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Side slope sedimentation following new work dredging on the Lower Columbia River, Oregon and Washington

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Lower Columbia River, Oregon and Washington**

Babcock, Sarah J., M.S.

San Jose State University, 1989

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SIDE SLOPE SEDIMENTATION FOLLOWING NEW WORK DREDGING ON
THE LOWER COLUMBIA RIVER, OREGON AND WASHINGTON

A Thesis

Presented to

The Faculty of the Department of Geology

San Jose State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

By

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May, 1989

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ABSTRACT

Side slope sedimentation from navigation channel side slopes following "new work" dredging (increased channel dimensions) is a large, but short-term, contributor to bedload sedimentation on the Lower Columbia River. Prediction of rates and volumes of increased sedimentation can be used to forecast maintenance dredging requirements following new work dredging events. Side slope sedimentation decreases exponentially with time, reaching equilibrium conditions in 3 to 6 years. INFIL was designed to construct an exponential decay curve that distributes annual side slope sedimentation over the readjustment period. INFIL was calibrated by adjusting input variables to match historic records of side slope sedimentation following new work dredging at six study sites. Calibration results show that percentages of total side slope sedimentation during the first year of the readjustment period are sensitive to both the length of the readjustment period and the depth of the dredging excavation.

INTRODUCTION

Side slope sedimentation from navigation channel following "new work" dredging is a large, though short-term, contributor to bedload sedimentation on the Lower Columbia River. New work dredging is dredging that occurs in previously undredged areas, or which increases channel depths and/or widths in established navigation channels. Increased side slope sedimentation contributes to bedload sedimentation and increases maintenance dredging requirements. Prediction of rates and volumes of this increased bedload sedimentation can be used to forecast increased maintenance dredging volumes following the excavation of increased depths and/or widths in navigation channels.

Since 1986, the U.S. Army Corps of Engineers has been required to share construction and maintenance expenses with the project sponsor. For small navigation projects, cost sharing will not exceed a predetermined spending cap (e.g., \$4.5 million) when the sponsor assumes all project expenses. For scheduling and budgeting purposes, the Corps needs to identify when this spending cap will be reached.

Historic maintenance dredging records on the Lower Columbia River show increased dredging volumes following new work dredging. This increased dredging results from sediment contributed by channel side slopes as they readjust

from steep dredge cuts (1:3) to more gently sloping natural or equilibrium slopes (usually 1:10 to 1:30). An understanding of the rates and volumes of side slope sedimentation is required to predict local dredging requirements on a particular reach.

A variety of empirical procedures can be and have been used to predict sedimentation responses to new work dredging events. Two potentially useful prediction methods are 1) use of dredging experience gained from nearby areas, and 2) analysis of historic dredging data to estimate the bedload sedimentation record. The first method can be a valid prediction method only if the channel in the nearby area is similar to the channel being evaluated. The second method estimates bedload sedimentation rates from historic dredging records. The problem with this second approach lies in the availability and quality of data to be used in the evaluation. Scarce data are insufficient to determine representative sedimentation rates. Extrapolation from non-representative bedload sedimentation rates results in an unreliable prediction.

This study is designed to estimate rates and volumes of side slope sedimentation from the navigation channel of the Lower Columbia River following new work dredging. Of particular interest is the development of quantitative methodology capable of predicting rates and volumes of side

slope sedimentation following future new work dredging of the navigation channel.

Scope of Investigation

The task of isolating side slope sedimentation from other sources of bedload sedimentation is complicated by the navigation channel development. Concurrent construction of river engineering structures combines to change bedload sedimentation by reducing flood peaks and upstream sediment supply, and changes river hydraulics by altering the channel cross-section shape and area. Additional complications arise from a number of economic and operational variables which cause maintenance dredging volumes to be different from bedload sedimentation volumes. These controlling factors include annual funding, dredging plant availability, and overdredging the channel or advance maintenance dredging.

Over the years, the U.S. Army Corps of Engineers has empirically proven that side slope sedimentation following new work dredging in the Columbia River estuary declines exponentially until equilibrium slopes are re-established (Ogden Beeman and others, 1985; Evarts, and others, 1987; and U.S. Army Corps of Engineers, 1988). An intuitive empirical method used by the Corps distributes total side slope sedimentation over the readjustment period in an

exponential decay configuration (U.S. Army Corps of Engineers, 1988). The INFIL program is designed to estimate side slope sedimentation volumes to construct an exponential decay curve.

In addition, this study will identify sediment or slope characteristics that can be used to predict side slope sedimentation for areas where historic dredging records are missing or insufficient. Evaluations of channel morphology and bedload sediment grain size parameters will identify pertinent characteristics that can be used to verify and refine the empirical INFIL methods.

Selection of Study Sites

The Corps, as requested by the Port of Portland, initiated feasibility studies for the construction of anchorages at Slaughters Bar, Kalama Reach, Henrici Bar, Willow Bar and Lower Vancouver Bar (figure 1). Henrici Bar, located immediately downstream of Willow Bar, was excluded from the 1987 sediment sampling program and is not included in this study. Study areas were selected at Slaughters Bar, Lower and Upper Dobelbower Bars, Kalama Reach, Willow Bar, and Lower Vancouver Bar (figure 1). All study areas had sufficient dredging and hydrosurvey records for use of INFIL methods.

Figure 1. Index map of study areas on the Lower Columbia River, Oregon, and Washington.

Study areas were selected at reaches with various sediment types, in order to identify any differences due to sediment or slope characteristics. During construction of the 40-foot navigation channel, gravel and well-cemented sand were dredged at Lower Vancouver and Slaughters Bars (Hickson, 1965). Silt and sand materials were dredged at Kalama Reach and Willow Bar. The Lower and Upper Dobelbower Bars were included in this study because they were inundated by Mt. St. Helens mudflow sediment.

DEVELOPMENT OF LOWER COLUMBIA RIVER DRAINAGE

Morphologically significant changes have occurred in the Columbia River drainage in the recent geological past. Changes have been imposed during present times by engineering modification of river discharge and channel morphology. However, volcanic eruptions and dam construction are estimated to have produced the greatest effects.

Geologic Setting

Geologic materials in the Lower Columbia River valley consist of two general types. Miocene to Pliocene age consolidated rocks, chiefly basaltic lava flows and breccias, underlie Pleistocene and Holocene unconsolidated and semiconsolidated gravel, sand, silt, and clay materials. The older consolidated rocks generally form the foothills of the Lower Columbia, while the younger unconsolidated and semiconsolidated materials form the terraces and flood plains. The structure of the Portland-Vancouver area is thought to be the result of simultaneous downwarping of the older consolidated rocks into a shallow basin, coupled with the deposition of coarse sands and gravels of the Troutdale Formation during the Pliocene (Mundorff, 1964). Subsequently, during the Pleistocene an extensive delta, called the Portland Delta gravels, filled the head of the

valley at the mouth of the Columbia Gorge and spread onto adjacent lowland areas (Mundorff, 1964).

Present topography is a result of both the excavation of a portion of the Troutdale and Portland Delta gravels by the Columbia River, and of the subsequent post-glacial sea level rise of about 300 feet. The lower Columbia River valley flooded during the sea level rise causing extensive deposition of silt and clay materials in a low energy estuarine-lacustrine environment. These deposits form the majority of the bank materials that are found in the modern Columbia River lowlands. Present river geometry is controlled by these erosion-resistant silt and clay materials (Dodge, 1971).

Geologic Units of the Lower Columbia River

Major geologic units of the lower Columbia River are summarized in Table 1, from descriptions in reports by Hodge (1938), Threasher (1942), Wilkinson and others (1946), Lowry and Baldwin (1952), Trimble (1957, 1963), Roberts (1958), Snavely (1964), Strong (1964), Livingston (1966), Whetten and others (1969), Lister et al. (1967), Knebel and others (1968), Newton (1969), Gilchrist (1974), and Allison (1978 a, b). These authors have studied the underlying older rocks; the volcanic materials, the Columbia River Basalt, the deep valley fill, and the Troutdale Formation.

Table 1. Composite Column of Geologic Units for Lower Columbia River Valley.

Geologic Age	Type of Deposit or Formation Name	Thickness (feet)	Material Description
Holocene	Artificial Fill	0 - 15	Sand, silt pebbles, gravel and dredged channel deposits.
Holocene	Recent Alluvium (Columbia River bank material)	0 - 130	Sand, gravel, silt, mud, clay. Flood plain and stream channel deposits generally well-sorted and stratified. Gravel mostly basaltic and andesitic rocks.
Pleistocene	Older Alluvium (alluvium, alluvial fans, lacustrine and terrace deposits)	0 - 300	Sand, very fine sand, silt, gravel and clay. Stratified, cross-bedded and lenticular bedded deposits.
Pliocene	Boring Lavas	0 - 230	Olivine basalt, light gray.
	Troutdale Formation	0 - 1000	Quartz bearing conglomerate and vitric sandstone. Lenticular bedding.
	Columbia River Basalt	0 - 1000	Black, low olivine basalt.

From: Griffin (1956), Mundorff (1964), Hogensen (1965), Hoffstetter (1984)

However, they tend to ignore the recent geology, or lump younger deposits into "recent alluvium" consisting of undifferentiated gravel, sand, silt, and clay.

The geologic materials of concern in this study are the Holocene and Pleistocene alluvial sediments. Some data on the younger sediment fill are given by Griffin and others (1959), Mundorff (1964), Hogensen and Foxworthy (1965), and Hoffstetter (1984). All of these reports provide aquifer descriptions and cross-sections in the Portland-Vancouver area. These data are supplemented by borehole descriptions and cross-sections obtained from unpublished material from CH2M Hill (1971, 1974) and the U.S. Geological Survey (1984) for the East Portland area. Very little information has been published about the depth or areal extent of the recent alluvial materials located downstream of the Portland-Vancouver area.

Various drainage district design memoranda from the Portland District, Corps of Engineers (U.S. Army Corps of Engineers, 1957a, 1957b, 1957c, 1959, 1960a, 1960b), estimate the depths, distribution and general materials units contained in the Columbia River flood control drainage districts. The only well logs that have been evaluated for this study are those published in Mundorff's report (1964).

Holocene Alluvium and Artificial Fill. Present river geometry is controlled in part by bedrock outcrops and deposits of gravel and boulders. However, it is mainly controlled by the erosion-resistant silt and clay materials that line the banks of the Lower Columbia River. This bank material is firm silty clay that is relatively stable, but is subject to slow erosion in some river bends (Dodge, 1971). These materials occur in thin layers of clay interbedded with silt in the Portland-Vancouver area (CH2M Hill, 1971, 1974). The Holocene consists of materials similar to the Pleistocene alluvium, except the Holocene alluvium is generally finer in size and shows less stratification (Trimble, 1971).

Older Alluvium. Older post-Pleistocene channel deposits fill the Pleistocene Columbia River valley 200 to 300 feet deep forming the Columbia Sands aquifer (Hoffstetter, 1984; CH2M Hill, 1971, 1974). This deposit consists of medium sand interbedded with occasional layers of silt and gravel zones.

Pleistocene gravels tend to be coarse near the mouth of the Columbia River Gorge (about 25 miles east of Portland on Figure 2) and finer downstream in the openwork gravels of the Scappoose area. These gravels are found at various depths below the fine-grained Holocene alluvial materials.

Figure 2. Regional map of Lower Columbia River and major tributaries.

In the Scappoose and the central Sauvie Island area, gravel is exposed at the surface in a layer 40 to 95 feet thick. These deposits are located along the east side of the Sauvie Island and in western Vancouver (U.S. Army Corps of Engineers, 1960b; Mundorff, 1964). In north Portland, the gravel layer is 80 feet below the surface, dipping westward to a depth of 110 feet at the Multnomah channel area near Sauvie Island (U.S. Army Corps of Engineers, 1957a; Hogensen and Foxworthy, 1965).

