pattern is consistent with the general increase in runoff throughout the 1940s at the Humptulips River gauge, but cannot be confirmed in the absence of earlier data. Comparison of this "trough" in the annual discharge curve to the river bed elevation shown in Figure 5 for the Satsop River suggests that river bed elevation has changed in response to this period of abnormally low flows.

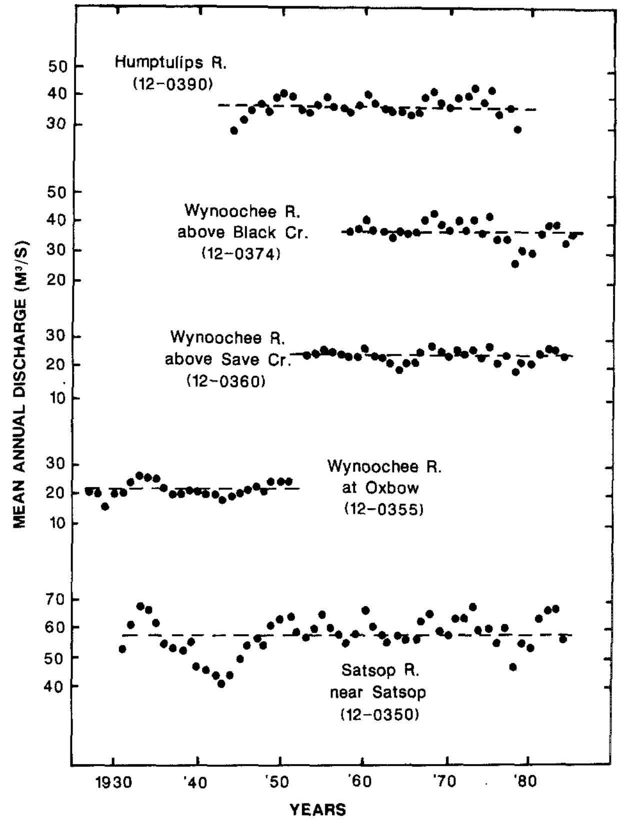

Figure 6. Three-year, running-average annual discharge for the period of record at five U.S. Geological Survey gauges.

The effect of this correspondence between the series of low-flow years and the series of years of river-bed degradation in the Satsop River is to account for the fluctuations in the pre-1960 portion of the record of river bed elevation at the Satsop River station, and thus to emphasize the existence of the climatically anomalous post-1960 degradation. The plots of long-term runoff do not suggest any change in runoff that could have brought about the post-1960 degradation common to the three rivers. This observation, in combination with the lack of degradation upstream and the presence of degradation downstream on the Wynoochee River, rule out the possible role of climatic change in causing the post-1960 degradation on the three rivers.

The spatial and temporal association of gravel mining and river bed degradation appears to present the key to the imbalance between calculated replenishment rates and reported offtakes. In the summer of 1966, gravel mining in the Wynoochee River increased from an undocumented, but presumed small rate, to a rate in excess of 40,000 m^3/yr (Fig. 4); the river bed at the Black Creek gauge declined 0.06 m during the next year. Gravel harvesting continued on the Wynoochee River through 1985 at a rate of about 20,000 m^3/yr, and the bed continued to degrade. There is even a close annual correspondence between gravel harvest quantities in the Wynoochee River and bed degradation at the Black Creek gauge: Figure 4 shows a documented, large increase in gravel harvest in 1979, 1980, and 1981, and it is in 1980 and 1981 that the most rapid bed lowering occurs at the gauge (Fig. 5). The second largest annual increase in gravel harvesting occurred between 1965 and 1966 (Fig. 4), and a noticeable increase in the rate of bed lowering occurred between 1966 and 1967 (Fig. 5). There has been no documented gravel harvesting above about Rkm 24 during this period; there has been no degradation (and, in fact there has been a moderate aggradation) upstream at the Save Creek gauge.

There is also an apparent temporal association of greatly increased rates of gravel mining (Fig. 4) in the upper Humptulips River and bed degradation at the Humptulips gauge (Fig. 5). There are noticeable increases in the rates of documented gravel harvesting as well as the inferred, higher rates in the 1958–1960 and 1975–1976 periods (Fig. 4), and these correspond to noticeable increases in the rate of bed degradation within the same two time periods (Fig. 5).