Although not well documented, the thickness of the fine-grained Holocene and Pleistocene alluvial materials (silt, clay and sand with silt) has been estimated at various locations along the flood plain of the Lower Columbia River. Design memoranda of the Portland District, Corps of Engineers, estimate the silt-clay layer to be 150 feet thick between the east end of Cathlamet Bay and up to Longview area, 20 to 50 feet thick at Rainier, 40 to 150 feet thick at Scappoose, 40 to 90 feet thick at Sauvie Island, and 20 to 80 feet thick along the Portland Peninsula (U.S. Army Corps of Engineers, 1957a, 1957b, 1957c, 1959, 1960a, 1960b, 1964, 1971). Along the I-205 freeway alignment in East Portland, the silt-clay layer thickens southward from 10 to 16 feet on the Washington side to 35 to 40 feet on the Oregon side (CH2M Hill 1971, 1974). In unpublished geologic cross sections in the Portland well

field (U.S. Geological Survey, 1984), just east of the Portland, the silt-clay layer thickens westward from 8 to 60 feet to 30 to 80 feet (Hoffstetter, 1984). Existing groundwater reports show that the fine- to medium-grained silt and clay alluvium ranges from 20 to 140 feet deep in wells in the Vancouver area (Mundorff, 1964). Hogensen and Foxworthy (1965) identify silt-clay alluvial materials to depths of 95 and 174 feet in Portland area wells located along the Columbia River.

Modern Channel Deposits

Modern channel materials consist of coarse sand and gravel with very little fine material. Dodge (1971) described the majority of the Columbia River bedload as consisting of clean sand and silt. Whetten and others (1969) described the bedload sediments as mainly andesitic volcanic materials derived from Mt. Hood and Mt. St. Helens. These modern channel sediments are considered similar in composition to the ancient channel deposits of the Pleistocene and Holocene described by Hoffstetter (1984) as the Columbia River Sands aquifer.

Channel sediment placed on the bank at dredged material disposal sites is reworked and redistributed by river and wave processes. Actual thickness of the dredge material layer is controlled by its location in relation to pile

dikes, distance from the bankline and to a lesser extent, distance from the disposal site. The character of the sediments is spatially diverse, varying from fine silty sand on flat shoal areas to coarse gravel lenses near the landward ends of pile dikes.

Natural Channel Development

The Columbia River drainage basin has undergone natural changes in channel morphology and sedimentation in the relatively recent geologic past. Channel displacements resulted from glacial deluges (Spokane Floods), lava flows, and giant landslides in the Columbia gorge (U.S. Army Corps of Engineers, 1986). Sedimentation changes have resulted from regional folding and uplift of the Cascade Range, post-glacial changes in sea level, influx of volcanic mudflows, and sediment load changes from climatic and vegetation changes (U.S. Army Corps of Engineers, 1986).

Channel Impacts from Human Intervention

Major channel impacts in historic time include land use practices adjacent to the Columbia River channel that indirectly affect sediment and hydraulic discharges, and river engineering impacts that directly affect sediment and hydraulic discharges. The most significant historical impact has been the result of river engineering practices.

Indirect impacts include sediment load increases from early farm development and logging. Later improvements in agriculture and forestry practices have reduced these sediment contributions to background levels. Urban development and road construction have contributed to increased runoff and sediment load. Undetermined sediment and runoff impacts have resulted from flood plain changes due to levees, fill and other encroachments. Local contributions to the sediment load have been reduced by eliminating erosion at bank protection structures (U.S. Army Corps of Engineers, 1986).

The most obvious change in historical time has been the damming of the Columbia River, with resultant changes in peak and low discharges and the reduction of sediment transportation. Other direct channel impacts include channel mining for construction and landfill material, development of navigation channel consisting of channel changes from navigation channel dredging and river constriction projects, and dam and reservoir construction which changed the discharges of water and sediment, reducing the volume of sediment transported (U.S. Army Corps of Engineers, 1986).

Development of Navigation Channel

The lower Columbia River navigation channel is maintained to authorized dimensions of 40 feet deep by 600 feet wide (U.S. Army Corps of Engineers, 1987). The navigation channel is usually situated along the river's thalweg and much of the channel is naturally deeper than the 40-foot authorized depth. There are 27 bars downstream of the Interstate Bridge at Vancouver, Washington, that require regular maintenance dredging. Greater channel depths were created and maintained by periodic dredging and channel control structures. Channels through the bars are successfully maintained by river control structures including permeable timber pile dikes, revetments, groins, and strategically placed dredge material berms, supplemented by dredging (figure 3). "Pile dike" is a term used in Portland to describe control structures composed of timber piling driven closely spaced in a line, usually normal or nearly normal to the bankline and extending into the river.

Originally the Columbia River below the Portland-Vancouver area had shoal areas with natural depths of 12 to 15 feet at low water (Hickson, 1965). Channel depths at many natural shoal locations on the Columbia River were not deep enough for deep draft ocean vessels. A 25-foot channel was authorized in 1892. Authorized channel depth

Figure 3. Navigation channel control structures in study areas in 40-foot channel in 1971 (from Dodge, 1971).

changed from 25 feet to 30, 35, and 40 feet in 1912, 1930, and 1962 respectively (U.S. Army Corps of Engineers, 1987). Authorized widths increased from 300 feet in 1912, to 500 feet and 600 feet in 1930 and 1962 respectively (U.S. Army Corps of Engineers, 1987).

Dredging and Disposal

Dredging by the Corps of Engineers began on the Columbia River in 1875 at St. Helens Bar. Dredging the rest of the Lower Columbia River started around 1895 probably in response to the 1894 flood, which is the largest on record. Dredging to maintain navigation depths is an annual operation on nearly all reaches of the lower Columbia, although dredging is at much lower levels since the mid-1970's reduction of peak flows and sediment transport (U.S. Army Corps of Engineers, 1986). More reaches are now nearly self maintaining.

Increasing channel depth led to an initial large increase in the maintenance dredging volumes after the new channel was constructed, the dredging then decreased to a more constant level. Dredges normally excavate, during advance maintenance dredging, 2 to 5 feet below project depth to allow for inaccuracies and to provide authorized project depths throughout the rest of the year.

River Control Structures

Dredging alone does not maintain authorized channel depths for the entire year. Project dimensions can be maintained by natural scouring action in an appropriately sized channel cross-sectional. River control structures are used to develop appropriately sized channel cross-sections. River control structures used on the Lower Columbia River are timber pile dikes, revetments, groins and dredge material islands, back channel closures, and nearshore berms constructed of sand fill material.

Effects of contraction control works have been marked. Hickson (1965) indicated that the riverbed, in areas of former shoals was lowered 20 feet from mid-1930's to mid-1960's. Under the 35-foot project, annual maintenance dredging volumes were significantly reduced on all the bars between Vancouver and the estuary. More recently, a review of the performance of the pile dike fields indicated that they appear to be capable of reducing bank erosion, but are less adequate as flow control structures (U.S. Army Corps of Engineers, 1988). This loss of flow control ability is due to reduction of flood peaks caused by upstream dams (U.S. Army Corps of Engineers, 1988).

Channel Mining Operations

The Port of Portland has been dredging bedload sediment from four areas on the Columbia River, one near the mouth of the Willamette River, to be used as fill for the Rivergate Industrial area in northwest Portland. Fill material dredged by the Port is not placed on the river banks, where it can be eroded by wave erosion and re-entrained as bedload, thus it is permanently removed from the river system (Abbe, 1988, personal communication). This sediment removal lowers the bedload sediment input to downstream reaches, and reduces annual shoaling and maintenance dredging requirements.

Dam Construction

Water resources development in the Columbia River Basin is extensive. With 13 dams on the main stem, and 39 on major tributaries, most river reaches are controlled by dam regulation. Dam regulation has had two major effects; reducing flow extremes and reducing sediment transport. Shoaling, in reaches on the Lower Columbia River, has been much lower since the large storage reservoirs were completed in British Columbia in the 1970's (U.S. Army Corps of Engineers, 1988).

Streamflow regulation by the dams reduces peak water discharges while increasing low flow discharges. Reduction of peak discharges and a reduction in the percent of time the highest discharges are experienced, as shown by the flow-discharge curves (figure 4), has lowered the sediment transporting capacity of the river. This greatly reduces the amount of sediment transported downstream. The reduction in the 2-year flood, a common indicator, from around 600,000 cfs to about 360,000 cfs makes the Columbia River an oversized river (i.e. channel larger than necessary to convey its flow). Normally, sediment deposition would occur in an oversized channel as the river adjusts to reduced flows. This has not occurred on the lower Columbia River due to the low sediment inflow from upstream sources (U.S. Army Corps of Engineers, 1988).

In addition to decreasing discharges, upstream storage has significantly reduced the sediment load transported through the lower Columbia system. Upstream dams are thought to be trapping a large part of the suspended sediment in their reservoirs, although surveys in Bonneville pool have not shown significant deposits (Hickson, 1961; Whetten, 1969). In addition, the upstream bedload sediment load is reduced. This is thought to be the result of delta formation where streams enter the reservoirs, although no studies have been made to confirm

Columbia River Basin Cumulative Frequency Curve - Maximum Annual Daily Discharge
Spring and Summer Freshets for Columbia River at The Dalles, Oregon

Curve 1 - unregulated discharge based on the period 1858-1985 (128 years). Historic streamflow was adjusted to eliminate the effects of reservoir regulation, but reflect the effects of natural storage in lakes and channels, and was further adjusted for irrigation depletions to a 1985 level of development.

Curve 2 - regulated discharge reflecting a 1985 level of development. Regulated flows are based on a relationship with unregulated discharge as derived from recent historic regulations and computer simulations.

Figure 4. Comparison of flow discharge curves for pre-regulated and regulated discharges for Columbia River (from USACE, 1988).

this hypothesis (Palmer, 1985; personal communication).

These human impacts on river hydraulics and sediment transport capacity on the lower Columbia River affect shoaling characteristics in many reaches. However, they do not show up distinctly on the dredging record, and their contributions to shoaling have not been quantitatively defined.

BEDLOAD SEDIMENTATION ON LOWER COLUMBIA RIVER

Shoaling patterns on any reach of a river results from the interrelationship of many hydraulic and bedload sedimentation factors. Hydraulic factors operating on any reach of the lower Columbia River are:

1. annual river runoff or freshet discharge characteristics and effects on upstream bank erosion,
2. hydraulic effects of upstream river control works and their tendency to pass sediment into reach of interest,
3. hydraulic effects of river control works that control river cross-sectional area and shape, in reach,
4. location of navigation channel in relation to the river thalweg, and
5. channel location in relation to river bends.

These characteristics affect natural river bar migration patterns and sediment entrainment upstream.

Sedimentation factors operating on any reach of the lower Columbia River are:

1. type and availability of sediment being transported downstream by the river,
2. temporary side slope sedimentation following increases in channel dimensions,

3. erosion and redeposition of dredge disposal material, and
4. nature and availability of bank material.

These characteristics control the amounts of locally entrained sediment.

Upstream sediment input to bedload sedimentation is controlled by Columbia River discharge conditions. Below 110,000 cubic feet per second (cfs) discharge, little sediment transport occurs (i.e. 1,000 to 2,000 tons/day) (U.S. Army Corps of Engineers, 1986). Significant movement of sediment (i.e. 11,000 to 45,000 tons/day) occurs between 300,000 and 400,000 cfs discharge (U.S. Army Corps of Engineers, 1986; Erickson, 1988, personal communication).

Most local sediment inputs to bedload sedimentation on a reach are controlled by ship wakes, wind waves, and pile dikes. All sediment inputs except those from side slope sedimentation are controlled by hydrologic, meteorologic, and ship wake conditions instead of proximity to new work dredging events. Channel side slopes produce elevated sedimentation rates for about 3 to 6 years following new work dredging (Ogden Beeman and others, 1985). Although this increased sedimentation is a transient phenomenon, it can create a large increase in local sediment input to a reach which increases sediment volumes to be dredged. Therefore, side slope sedimentation is an important

consideration in projecting maintenance dredging requirements. Maintenance dredging is the major factor in forecasting post-construction costs in Corps budgets for navigation projects.

Hydrology of the Lower Columbia River

Columbia River discharges are dependent on runoff conditions, reservoir operations, and ocean tides. The highest discharges generally occur in May or June as a result of snowmelt in the Canadian headwaters. The low flows, in the 100,000 cfs range, occur in September and October before the runoff from winter rains begins (U.S. Army Corps of Engineers, 1988).

Upstream storage projects store water during high flow periods to be released during low flow periods for hydropower generation. This storage has reduced the 2-yr flood peak from near 600,000 cfs under unregulated conditions to slightly over 360,000 cfs with regulation (figure 4). The decrease in high flows is especially important to the river hydrology, as sediment movement is an exponential function of water discharge (U.S. Army Corps of Engineers, 1988). The change in the flow-discharge curve has reduced the average annual sediment yield at Vancouver from 12 million cubic yards (mcy) before 1962 to 2 mcy by the early 1970's (U.S. Army Corps of Engineers, 1986).

Sediment Transport on the Lower Columbia River

Historically, most of the sediment transport has been during the spring snowmelt or "freshet" which occurs between May and July, lasting from 30 to 60 days. Much of the year suspended sediment is low, and the river is relatively clear (Hickson, 1965). Suspended sediment, with sources far upstream of the study locations on the lower river, moves through the river at near flow velocities. Bedload is transported at or near the bottom as bedforms ranging from small-scale ripples to large sand waves. Bedload transport occurs more slowly during downstream migration of sand waves on the river bed. These waves range in size from 3 feet high and 60 feet long to as much as 12 feet high and 600 feet long (Whetten, 1966; U.S. Army Corps of Engineers, 1988). The largest waves often have crests above the authorized channel depth of -40 feet, creating shoal conditions. Bedload sedimentation was found to be the main cause of shoaling on the lower Columbia River (U.S. Army Corps of Engineers).

The sediment load of the regulated Columbia River, relatively small compared to other rivers of its size, is constrained by a lack of sediment supply upstream. The upstream reservoirs trap most of the sediment produced east of the Cascades and erosion rates west of the Cascades are

very low (U.S. Army Corps of Engineers, 1988). More complete flow regulation resulting from upstream dams has resulted in an estimated 80 percent reduction in suspended sediment transport and a 90 percent reduction in bedload transport, on an average annual basis (U.S. Army Corps of Engineers, 1988).

Bedload Transport

Sediment transport rate for the Columbia River has been estimated by many investigators at different times. Estimates summarized by Whetten and others (1969) and by Hickson (1960) are listed in Table 2. Following more complete river regulation in the 1970's, the total annual sediment load is now only about 2 mcy annually (U.S. Army Corps of Engineers, 1988). The bedload portion is about 0.5 mcy annually. More recently, the bedload transport rate of 1.9 mcy per year, was estimated from annual dredging volumes between 1968 and 1985 in the Vancouver Turning Basin, just upstream of Vancouver, Washington (U.S. Army Corps of Engineers, 1986). In addition, bedload transport can be estimated from the rate of movement of sand waves. Movement of sand waves at the downstream end of Sauvie Island (RM 90), showing 0.05 to 0.2 mcy bedload transport annually, may be too low as freshet conditions (with higher discharge and sediment transport rates) were excluded from the period

Table 2. Estimated Sediment Transport Rates in Lower Columbia River.

Researcher (Reference Date)	Sediment Transport Estimation Method	Date Sampled	Reach Sampled	Sediment Transport Rate		
Suspended Sediment Load				(kg/year)	(tons/year)	(cy/year)
Van Winkle (1914)	suspended sediment	1910-1911	Cascade Locks	6,400 million	6,293,266	5,010,562
Hickson (1960)	suspended sediment			9,000 million	8,849,906	7,046,104
USACE (1986)	suspended sediment	pre-1960's	Vancouver, WA	16,500 million	16,203,445	12,900,832
USACE (1986)	suspended sediment	post-1960's	Vancouver, WA	2,800 million	2,746,770	2,186,919
Bedload Sediment Load				(kg/year)	(tons/year)	(cy/year)
Hickson (1960)	bedload sediment			4,000 million	3,933,291	3,131,601
Whetten et al (1969)	bedload sediment	average conditions		< billion	9,800,000	7,802,548
Ogden Beeman (1985)	bedload (sand)	1940's-50's	Lower Columbia	4,600 million	4,536,000	3,600,000
Ogden Beeman (1985)	bedload (sand)	1985	Lower Columbia	935 million	919,800	730,000
USACE (1986)	bedload sediment	2/78-11/78	Vanc Turn Basin	983 million	966,420	767,000
USACE (1986)	bedload sediment	2/82-8/82	Vanc Turn Basin	1,912 million	1,880,139	1,492,174
USACE (1988)	unmeasured sediment	pre-1960		1,922 million	1,890,000	1,500,000
USACE (1988)	unmeasured sediment	post-1960		256 million	252,000	200,000
Sand Wave Size and Speed				(kg/day)	(tons/day)	(cy/day)
Haushild et al. (1966)	sandwave size/speed	1962-1963	Pasco to Vancouver	9,966 million 20,000 million	9,833,228 19,666,457	7,829,003 15,658,007
Whetten and Fullam (1967)	sandwave size/speed	July 1966	Bonneville Reservoir	200,000	196,665	156,580
USACE (1988)	sandwave speed	1988	Sauvies Island	256 million 641 million	252,000 630,000	200,000 500,000
Total Sediment Load				(kg/day)	(tons/day)	(cy/day)
Hidaka (1966) Haushild et al.	depth-integrated mean daily discharge	1962-1963	Vancouver Washington	7,600 million	7,473,254	5,950,043

of record (U.S. Army Corps of Engineers, 1988).

Bedload sedimentation is difficult to measure, and no attempts have been made to obtain quantitative measurements in the Columbia River. The U.S. Geological Survey has developed an empirical relationship between discharge and unmeasured load at Vancouver, Washington using the modified Einstein equation (U.S. Army Corps of Engineers, 1986). Applying that relationship to the pre-1960 and post-1960 flow duration curves yielded average annual bedload estimates of 1.5 mcy pre-1960 and 0.2 mcy post-1960 (table 2). Unmeasured sediment discharge, consisting mainly of sand or coarser sediments, is defined to be the volume difference between the calculated value for total sediment discharge and the measured value for suspended sediment discharge. Bedload transport can be approximated by unmeasured sediment discharge (Appendix A).

Unmeasured load for the Willamette River, the major tributary to the lower Columbia River, is not accounted for in this analysis for three reasons:

1. the data for determining it are not available,
2. the Willamette contributes much less discharge than the Columbia (drainage of 11,200 square miles vs 241,000 square miles respectively),
3. dredged areas in the lower Willamette trap much of the sediment moving as bedload, resulting in a

relatively insignificant amount reaching the Columbia.

Tributaries downstream of the Willamette, such as the Kalama, Cowlitz, and Lewis Rivers, have significantly smaller discharges than the Willamette River. In addition, no method to compute unmeasured sediment discharges has been developed and these sediment inputs are not included in this analysis.

Catastrophic sediment inflows, such as the Mt. St. Helens mudflow, obviously provide large amounts of total sediment to the Lower Columbia River. The bedload sediment contribution from the Cowlitz has averaged 2 mcy for the past several years (Chesser, 1989, personal communication). However, this has not significantly increased the annual dredging downstream (U.S. Army Corps of Engineers, 1988).

Bedload transport through a reach is the net downstream transport and does not account for the total volume of sediment moved within a reach during the year. So while bedload sediment passing into or out of the reach may be only 0.2 mcy per year, many times that volume may move within the reach area (U.S. Army Corps of Engineers, 1988). This internal bedload movement accounts for the dredging volumes being over 1 mcy per year when sediment transport (suspended bed material plus bedload) into the area is only

0.4 mcy per year (U.S. Army Corps of Engineers, 1988).

Bedload Sedimentation

Most shoaling within a reach results from bedload sedimentation derived from local sources, such as:

1. hydraulic adjustments to river control structures,
2. natural river bar migration,
3. re-entrainment of dredge disposal material, and
4. material contributed during readjustment of channel side slopes following new work dredging.

Sedimentation caused by channel readjustments to river control structures are low in the study areas, because the channel has adjusted to the 40-foot channel conditions that were instituted in the 1960's. Sedimentation from river bar migration occurs in areas where the navigation channel cuts across the downstream side of a moving bar. Erosion and redeposition of river bar material in the navigation channel is directed by river hydrology. Re-entrainment of dredge disposal material is affected by dredging methods used on a reach. Material erodes more quickly when disposed of in nearshore areas by hopper dredging and more slowly when deposited along the shoreline by pipeline dredging (U.S. Army Corps of Engineers, 1988). Erosion rates for shoreline dredged deposits are controlled primarily by shipwake and wave activity (Abbe, 1988, personal communication), and

redemption rates are controlled by river hydrology (U.S. Army Corps of Engineers, 1988).

Sedimentation from channel side slope adjustments following new work dredging are relatively independent of river hydrology and surface wave erosion. This side slope sedimentation occurs when a dredge cut disturbs an otherwise stable river bed. The cut may lower the toe of the slope or some point along the side slope. The side slope will become unstable and sediment will be transported into the channel. These slope adjustments appear to continue until the side slope has returned to an equilibrium configuration; usually a similar configuration as the original slope before dredging (U.S. Army Corps of Engineers, 1988).

For the purposes of this study, bedload sedimentation within a reach is defined to be the sum total of all sediment contributions to bed material in the navigation channel within a designated reach (eg., Slaughters Bar). This bed material, located within the navigation channel prism (authorized channel dimensions) is removed during regularly scheduled maintenance dredging. Averaged annual maintenance dredging volumes, in reaches with equilibrium side slopes, can be used to approximate bedload sedimentation. Sediment sources, both upstream and local, may be located outside the dredging prism, but are not derived from the side slopes adjacent to the navigation

channel (figure 5). For up to 3 to 6 years during side slope readjustment after a new work dredging project is constructed, the maintenance dredging volumes are much higher than those for locations with equilibrium side slopes (Ogden Beeman and others, 1985; Evarts and others, 1987). These additional dredging volumes are defined as side slope sedimentation. Sources for this side slope sedimentation are the local channel side slopes adjacent to the dredging prism (figure 5).

These study methods identify and quantify historic side slope sedimentation contributions to bedload sedimentation following new work dredging. In addition, these methods will predict rates and volumes of future side slope sedimentation following construction of navigation, in areas where historic side slope sedimentation can be determined from maintenance dredging records.

Figure 5. Comparison of locations for source of bedload sedimentation under equilibrium conditions to source of side slope sedimentation following new work dredging. Dredging prism is area defined by depth and width of navigation channel.