Our assessment of gravel harvesting rates in the Satsop River relies more on estimates than is the case for the other two rivers, and so it is less certain that there is an exact association between bed-elevation changes and gravel harvesting. But in this case, too, there is at least a general correspondence between increased rates of gravel harvest and bed degradation dating from the mid-1960s.

Reconciliation of Imbalance between Offtake and Replenishment

To estimate the total amount of gravel that has been eroded from the river beds of the reaches most heavily mined, we assumed that the rates of bed lowering measured at the gauge sites could be applied throughout the reaches in which the most intensive gravel removal has occurred. On the Wynoochee River, this reach lies between Rkms 3 and 18 but excludes operations at Rkms 21–22. The relatively low rates of removal estimated for this short, upper reach in combination with an apparent absence of degradation at a bridge site at Rkm 21 (Collins and Dunne 1986) suggests that in this reach the river bed is not undergoing a net lowering.

The average rate of bed lowering at the Above Black Creek gauge between 1966 and 1985 is 0.03 m/yr (Fig. 5), which together with an average river bed width of 45 m indicates an annual rate of bed-material excavation of 20,200 m^3/yr between Rkms 3 and 18. Over the 19-yr period during which degradation is evident at the Black Creek gauge, this rate would have caused the removal of 380,000 m^3. The minimum amount of gravel extracted during this period (from Fig. 4) minus the annual supply is (470,000 − 73,000 m^3 =) 400,000 m^3.

A similar computation made for the intensively mined reach of the Humptulips River between Rkm 26 and Rkm 45, using the lowering recorded at the gauge, shows an annual rate of bed-material erosion of 24,000 m^3/yr, or 600,000 m^3 over the past 25-yr period. The minimum documented rate of gravel removal in the 1960–1985 period is 320,000 m^3, and the larger estimate is 760,000 m^3 (Fig. 4). Figure 4 indicates that the average replenishment rate for this reach was between 1,900 and 5,000 m^3/yr (47,500–125,000 m^3 in the 25-yr period). Thus the estimated river-bed lowering approximately balances the difference between the replenishment rate and the higher estimated volume of gravel removal. Subtracting the annual supply from 320,000 m^3 gives an approximate amount of gravel harvest in excess of supply of 230,000 m^3. Figure 4 indicates that the higher, estimated rate of gravel removal (760,000 m^3) is more than twice this amount; use of this figure would bring into agreement the amount of bed material erosion (530,000 m^3) and gravel harvest in excess of supply (600,000 m^3).

On the Satsop River, a computation made using the average lowering at the gauge applied to a 3-km-long reach that includes all of the gravel harvest operations gives an annual rate of bed material erosion of about 5,000 m^3/yr over the past 20 yr. Because the annual supply is estimated to be about 8,000 m^3/yr (Fig. 3), this implies that about 12,000 m^3/yr are being harvested. As mentioned before, gravel harvest rates on the Satsop River are uncertain. However, from 1978 to 1985 the documented rate of gravel harvest was 10,000 m^3/yr.

Summary

Annual volumes of gravel transport in the Humptulips, Wynoochee, and Satsop rivers were determined by three, fully independent methods, which yield answers in close agreement. The annual volumes vary between rivers, and generally decrease downstream as declining transport capacity and particle attrition reduce the amounts of sediment that can be carried as bedload. Through the reaches from which gravel has been harvested, the annual bedload supply decreases downstream from 4,000–8,000 m^3 to about 2,000–3,000 m^3 in the Humptulips and Wynoochee rivers, but remains at approximately 8,000 m^3 throughout the lower Satsop River.

The rate of gravel removal from bars during the past two or three decades has exceeded the rate of supply by more than tenfold. The differences between supply and removal appear to have been accommodated by scouring of gravel from the channel beds which have been lowered at a rate of approximately 0.03 m/yr during the past 20–30 yr, according to U.S. Geological Survey gauging station records. The computed volumes of river-bed lowering are approximate because there are so few stations at which the degradation is known accurately. It is not possible with the available data to make more detailed computations or to take into account local effects associated with individual operations. However, the spatial and temporal associations between gravel removal and bed degradation is clear, and a best estimate of the magnitude and extent of lowering provides a volume that is remarkably close to the discrepancy between the estimated volumes of replenishment and offtake in at least two of the three-rivers.

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