SIDE SLOPE SEDIMENTATION

Historically, dredging records show increases in maintenance dredging volumes in years following new work dredging events (U.S. Army Corps of Engineers, 1988). The major component of these increased dredging volumes is the sediment that is contributed from navigation channel side slopes (Evarts and others, 1987; U.S. Army Corps of Engineers, 1988). After dredging is completed, oversteepened side slopes slump into the dredge cut, temporarily increasing local bedload sedimentation, until equilibrium side slopes are reestablished (Gristrain and Lavygin, 1987). Also, elevations of undredged slopes that are adjacent to the channel will decline as side slopes readjust from the steep sided dredge cuts to more shallow angles that are typical of the natural or equilibrium side slopes (figure 6).

Unlike "natural" sources of sedimentation, such as those from upstream or local sediment sources that fluctuate with hydrologic conditions, side slope sedimentation causes a temporary increase in bedload sedimentation that is independent of river hydrology. Designed dredged slopes are generally 1:3. Equilibrium side slopes are less steep than designed dredge cuts, except for those found on the outside of river bends (U.S. Army Corps of Engineers, 1988). Generally, equilibrium slopes vary

Figure 6. Readjustments in channel side slopes after new work dredging. Dredge cuts on lower Columbia River are 1:3.

from 1:10 in the lower Columbia River to 1:100 in the Columbia River estuary (Evarts and others, 1987).

After the side slopes have become stabilized, there are two possible channel cross-section configurations that could exist (figure 7). The first configuration retains the natural or equilibrium channel side slopes, but slope elevations become deeper. The second configuration develops steeper channel side slopes than the natural or equilibrium slopes. This new side slope will intersect the old channel boundary some distance from the navigation channel.

Side slopes will gradually readjust to equilibrium configurations. Side slope sedimentation volumes decrease for several years following new work dredging, usually 3 to 6 years when the dredge cuts are between 2 and 5 feet (Ogden Beeman and others, 1985). According to the Corps engineering experience (1988), this decrease can be approximated by an exponential decay curve (Ogden Beeman and others, 1985; Evarts and others, 1987).

Maintenance dredging records were used to approximate sedimentation rates on the Lower Columbia River. It is difficult to differentiate increased maintenance dredging volumes caused by side slope sedimentation from that caused by impacts of river engineering works, and other technical and economic factors that determine the extent of annual

Figure 7. Two possible navigation channel side slope configurations that can develop during readjustment to equilibrium slopes following new work dredging (from Evarts and others, 1987).

dredging activities. To identify side slope sedimentation volumes, maintenance dredging records need to be "normalized" or corrected to minimize the variations from technical and economic factors. Thus, the corrected dredging record will more closely approximate the annual bedload sedimentation for the reach. Several methods were used to approximate annual bedload sedimentation from maintenance dredging records (see Appendix B).

None of the methods used to correct maintenance dredging records would adequately approximate annual bedload sedimentation. Therefore, identification of side slope sedimentation volumes, in order to prove an exponential decline following new work dredging, was not possible. Past engineering experience at the U.S. Army Corps of Engineers (1988) has proved, with empirical methods, that side slope sedimentation following new work dredging in the Columbia River estuary declines exponentially.

It is not the intent of this study to prove that decreases in side slope sedimentation following new work dredging are best represented by an exponential decay curve. Rather, INFIL was developed by the Corps (1988) to construct representative exponential decay curves for side slope sedimentation based on input values obtained from maintenance dredging data at each study area and to predict future side slope sedimentation volumes.

INFIL PREDICTION OF SIDE SLOPE SEDIMENTATION

Side slope sedimentation volumes increase substantially following new work dredging where new navigation channel depths and/or widths have been excavated. INFIL was developed to construct exponential decay curves that estimate the amount of side slope sedimentation for each year of the readjustment period. INFIL can also be used to predict side slope sedimentation during the readjustment period following future new work dredging episodes. However, INFIL needs to be calibrated using historical data before it can be used to predict future side slope sedimentation can be predicted. For this study, INFIL was calibrated by estimating historic side slope sedimentation volumes and volumes using U.S. Army Corps of Engineers (1988) dredging records (as shown in figure 8) for the period 1895 to 1985 for each study area.

INFIL Model

The INFIL model was developed by Harold Herndon and Laura Hicks at Portland District, Army Corps of Engineers, in 1986 for in-house use. This model was designed to construct an exponential decay curve that distributes the total volume of side slope sedimentation over the readjustment period. In order to develop this model, several items need to be estimated in the following steps:

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Figure 8. Maintenance dredging volumes for Kalama Reach study area for period of record from 1895 to 1985 (US Army Corps of Engineers, 1988).

1. Make a determination of what equilibrium slopes will be after the readjustment period.
2. Make a determination of what dredging requirements will be under "equilibrium conditions".
3. Determine the amount of material from side slope adjustment.
4. Estimate the number of years for adjustment.

Items 1, 2, and 4 are estimates based on analysis of maintenance dredging records, historical hydrosurveys, and engineering judgment. Item 3 can be calculated based on the determination made in Item 1.

With the "knowns" determined from steps 1 through 4, the expression $Y = Y_0 * e^{-kt}$ can be evaluated for the value of k (figure 9). This evaluation requires an additional estimate of the percentage of the side slope material which will enter the dredged channel in the first year. After the value of k has been determined, one can calculate the annual dredging requirements for the deepened channel.

INFIL Program

INFIL program, written in Basic (Appendix C), was developed from the INFIL model to construct an exponential decay curve using the following four items as input:

- Item 1. Average or "equilibrium" bedload
sedimentation from both upstream and local

Figure 9. Development of INFIL model.

sources in cubic yards.

Item 2. Length of readjustment period following new work dredging in years.

Item 3. Initial percent of total side slope sedimentation (Item 4) entering the channel during the first year of the readjustment period.

Item 4. Total volume of side slope sedimentation at end of the readjustment period.

Maintenance dredging records are used to estimate INFIL Items 1, 2, and 4 (figure 10). As discussed previously in the Side Slope Sedimentation section, these dredging records need to be corrected to estimate bedload sedimentation volumes (Appendix C). No conversion was successful, and cumulative plots for maintenance dredging volumes (figure 11) proved to be the only workable method.

Item 2, the length of readjustment period following new work dredging, is determined at the break-in-slope location on the cumulative maintenance dredging curve (figure 11), a difficult location to pinpoint on the plot. In order to more clearly identify the break-in-slope location, cumulative maintenance dredging volumes were plotted as a semi-log graph (figure 12). The best year(s) location(s) are selected to run INFIL. The Ogden Beeman depth method (1985) can be used as a check for the length of

Figure 10. Maintenance dredging volumes at Kalama Reach study area following three new work dredging events (USACE, 1988).

Figure 11. Cumulative plot of maintenance dredging volumes at Kalama Reach study area following new work dredging events (US Army Corps of Engineers, 1988). Slope of dashed line is average bedload sedimentation.

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Figure 12. Semi-log plot of cumulative maintenance dredging volumes at Kalama Reach study area (U.S. Army Corps of Engineers, 1988). Break-in-slope indicates end of side slope readjustment period.

the readjustment period. This method estimates the readjustment period at 3 to 4 years of readjustment for depth increases of less than 5 feet and 6 months to one year for every foot of increased channel depth of 5 feet or more. For example, a depth increase of 3 feet would be expected to produce a readjustment period of 1.5 to 3 years. Sets of INFIL runs were made for each possible readjustment period for each new work dredging event.

Item 1, average bedload sedimentation, was estimated from the slope of the cumulative maintenance dredging curve beyond the break-in-slope location which indicates the end of the readjustment period (figure 11). To confirm this value, average bedload sedimentation can be estimated from the average of raw maintenance dredging volumes for the time period following the readjustment period (figure 13). These two values should be similar, and sets of INFIL runs were made for each bedload sedimentation value for each new work dredging event.

Item 4, total volume of side slope sedimentation at the end of the readjustment period, is determined from the cumulative maintenance dredging volume at the break-in-slope location on the cumulative dredging plot (figure 11), minus the cumulative bedload sedimentation volume at the same location. If more than one readjustment period was selected, total side slope sedimentation volumes were

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Figure 13. Dashed line indicates average bedload sedimentation following three new work dredging events, as plotted on maintenance dredging records (USACE, 1988).

estimated for each period. Sets of INFIL runs were run for each readjustment period for each new work dredging event.

Item 3, the initial percent of total volume of side slope sedimentation (Item 4, above) entering the navigation channel during the first year of the readjustment period, is first estimated and then adjusted through successive iterations of INFIL until a successful run is completed. An initial estimate can be determined from the raw maintenance dredging record. From this record, the largest annual dredging volume during the readjustment period is divided by the cumulative volume of maintenance dredging during this period. This percent can be used as the first estimate for initial percent (figure 14).

INFIL Calibration

In this study, INFIL was calibrated by the simulation of historic side slope sedimentation following new work dredging episodes on the Lower Columbia River. Estimates for the input items are derived from maintenance dredging records of the U.S. Army Corps of Engineers. From these records, three episodes of "new work" dredging were selected (figures 8 and 10). In the 1930's and 1960's, authorized navigation channel dimensions were increased to 35 x 500 feet and 40 x 600 feet, respectively. In addition, an intensive program of advance maintenance dredging, or

Figure 14. Method for estimating initial percent of total side slope sedimentation by dividing largest maintenance dredging volume in readjustment period by total side slope sedimentation volume (hatched area) for three new work dredging episodes on Kalama Reach (USACE, 1988).

overdredging to extend period of effective channel depths, was instituted in the late 1950's, which increased navigation channel depths without any width increases. An initial value for Item 3, the initial percent of total side slope sedimentation, is selected and adjusted through successive INFIL iterations until the side slope sedimentation volume for the last year of the readjustment period most closely approximates the average bedload sedimentation volume for Item 1.

The Kalama Reach was selected as the test case to establish procedures for calibration and prediction by INFIL. The Corps started investigations for anchorage sites on the lower Columbia River at the Kalama Reach; and they needed to predict what the probable side slope sedimentation contribution to maintenance dredging requirements would be following project excavation. These dredging volumes are then used to forecast maintenance costs in the project budget.

Calibration Methods

INFIL calibration starts with an initial run using the first estimate of initial percent (Item 3). Sediment volumes for each year of the readjustment period are calculated by INFIL and printed. To check for a successful run, the sediment volume for the last year of the

readjustment period is compared to the average bedload sedimentation volume, input as Item 1. A successful run is identified when the last sediment volume of the readjustment period closely approximates the average bedload sedimentation (figure 15).

Calibration Results

INFIL runs were made for all study reaches using both sets of average bedload sedimentation volumes. Calibration runs were made to establish values for the percent of total side slope sedimentation contributed during the first year of the readjustment period. This initial percent was estimated for readjustment periods greater than two years, since a two-year readjustment period did not produce successful runs. All study reaches, with 5 or more years of annual maintenance dredging following new work dredging, produced successful runs (Appendixes D and E). INFIL would not work on a reach with a hiatus in annual maintenance dredging of two or more years.

Initial percent values were produced for both sets of side slope readjustment periods, which ranged between 3 and 7 years, in Tables 3 and 4. Comparisons between initial percent results from new work dredging, with both depth and width increases, to those from new work dredging, with only depth increases, are shown in Table 5. Comparisons between

Kalama Reach 35-foot Authorized Channel Deepening 1932-1959

Estimated total yield from side slope adjustment (in cubic yards) 125743
 number of years to reach equilibrium section 3
 Estimated final annual yield (est. bedload sedimentation) after slope adjustment
 (in cubic yards) 378419
 Percentage of total side slope yield to be used as initial yield estimate (percent as decimal) .7

YEAR	SEDIMENT VOLUME
1	434991.2
2	403662.4
3	378313
Total Yield	1261000

Kalama Reach Advanced Maintenance Dredging 1950-1968

Estimated total yield from side slope adjustment (in cubic yards) 617063
 number of years to reach equilibrium section 3
 Estimated final annual yield (est. bedload sedimentation) after slope adjustment
 (in cubic yards) 427393
 Percentage of total side slope yield to be used as initial yield estimate (percent as decimal) .76

YEAR	SEDIMENT VOLUME
1	700385
2	547170.8
3	427473.4
Total Yield	1899662

Kalama Reach 40-foot Authorized Channel Deepening 1969-1985

Estimated total yield from side slope adjustment (in cubic yards) 423886
 number of years to reach equilibrium section 3
 Estimated final annual yield (est. bedload sedimentation) after slope adjustment
 (in cubic yards) 214863
 Percentage of total side slope yield to be used as initial yield estimate (percent as decimal) .75

YEAR	SEDIMENT VOLUME
1	395126.6
2	293315.1
3	217737.2
Total Yield	1066973

Figure 15. Example of final INFIL runs for three episodes of new work dredging. Sediment volumes represent side slope sediment volumes contributed during each year of the readjustment period.

Table 3. INFIL results showing percent of total side slope sedimentation volume contributed during the first year of the readjustment period for various depth and width increases in navigation channel dimensions.

REACH	PERIOD OF RECORD	INCREASED DIMENSIONS		READJUSTMENT PERIOD		VOLUME SIDE SLOPE SEDIMENTATION *		BEDLOAD SEDIMENTATION **		% TOTAL VOLUME CONTR IN YR 1	
		DEPTH	WIDTH	CUM DR	AVE DR	CUM MAINT	AVE MAINT	CUM MAINT	AVE MAINT	CUM DR	AVE DR
DOBELBOWER	1933-1955	+2'	+200'	3	3 4	434343	403581 118476	706488	716742 730318	71	71 51
KALAMA	1932-1959	+2'	+200'	3	3 4	125743	157939 478100	378419	367687 251125	70	70 57
KALAMA	1969-1985	+3'	+100'	(2) 3	3 4	423886	393886 300600	214363	224363 231082	79	78 55
L. VANCOUVER	1936-1959	+5'		(2) 3	3 4 5	721098	152367 1045406 89088	714133	903710 922719 947664	73	68 56 40
L. VANCOUVER	1966-1985	+8'		4	4 7	629238	594514 677054	57129	65810 116786	76	73 35
SLAUGHTERS	1932-1959	+2'	+200'		3 4		156594 525865		471226 446608		69 54
SLAUGHTERS	1973-1979	+2'	+100'	4	4	363084	989796	313357	156679	54	68
WILLOW	1964-1985	+5'	+100'		3 4 5 6		839104 1113207 1627293 1532111		286796 271568 240582 247088		83 63 53 42

* VOLUME OF SIDE SLOPE CONTRIBUTION IS DERIVED FROM SUBTRACTING X YEARS OF BEDLOAD SEDIMENTATION VOLUME FROM TOTAL CUMULATIVE MAINTENANCE DREDGING

** BEDLOAD SEDIMENTATION SOURCES:

CUM MAINT - SLOPE OF LINE FIT TO CUMULATIVE MAINTENANCE DREDGING CURVE AFTER BREAK-IN-SLOPE

AVE MAINT - AVERAGE OF MAINTENANCE DREDGING VOLUMES FOR PERIOD OF RECORD FOLLOWING THE END OF READJUSTMENT PERIOD

Table 4. INFIL results showing percent of total side slope sedimentation volume contributed during the first year of the readjustment period for various depth and no width increases in navigation channel dimensions.

REACH	PERIOD OF RECORD	INCREASED DIMENSIONS	READJUSTMENT PERIOD		VOLUME SIDE SLOPE SEDIMENTATION *		BEDLOAD SEDIMENTATION **		% TOTAL VOLUME CONTR IN YR 1	
			CUM DR	AVE DR	CUM MAINT	AVE MAINT	CUM MAINT	AVE MAINT	CUM DR	AVE DR
L. DOBELBOWER	1959-1966	+5'		3		830076		215008		87
				5		1188842		213140		51
U. DOBELBOWER	1959-1966	+5'		3		1214035		205873		95
				4		1382414		181818		71
KALAMA	1960-1968	+3'	3	3	617063	685466	427533	404732	76	77
				4		398411		440614		54
SLAUGHTERS	1960-1965	+3'		3		877847		591869		76
				4		1087067		613237		56
	1966-1972	+3'		3		1100221		262795		89
				4		1736195		235199		70

* VOLUME OF SIDE SLOPE CONTRIBUTION IS DERIVED FROM SUBTRACTING X YEARS OF BEDLOAD SEDIMENTATION VOLUME FROM TOTAL CUMULATIVE MAINTENANCE DREDGING

** BEDLOAD SEDIMENTATION SOURCES:

CUM MAINT - SLOPE OF LINE FIT TO CUMULATIVE MAINTENANCE DREDGING CURVE AFTER BREAK-IN-SLOPE

AVE MAINT - AVERAGE OF MAINTENANCE DREDGING VOLUMES FOR PERIOD OF RECORD FOLLOWING THE END OF READJUSTMENT PERIOD

Table 5. Comparisons of initial percent of total side slope sedimentation, contributed during the first year of the readjustment period, between new dredging with depth and width increases and new work dredging with only depth increases.

READJUSTMENT PERIOD (yrs)	DEPTH INCREASE (ft)	INITIAL PERCENT OF SIDE SLOPE SEDIMENTATION DURING FIRST YEAR OF READJUSTMENT		
		DEPTH AND WIDTH INCREASE		DEPTH INCREASE
		1930'S	1960'S	
3	2	71, 71, 70, 70, 69 AVERAGE = 70		
	3		79, 78 AVERAGE = 79	76, 77, 76, 89 AVERAGE = 80
	5	73, 68 AVERAGE = 71	83	87, 95 AVERAGE = 91
4	2	54, 51, 57 AVERAGE = 54	54, 68 AVERAGE = 61	
	3		55	54, 56, 70 AVERAGE = 60
	5	56	63	71
	8		76, 73 AVERAGE = 75	
5	5	40	53, 53	51
6	5		42, 42	
7	8		35	

initial percent results by characteristic sediment type are shown in Table 6. Figure 16 shows a plot of the comparison of the initial percent of side slope sedimentation for each new work dredging event.

INFIL calculations for declining side slope sedimentation during the readjustment period are able to adequately approximate average bedload sedimentation volumes. Several trends for initial percent values were extracted from the results in Table 5. First, the initial percent values for depth only new work dredging are larger than those for depth and width new work dredging. Second, the initial percent values tend to increase with larger increases in channel depths for the same length of readjustment period. Third, the initial percent values tend to decrease with increasing length of the readjustment period. Similar trends for initial percent values, compared by sediment type, were extracted from Table 6.

Prediction by INFIL

INFIL can be used to predict side slope sedimentation, and therefore maintenance dredging requirements, for future new work dredging in navigation channels. Successful runs are made in the same manner as in the calibration method. However, several of the INFIL input items are estimated from different sources using different methods. The Kalama

Table 6. Comparisons of initial percent of total side slope sedimentation, contributed during the first year of the readjustment period, between characteristic sediment types on a reaches.

READJUSTMENT PERIOD (yrs)	DEPTH INCREASE (ft)	INITIAL PERCENT OF SIDE SLOPE SEDIMENTATION DURING FIRST YEAR OF READJUSTMENT			SILT AND CLAY W/ MUDFLOW
3	2	69	70, 70	71, 71	
	3	76, 89 AVERAGE = 83	76, 77, 78, 79 AVERAGE = 78		
	5	68, 73 AVERAGE = 71	83	87, 95 AVERAGE = 91	
4	2	54, 54, 68 AVERAGE = 59	57	51	
	3	56, 70 AVERAGE = 63	54, 55 AVERAGE = 55		
	5	56	63	71	
5	8		76, 73 AVERAGE = 75		
	5	40	53, 53	51	
	5		42, 42		
7	8	35			

INFIL COMPARISONS

DEPTH/WIDTH VS DEPTH ONLY INCREASES

Figure 16. Plot of initial percent of total side slope sedimentation during the first year of readjustment. Comparison between new work dredging with depth and width increases and new work dredging with only depth increases in channel dimensions.

Reach (figure 17) was used as a test case to predict maintenance dredging requirements following excavation of an anchorage site adjacent to the navigation channel.

Prediction Methods

In the INFIL prediction mode, input values for Item 1, average bedload sedimentation rate, and Item 3, initial percent of side slope sedimentation, are those which have been estimated by the calibration methods. These same values will be used in the prediction runs. Item 2, the number of years in the readjustment period, and Item 4, the total volume of side slope sedimentation, can be estimated using the methods described below.

Item 2, the length of readjustment period, can be estimated from the Ogden Beeman depth method (1985), using average depth increases in the planned excavation. These average depths increases are estimated from cross-section plots constructed from the most recent hydrosurvey data. Generally two readjustment periods are run to bracket the range of predicted annual side slope sedimentation for each year.

Item 4, the total volume of side slope sedimentation, can be estimated using the double-end-area engineering method for calculating cross-sectional volumes for a specified stretch of channel (Appendix F). The double-end-

Figure 17. Location of anchorage sites at Kalama Reach used as test case for INFIL prediction of side slope sedimentation (U.S. Army Corps of Engineers, 1988).

area calculation is based on an estimate of the total cross-sectional area that is expected to slough into the dredging prism, during the readjustment period.

INFIL prediction runs use the same procedures as those in the calibration section. The initial percent value is adjusted until a successful run is achieved. However, the initial percent value can not be adjusted below 30% (Ogden Beeman and others, 1985). If a successful run is not achieved with a 30% initial value, it must then must be held constant at 30% and the length of the readjustment period reduced until a successful run is achieved. INFIL calculations of annual side slope sedimentation can then be used to predict a range of approximate maintenance dredging requirements following a new work dredging event.

Prediction Results

INFIL prediction runs used input parameters listed in Table 7. Runs were made using two values for average bedload sedimentation for both periods of side slope readjustment. The 6-year readjustment period produced successful runs for both volumes for average bedload sedimentation using an initial percent (Table 8). The 13-year readjustment period did not produce successful runs for initial percent values over 30 percent. Therefore, the length of the readjustment period was reduced successively

Table 7. INFIL input parameters (Items 1 to 4) for prediction runs at Kalama Reach anchorage site.

INFIL INITIAL INPUT PARAMETERS

Estimated Bedload Sedimentation = 21,907 to 23,058 cy

Side Slope Readjustment Period = 6 to 13 years *

Initial Percent of Total Side Slope
Sedimentation During First Year = 47 to 59

Total Side Slope Sedimentation = 270,800 cy **

* Ogden Beeman (1985) Depth Method for estimating side slope readjustment period at 6 months to 1 year per foot of deepening:

Estimated depth increase: 12.6 feet
Estimated readjustment period: 6 to 13 years

** Double-end-area method in Appendix F.

Table 8. Results of INFIL prediction runs for Kalama Reach anchorage study. Sediment volumes represent annual side slope sedimentation during the readjustment period.

Number of Years	Initial Yield %	Sediment Volume	Estimated Bedload	Initial Yield %	Sediment Volume	Estimated Bedload
1	30	86,709cy	21,907cy	30	88,006cy	23,058cy
2		72,890cy			74,259cy	
3		61,273cy			62,660cy	
4		51,508cy			52,872cy	
5		43,299cy			44,613cy	
6		36,399cy			37,645cy	
7		30,598cy			31,764cy	
8		25,722cy			26,803cy	
9		21,622cy			22,616cy	
Total Yield		461,474cy			478,322cy	

Number of Years	Initial Yield %	Sediment Volume	Estimated Bedload	Initial Yield %	Sediment Volume	Estimated Bedload
1	47	109,949cy	21,907cy	47	110,144cy	23,058cy
2		79,588cy			80,698cy	
3		57,611cy			59,124cy	
4		41,703cy			43,318cy	
5		30,187cy			31,737cy	
6		21,852cy			23,252cy	
Total Yield		397,916cy			409,148cy	

to a period of 9 years before a successful run was achieved for an initial percent of 30 percent (Table 8). INFIL calculations for side slope sedimentation were graphed in figure 18, comparing the 6-year readjustment period to the 9-year readjustment period for both volumes for average bedload sedimentation. These results bracket the range of annual side slope sedimentation volumes that can be expected following a projected new work dredging event. These results have not been tested because construction of the Kalama anchorage had not started when this study was completed.

Limitations to INFIL Method

The INFIL method of simulating or predicting side slope sedimentation rates and volumes following new work dredging events is a highly simplified method, based on averaging annual dredging volumes over a multiple year time period, over an entire river reach 2 to 3 miles in length. In this study and at this level of development, INFIL can not be used to predict exact maintenance dredging requirements on an annual basis. In addition, INFIL methods developed in this study can not be applied to areas lacking historic dredging or hydrosurvey records.

Four major limitations to INFIL have been identified as needing more work in order to refine the simulation and

KALAMA ANCHORAGE SIDE SLOPE SHOALING

Figure 18. Comparing annual side slope sedimentation for 6 year and 9 year readjustment periods. Plots compare results for each value for average bedload sedimentation.

predictive capabilities. These are:

1. An assumption of an exponential decay configuration for side slope sedimentation, during the readjustment period following new work dredging, is empirical. INFIL needs to be tested with actual bedload sedimentation volumes to see if the decline in side slope sedimentation is adequately described by an exponential decay curvey.
2. Annual bedload sedimentation volumes for INFIL inputs are an average, when actual values vary with annual number of sediment transporting discharges on the Columbia River. Additional problems arise in dealing with the nature of bedload sediment movement as sandwaves, when estimating average bedload sedimentation volumes for project areas shorter than the 2 to 3 mile length of the entire reach.
3. Other INFIL inputs require estimates of the same parameters calculated as outputs, such as those for total side slope sedimentation volume, initial percent of total side slope sedimentation during the first year of the readjustment period, and the length of the readjustment period.

4. No existing method can be used to verify correlation between INFIL calculations for side slope sedimentation and increased maintenance dredging volumes following new work dredging.

CHANNEL MORPHOLOGY AND BEDLOAD SEDIMENT CHARACTERISTICS

Using available data, side slope characteristics for the geomorphic areas and grain sizes for bedload sediment samples were analyzed for all study sites. These analyses attempted to identify characteristics and trends that could be used to develop INFIL methods for channel areas lacking historic dredging and hydrosurvey records.

River channel morphology has been classified into eight geomorphic categories based on the presence or absence of river bends and shoals, and the influence of channel control structures. Pile dikes exert a hydraulic influence approximately three pile dike lengths downstream. Cross-sections along each study reach, classified by geomorphic category, are listed in Appendix G.

Many sediment samples of bed materials were taken in the lower Columbia River and estuary by the Corps of Engineers during a survey in 1959. Average grain size was found to increase upstream from the mouth, as indicated by samples taken at the Astoria upper boat basin and the Beaver Army Terminal (about 40 miles upstream of Astoria), from 0.4 mm to 0.6 mm (Kidby, 1965).

Morphologic and Sediment Analyses Methods

Channel side slope information was extracted from cross-section data obtained from previous study of shoaling

on the lower Columbia River by Ogden Beeman and others (1985) and from Lower Columbia River anchorage studies (U.S. Army Corps of Engineers, 1988). For each study area, for both the Oregon and Washington sides, characteristic side slopes were selected when data were available. Cross-section slopes were simplified into one or two composite slopes (i.e. upper and lower slopes) for each side of the channel (figure 19). Elevations of base of slope and break-in-slope were identified and compared to adjacent slope angles. These representative side slopes were evaluated to identify any short-term or long-term trends. Side slope angles were compared to base of slope elevations for each geomorphic category to discover any correlations between break-in-slope locations, side slope characteristics and geomorphic categories. In addition, comparisons were made between reaches and for a combination of all the reaches, in order to uncover any correlations to geomorphic categories by reach, or to reach characteristics and geomorphic categories.

In 1987, bedload sediment was sampled and sieved for grain size composition at each study site. In addition, grain size data from previously analyzed sediment samples, from 1980 and 1982-84, were used for comparison with the 1987 samples (U.S. Army Corps of Engineers, 1988). The locations of all sediment samples at each study reach are

Figure 19. Example of composite slope angles on sample cross-section showing upper and lower slopes (USACE, 1988).

listed in Appendix G. Analysis of grain size parameters included mean grain size, sorting, skewness, and kurtosis values. The grain size parameters for the 1987 sediment samples were compared to sample depth, by location, to identify any correlations to channel depth. Next, the grain size parameters were compared to each other (such as sorting vs skewness) by location, to identify any trends at a reach or correlations between study areas. A third comparison was made for grain size characteristics by geomorphic location, such as the presence or absence of channel bends, shoals, or within hydraulic influence of pile dikes (within three pile dike lengths downstream).

Results of Morphologic and Sediment Analyses

No discernable side slope trends were observed for any of the geomorphic categories. Side slopes located on the outside of channel bends were uniformly steep, 1:3 to 1:9, especially where there were no shoal areas in the channel. Problems were encountered in using the hydrosurvey data. Data were often missing near the banklines, especially where the channel was deep close to the bankline. Therefore, it was difficult to define entire slope configurations in these deep nearshore areas. Data points along the cross-sections were often 50 feet to 100 feet apart. This coarse spacing limited the usefulness of side slope analysis when used to

identify rates and volumes of side slope sedimentation contributed during the period of readjustment to equilibrium configurations.

Grain size parameters yielded no obvious trends for comparison by depth, by reach, or by geomorphic category. Problems were encountered in the sampling location scheme. Samples, which were scattered throughout the study areas, were obtained during varying flow conditions and from unspecified locations in the channel cross-section.

More detailed hydrosurveys taken before and at frequent intervals after a new work dredging event would allow examination of slope development mechanisms and refine the INFIL assumptions used in estimating rates and volumes of side slope sedimentation. Analyses of sediment samples obtained under a more comprehensive sampling plan are needed to derive more definitive results. This level of analysis will allow no characterization by study reach, and thus, no prediction of side slope sedimentation by channel morphology or bedload sediment characteristics.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

INFIL calibration results give a reasonable simulation of historic side slope sedimentation, using exponential decay to estimate annual side slope sedimentation volume during the readjustment period. However, several limiting factors were discovered in the annual maintenance dredging records. INFIL would not produce successful runs for new work dredging events for depth increases of 3 to 5 feet, when the subsequent period of annual maintenance dredging was less than five years. INFIL also would not produce successful runs for a period of maintenance dredging records containing a hiatus of two or more years.

Initial percent values, compared by type of new work dredging, showed a tendency to be larger for new work dredging with only depth increases. They showed no consistent trends with regard to characteristic sediment type or to pre-regulated (1930's to 1960's) and regulated (1970's and 1980's) flow conditions on the Lower Columbia.

Initial percent values are, however, sensitive both to the amount of excavated increase in channel depth and to the length of the readjustment period. Initial percent values declined with increased length of the readjustment period. Conversely, initial percent values increased with deeper

new work dredging excavation depths. Therefore, the procedures for estimating the values for increased channel depths following new work dredging and the length of the readjustment period are important in determining the best value for initial percent and the shape of the exponential decay curve.

In this study, at this level of development, INFIL cannot be used to predict dredging requirements on an annual basis. However, it will give a reasonable estimate of increased side slope sedimentation that will be contributed during the readjustment period following new work dredging. Although INFIL cannot be used for areas without historic dredging or hydrosurvey records, it is the best method that has been developed to date. In addition, INFIL would be transferable to other river systems with adequate dredging and hydrosurvey records.

Attempts to establish predictive methodology for side slope sedimentation following new work dredging, based on channel morphology (geomorphic categories) or sediment characteristics (primarily grain size and sorting), were unsuccessful using available data. Therefore, methods for predicting maintenance dredging requirements for areas not previously dredged were not determined. Prediction of side slope sedimentation by INFIL is restricted to channel areas that are regularly maintained by dredging.

Recommendations

INFIL is a reasonable predictor of future side slope sedimentation only when adequate dredging records and channel surveys are available. Methods that will predict side slope sedimentation for areas with inadequate dredging records or hydrosurveys, or areas that historically are undredged, need to be developed from empirical relationships between channel side slopes, geomorphic location, or sediment characteristics. In order for these relationships to be examined, a more complete data set needs to be collected.

Detailed bedload sediment sampling along selected cross-sections will allow correlation between sediment characteristics and channel depth, channel location, and discharge regime. Detailed sampling of channel cross-sections should be located in several different geomorphic categories along the Lower Columbia, in order to identify any hydrologic, geomorphic or other physical controls on sediment distribution and correlation with equilibrium side slope configurations.

Bank to bank surveys are important so that nearshore side slope are fully defined. A desirable sampling program would survey several cross-sections in a selected area before and after new work dredging event. Detailed

hydrosurveys could be used to identify mechanisms by which side slopes develop and to quantify volume changes following new work dredging, as side slopes readjust to equilibrium configurations. Changes in cross-sectional area can be compared to local shoaling volumes, to differentiate between the sediment remaining at the slope base and the sediment that is carried downstream out of the reach. In addition, monitoring of volumes in the downstream shoal areas could be examined to identify sediment accumulations following new work dredging.

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APPENDIX A

Estimated Bedload Sedimentation on the Lower Columbia River

Unmeasured Bedload Sedimentation on the Lower Columbia River

The US Geological Survey in Denver, Colorado has developed Table A-1 of slope and intercept values relating unmeasured sediment discharge and water discharge in the Columbia River at Vancouver, Washington (USACE, 1986). This table approximates bedload sediment discharge as a series of straight lines between seven control points (J) of discharge (YA) and unmeasured sediment discharge, or QUM (XA). SAM is the slope of the line between the control points and CAM is the intercept. A FORTRAN program will calculate unmeasured sediment discharge for Columbia River discharge. Due to the unavailability of a local Columbia River discharge data base, discharges at The Dalles, Oregon were used to calculate unmeasured sediment discharge.

Table A-1. Table of slope and intercept values for relating unmeasured sediment discharge and water discharge in the Columbia River at Vancouver, Washington.

POINT NUMBER (J)	DISCH (YA) [1000 cfs]	QUM (XA) [tons/day]	SAM (slope)	CAM (intercept)
1	110.0	2.0		
2	130.0	7.0	7.4991	-15.0077
3	150.0	18.0	6.6000	-13.1069
4	450.0	15700.0	6.1633	-12.1566
5	500.0	25200.0	4.4911	-7.7199
6	600.0	49900.0	3.7471	-5.7119
7	700.0	90000.0	3.8261	-5.9313

A FORTRAN program was developed using the US Geological Survey chart to compile a yearly unmeasured sediment discharges for the lower Columbia River. The complete program is listed below.

```

PROGRAM PSEDS
*****
PROGRAM PSEDS IS WRITTEN BY SALLY BABCOCK, PORTLAND DISTRICT CORPS
OF ENGINEERS. IT TAKES DISCHARGES FOR THE COLUMBIA RIVER AT
WARRENDALE (THE DALLES FOR MISSING DATA) AND COMPUTES SUSPENDED
AND UNMEASURED SEDIMENT (BEDLOAD AND UNMEASURED SUSPENDED SEDIMENT)
QUANTITIES FOR PRE-1960'S AND POST-1960'S DISCHARGE REGIMES
*****
CHARACTER INPUT*8,DOUTPUT*8,YOUTPUT*8,SEDCOEF*8
CHARACTER ANSW*1,S*1,STAT*8
COMMON Z(400),DQUM(400),N(8),YA(8),XA(8),SAM(8),CAM(8)
DIMENSION X(35,35),Y(35,35)
INTEGER SED,SYEAR,EYEAR,TYEAR,CYEAR
REAL QUM,QUML
*****
ASSIGN SEDIMENT COEFFICIENT TABLE FILE NAME
*****
WRITE(3,*)"ENTER NAME OF SEDIMENT COEFFICIENT FILE"
READ(3,30)SEDCOEF
OPEN(25,FILE=SEDCOEF)
DO 100 I=1,8
  READ(25,10)N(I),YA(I),XA(I),SAM(I),CAM(I)
10  FORMAT(1X,I1,2X,F5.1,2X,F7.1,2X,F6.4,2X,F8.4)
  WRITE(3,10)N(I),YA(I),XA(I),SAM(I),CAM(I)
100 CONTINUE
*****
INITIALIZE SEDIMENT PROGRAM INPUT AND OUTPUT FILES
*****
999 WRITE(3,*)"ENTER THE INPUT FILE NAME"
  READ(3,30)INPUT
30  FORMAT(A8)
  WRITE(3,*)"ENTER THE DAILY SEDIMENT DISCHARGE OUTPUT FILE NAME"
  READ(3,30)DOUTPUT
  WRITE(3,*)"ENTER THE YEARLY SEDIMENT DISCHARGE OUTPUT FILE NAME"
  READ(3,30)YOUTPUT
  OPEN(20,FILE=INPUT)
  OPEN(21,FILE=DOUTPUT)
  OPEN(30,FILE=YOUTPUT)
  REWIND 20
  WRITE(3,*)"ENTER THE DISCHARGE STATION NUMBER (8 DIGITS)"
  READ(3,40)STAT

```

```

40 FORMAT(A8)
   WRITE(21,50)STAT
   WRITE(30,50)STAT
50 FORMAT(1X,"USGS STATION NUMBER ",A8 /)
   WRITE(3,*)"ENTER 4 DIGIT NUMBER FOR BEGINNING YEAR"
   READ(3,60)SYEAR
60 FORMAT(I4)
   WRITE(3,*)"ENTER 4 DIGIT NUMBER FOR ENDING YEAR"
   READ(3,60)EYEAR
   TYEAR=EYEAR-SYEAR+1
*****
   SELECT TYPE OF SEDIMENT DISCHARGE CALCULATION
*****
995 WRITE(3,*)"SUSPENDED SEDIMENT DISCHARGE      1"
   WRITE(3,*)"BEDLOAD SEDIMENT DISCHARGE        2"
   WRITE(3,*)"ENTER 1 OR 2"
   READ(3,20)SED
20 FORMAT(I1)
   WRITE(3,*)"PROGRAM IS NOW RUNNING"
   IF(SED.EQ.1) GO TO 700
   IF(SED.EQ.2) GO TO 701
   WRITE(3,*)"YOU ENTERED A WRONG NUMBER! PLEASE REENTER"
   GO TO 995
*****
   SUSPENDED SEDIMENT CALCULATION
*****
700 OPEN(34,FILE='W5')
   OPEN(43,FILE='W6')
   DO 200 II=1,TYEAR
674 READ(20,61)S
61 FORMAT(3X,A1)
   IF(S.EQ.'R') GO TO 675
   GO TO 674
675 BACKSPACE 20
   READ(20,70)CYEAR
70 FORMAT(68X,I4)
   IF(CYEAR.NE.SYEAR) GO TO 674
   DO 300 IJ=1,31
   READ(20,80)X1,X2,X3,X4,X5,X6,X7,X8,X9,X10,X11,X12
80 FORMAT(4X,12F10.0)
300 CONTINUE
   J1=0
   DO 325 I=1,12
   DO 375 J=1,31
   J1=J1+1
   Z(J1)=X(J,I)
   WRITE(34,90)Z(J1)
90 FORMAT(1X,F10.0)
375 CONTINUE
325 CONTINUE
   REWIND 34
   SSQUM=0.0
   DO 400 IK=1,372

```



```

      READ(34,101)Z(IK)
101  FORMAT(F10.0)
      QUM=0.0
      DISCH=Z(IK)
      QUM=(4.41*(10**-9))*(DISCH**2.31)
      DQUM(IK)=QUM
      WRITE(43,110)DQUM
110  FORMAT(F6.0)
      SSQUM=SSQUM+QUM
400  CONTINUE
      REWIND 43
      WRITE(21,125)CYEAR,SSQUM
      WRITE(30,125)CYEAR,SSQUM
125  FORMAT(I4,2X,F9.0," TONS/YEAR"/)
      READ(43,115)(DQUM(JK),JK=1,372)
      DO 600 IL=1,31
      WRITE(21,135)IL,(DQUM(JL),JL=1,12)
135  FORMAT(1X,I2,5X,12F6.0)
      WRITE(3,135)IL,(DQUM(JL),JL=1,12)
600  CONTINUE
      SYEAR=SYEAR+1
      CLOSE(34,STATUS='DELETE')
      CLOSE(43,STATUS='DELETE')
200  CONTINUE
      GO TO 800

*****
      UNMEASURED SEDIMENT (BEDLOAD) CALCULATION
*****
701  DO 201 II=1,TYEAR
      OPEN(34,FILE='W5')
      OPEN(43,FILE='W6')
677  READ(20,61)S
      IF(S.EQ.'R') GO TO 676
      GO TO 677
676  BACKSPACE 20
      READ(20,70)CYEAR
      IF(CYEAR.NE.SYEAR) GO TO 677
      DO 301 IJ=1,31
      READ(20,80)X(IJ,1),X(IJ,2),X(IJ,3),X(IJ,4),X(IJ,5),X(IJ,6),
      +X(IJ,7),X(IJ,8),X(IJ,9),X(IJ,10),X(IJ,11),X(IJ,12)
301  CONTINUE
      J1=0
      DO 326 I=1,12
      DO 376 J=1,31
      J1=J1+1
      Z(J1)=X(J,I)
      WRITE(34,90)Z(J1)
376  CONTINUE
326  CONTINUE
      REWIND 34
      BLQUM=0.0
      DO 401 IK=1,372
      READ(34,101)Z(IK)

```

```

      QUM=0.0
      DISCH=Z(IK)/1000
      IF(DISCH.LT.(110.0)) GO TO 998
      DO 501 J=2,8
      IF(DISCH.LT.YA(J)) GO TO 670
501  CONTINUE
670  SAMI=SAM(J)
      CAMI=CAM(J)
      DISCHL=ALOG10(DISCH)
605  FORMAT(1X,"DISCHL = ",F10.0)
      QUML=DISCHL*SAMI+CAMI
      QUM=10.0**QUML
603  FORMAT(1X,"QUM = ",F7.0)
      DQUM(IK)=QUM
      WRITE(43,115)DQUM(IK)
115  FORMAT(1X,F7.0)
      BLQUM=BLQUM+QUM
      GO TO 401
998  QUM=0.0
      DQUM(IK)=QUM
      WRITE(43,116)DQUM(IK)
116  FORMAT(1X,F7.0)
401  CONTINUE
      REWIND 43
      WRITE(21,125)CYEAR,BLQUM
      WRITE(30,125)CYEAR,BLQUM
      READ(43,115)(DQUM(JK),JK=1,372)
      WRITE(3,115)(DQUM(JK),JK=1,372)
      J2=0
      DO 601 I=1,12
      DO 630 J=1,31
      J2=J2+1
      Y(J,I)=DQUM(J2)
630  CONTINUE
601  CONTINUE
      DO 650 JI=1,31
      WRITE(21,136)JI,Y(JI,1),Y(JI,2),Y(JI,3),Y(JI,4),Y(JI,5),
      +Y(JI,6),Y(JI,7),Y(JI,8),Y(JI,9),Y(JI,10),Y(JI,11),Y(JI,12)
      WRITE(3,136)JI,Y(JI,1),Y(JI,2),Y(JI,3),Y(JI,4),Y(JI,5),
      +Y(JI,6),Y(JI,7),Y(JI,8),Y(JI,9),Y(JI,10),Y(JI,11),Y(JI,12)
136  FORMAT(1X,I2,4X,12F6.0)
650  CONTINUE
      SYEAR=SYEAR+1
      CLOSE(34,STATUS='DELETE')
      CLOSE(43,STATUS='DELETE')
201  CONTINUE
800  WRITE(3,777)
777  FORMAT(1X,"DO YOU WANT ANOTHER RUN (ENTER Y OR N)" /)
      READ(3,781)ANSW
781  FORMAT(A1)
      IF(ANSW.EQ.'N') GO TO 990
      GO TO 999

```

990 CLOSE 34
CLOSE 43
STOP
END

APPENDIX B

**Methods for Normalizing or Correcting Maintenance Dredging
Volumes to Approximate Annual Bedload Sedimentation Rate**

Methods for Normalizing or Correcting Maintenance Dredging Volumes to Approximate Annual Bedload Sedimentation Rate

Several methods can be used to estimate bedload sedimentation from maintenance dredging records. These are:

1. conversion to bedload sedimentation by real time intervals between dredging events, instead of annual dredging volumes during one fiscal year (Trawle, 1981),
2. conversion to bedload sedimentation by dividing dredged volumes by percent of total dredged navigation channel area for the entire reach,
3. conversion to bedload sedimentation by dividing dredged volumes by theoretical bedload sedimentation volumes as calculated in Appendix A, and
4. development of a cumulative maintenance dredging volume curve.

The successful method(s) reduced the average yearly fluctuations in bedload sedimentation to highlight the side slope sediment volume increases so that side slope sedimentation can be identified on the maintenance dredging records.

The first method produced a revised shoaling record, but did not reduce the yearly fluctuations as desired (figure B1). The second method produced a revised shoaling record but did not reduce the yearly fluctuations as desired

Figure B1. Conversion of maintenance dredging records to bedload sedimentation rates at Kalama Reach study area. Dredging volumes corrected by real time dredging intervals.

(figure B2). The third method produced a revised shoaling record but did not reduce yearly fluctuations as desired (figure B3). The cumulative maintenance dredging curve was the only method that could be used to separate side slope sedimentation from bedload sedimentation (figure B4).

Determination of the length of readjustment period (INFIL Item 2) was difficult to locate on the cumulative maintenance curve. A semi-log plot of the cumulative maintenance volumes was more effective in identifying the location of the break-in-slope (figure B5).

Figure B2. Conversion of maintenance dredging records to bedload sedimentation rates at Kalama Reach study area. Dredging volumes corrected by surface area of dredged channel.

Figure B3. Conversion of maintenance dredging records to bedload sedimentation rates at Kalama Reach study area. Dredging volumes corrected by estimated bedload sedimentation rates on the Lower Columbia River.

Figure B4. Cumulative maintenance dredging volumes at Kalama Reach study area.

100

Figure B5. Semi-log plot of cumulative maintenance dredging volumes as Kalama Reach study area. Break-in-slope indicates end of side slope readjustment period, about 2 years for 1960-65, 1966-68, 1969-85; about 3 to 4 years for 1933-48.

APPENDIX C

INFIL Program Code

Printout of INFIL Program in Basic

```

100 DIM Y(25)
110 CLS:FG=0
120 LET Q1$="Estimated total yield from side slope adjustment (in cubic
yards)"
130 LET Q2$="Number of years to reach equilibrium section"
140 LET Q3$="Estimated final annual yield (est. bedload sedimentation)
after slope adjustment (in cubic yards)"
150 LET Q4$="Percentage of total side slope yield to be used as initial
yield estimate (percent as decimal)"
160 PRINT Q1$
170 INPUT YTS
180 PRINT Q2$
190 INPUT YR
200 PRINT Q3$
210 INPUT YF
220 PRINT Q4$
230 INPUT PC
240 YO=PC*YTS+YF
250 YT=YTS+YF*YR
260 C1=YF/YO:C2=YT/YO
270 K=(1-C1)/C2
280 PRINT:INPUT"Do you want a printout of the results? If so, enter y or Y.
Defaults to no";ANS$
290 IF ANS$="Y" OR ANS$="y" THEN 300 ELSE 380
300 FG=1
310 LPRINT:LPRINT:LPRINT:LPRINT
320 LPRINT Q1$;:LPRINT YTS
330 LPRINT Q2$;:LPRINT YR
340 LPRINT Q3$;:LPRINT YF
350 LPRINT Q4$;:LPRINT PC
360 LPRINT:LPRINT:LPRINT
370 LPRINT "YEAR","SEDIMENT VOLUME"
380 PRINT "YEAR","SEDIMENT VOLUME"
390 FOR C=1 TO YR
400 X=(K*C)
410 Y(C)=YO*EXP(X)
420 IF C=1 THEN 430 ELSE 440
430 TY=(YO+Y(1))/2:GO TO 450
440 TY=TY+(Y(C)+Y(C-1))/2
450 PRINT C,Y(C)
460 IF FG=1 THEN 470 ELSE 480
470 LPRINT C,Y(C)
480 NEXT C
490 PRINT "Total Yield",YT
500 IF FG=1 THEN 510 ELSE 520
510 LPRINT:LPRINT "Total Yield",YT
520 LINE INPUT "Enter Y or y if another calculation wanted. Program
defaults to No and ends.",ANS$
530 IF ANS$="Y" OR ANS$="y" THEN 110 ELSE 540
540 END

```

APPENDIX D

Semi-log Plots of Cumulative Maintenance Dredging Curves for All Study Areas

Figure D1. Semi-log plot of cumulative maintenance dredging volumes at Slaughters Bar (USACE, 1988).

Figure D2. Semi-log plot of cumulative maintenance dredging volumes at Lower Dobelbower Bar (USACE, 1988).

Figure D3. Semi-log plot of cumulative maintenance dredging volumes at Kalama Reach (USACE, 1988).

Figure D4. Semi-log plot of cumulative maintenance dredging volumes at Upper Dobelbower Bar (USACE, 1988).

Figure D5. Semi-log plot of cumulative maintenance dredging volumes at Willow Bar (USACE, 1988).

Figure D6. Semi-log plot of cumulative maintenance dredging volumes at Lower Vancouver Bar (USACE, 1988).

APPENDIX E

Results of All INFIL Runs for All Study Areas on Lower Columbia River

APPENDIX F

Double-End-Area Method for Calculating Total Volume of Side Slope Sedimentation Following Excavation of Increased Navigation Channel Depths

Double-End-Area Method

The double-end-area calculations are based on an estimate of the cross-sectional area expected to contribute sediment during the side slope readjustment period. These cross-sections are constructed from past equilibrium slope configurations such as those that existed prior to new work dredging for the 35-foot and 40-foot channel deepenings. On the lower Columbia River, two possible side slopes readjustment configurations exist. The first is one where the side slopes do not steepen, but adjacent channel elevations decline. The other is one where side slopes steepen near the channel cutline, then pinch out to intersect the old channel boundary, some distance from the navigation channel. Side slopes along the Westport and Wauna Reaches (downstream of Slaughters Bar but above the estuary) have been extensively studied since the 40-foot channel deepening and have been found to have developed new slopes with the same slope angle at deeper elevations (USACE, 1988 unpublished data).

As the first step in applying the double-end-area method, select representative cross-sections for the project location that include area to be excavated (i.e. new work dredging). Obtain bank-to-bank hydrosurveys in areas with stable or "equilibrium" side slope configurations.

Equilibrium side slopes were estimated from cross-section plots at two representative locations in the proposed anchorage site. From the cross-section plots, simplified channel slopes were drawn and slope angles estimated (figure F1). Final cross-section slope angles were calculated as the mean of all years studied. For the Kalama anchorage site, slope angles ranged between 1:15 and 1:17, so the representative slope angle was chosen at 1:16. Side slopes appear to re-establish the same angle of repose at increased channel depths and do not develop steeper side slopes (see figure 5, p.26). Projection of this slope angle allows prediction of the extent of shoreward erosion, and the potential for undercutting at the bankline during side slope readjustment following new work dredging.

The next step was to construct cross-sections along the entire length of the project site at 500-foot intervals using the most recent hydrosurvey data available. Dredge cuts, estimated at 1:3, and equilibrium slope angles of 1:16 are superimposed over the channel cross-section. The areas enclosed by the superimposed slopes show how much material will be removed by dredging and how much will be contributed by side slope sedimentation during the readjustment period (figure F2). These areas are entered onto the double-end-area computational sheet in several steps.

Figure F1. Examples of historic channel cross-sections at Kalama Reach study area, showing historic equilibrium side slopes.

Figure F2. Examples of cross-section area that approximate side slope sedimentation following new work dredging for each channel location.

For Step 1, the distance between cross-sections and the side slope sediment area are entered on the computation sheet (figure F3) in columns labeled DISTANCE and CUT AREA respectively.

In Step 2, the column labeled CUT in the DOUBLE END AREAS category is filled in. The first entry, 357, is obtained by summing the first and second entries (0 and 357) in the CUT AREA column. Each entry is completed with the sum of the two adjacent values in the CUT AREA column.

In Step 3, the column labeled CUT under the QUANTITIES category is filled in. The first entry, 178,500 (cubic feet), is obtained by multiplying the DISTANCE 500 (feet) by the CUT AREA 357 (square feet). After each entry has been calculated, the total volume is summed up and divided by 54 to give the volume in cubic yards. This figure, 270,800 cy represents the total volume of side slope sedimentation contributed during side slope readjustment to equilibrium conditions.

COMPUTATION SHEET (Earthwork)

Project KALINA AIRPORT				Sheet 1 of 1			
ADJACENT TO TURNING EASEIN				Date 9/11/87			
Calculated <i>Samy, B. P. S. L.</i>			Checked				
Station	Distance	Cut Area	Fill Area	Double end areas		Quantities	
				Cut	Fill	Cut	Fill
73.35	500	0		357		178500	
73.40	500	357		2090		1045000	
73.45	500	1733		6040		3020000	
73.50	250	4307		9843		4921500	
74.00	500	5536		8251		4125000	
74.05	500	2915		5151		2575500	
74.10	500	2426		2436		1218000	
74.15		0				141623.250	
				Σ		270800	

Figure F3. Example of computation sheet for Double-end-area calculations of total side slope sedimentation from cross-sections.

APPENDIX G

Channel Morphology and Locations of Geomorphic Areas and Bedload Sediment Samples

Channel Morphology and Geomorphologic and Bedload Sediment Sample Locations

Slaughters Bar

Slaughters Bar extends from RM 63.2 to 67.1 (figure G1). Dominant features include a river bend at the upstream end and a bifurcation at Lord Island at the downstream end. Sites for 1987 samples are located between RM 64.50 and 65.20 on the Washington side ranging from 500 to 1200 feet from the navigation channel. Channel cross-sections have been constructed at 500-foot intervals between RM 64.05 and 65.40. These cross-sections fall into six geomorphic categories as indicated in Table G-1.

Lower Dobelbower Bar

Lower Dobelbower Bar extends from RM 67.1 to 69.9 (figure G2). Dominant features include a river bend at the upstream end, and bifurcations at the foot of Carrols Channel and the mouth of the Cowlitz River near mid-reach. No sediment samples were taken in 1987. Channel cross-sections have been constructed at 1000-foot intervals between RM 67.00 and 69.20. These cross-sections fall into five geomorphic categories as indicated in Table G-1.

Figure G1. Morphology of Slaughter's Bar study area (USACE, 1988).

Table G1. Geomorphology categories - river bends, shoals, and pile dike proximity. Asterisks indicate sediment sample locations.

REACH	BEND SHOAL NO P.D.	BEND NO SHOAL P.D.	BEND SHOAL P.D.	BEND NO SHOAL NO P.D.	NO BEND SHOAL P.D.	NO BEND NO SHOAL P.D.	NO BEND SHOAL NO P.D.	NO BEND NO SHOAL NO P.D.
SLAUGHTERS	65.20 65.25 65.30 65.35 * 65.40	65.10 65.15			64.10 * 64.15 64.20	64.25 64.35 64.40 64.45 * 64.50	64.05	64.30 65.00 65.05
L. DOBELBOWER		69.10 69.30 69.40		68.40 69.00 69.20	68.10		67.30 67.40 67.40 68.00	67.00 67.10 67.20 68.20 68.30
U. DOBELBOWER	70.45 71.10 71.30 71.35	70.00 70.10 70.15 70.30 70.35 70.40	70.50 71.00 71.05 71.15 71.20 71.25	70.05 70.20 70.25			71.40 71.45 71.50 72.00 72.05 72.10	72.15 72.20 72.25 72.30 72.35 72.40

Table G1 (cont.)

REACH	BEND SHOAL NO P.D.	BEND NO SHOAL P.D.	BEND SHOAL P.D.	BEND NO SHOAL NO P.D.	NO BEND SHOAL P.D.	NO BEND NO SHOAL P.D.	NO BEND SHOAL NO P.D.	NO BEND NO SHOAL NO P.D.
KALAMA	74.30 74.40 75.00 *		75.10	73.00 73.10	75.20 75.30 76.00		74.00 * 74.10 74.20 75.40 76.10 * 76.20	73.20 73.30 73.40 *
WILLOW	96.00 96.05 96.10 96.15 *				96.20 96.25 * 96.35 * 96.40 96.45		96.30 96.50 97.00 97.05 97.10 97.15 97.20 97.25	
L. VANCOUVER	103.50 104.00		103.40 * 104.05				102.30 102.40 102.50 103.00 103.05 103.10 103.20 103.25 103.30 * 103.35

Figure G2. Morphology of Lower Dobelbower Bar study area (USACE, 1988).

Upper Dobelbower Bar

Upper Dobelbower Bar extends from RM 69.9 to 72.8 (figure G3). Dominant features include a sharp river bend at the upstream end, a more moderate bend at the downstream end, and a bifurcation at the head of Carrols Channel. Sites for 1987 samples are located at RM 71.45. Channel cross-sections have been constructed at 500-foot intervals between RM 70.00 and 72.40. These cross-sections fall into six geomorphic categories as indicated in Table G-1.

Kalama Reach

Kalama Reach extends from RM 72.8 to 76.5 (figure G4). Dominant features include a river bend at the downstream end and two bifurcations, at each end of Sandy Island. Sites for 1987 samples are located between RM 74.35 and 75.10. Channel cross-sections have been constructed at 1000-foot intervals between RM 73.00 and 76.20. These cross-sections fall into six geomorphic categories as indicated in Table G-1.

Willow Bar

Willow Bar extends from RM 93.9 to 97.8 (figure G5). Dominant features include a river bend at mid-reach, and small channel bifurcation downstream. Sites for 1987 samples are located at RM 96.15, 96.25 and 96.35. Channel cross-sections have been constructed at 500-foot intervals

Figure G3. Morphology of Upper Dobelbower Bar study area (USACE, 1988).

Figure G4. Morphology of Kalama Reaches study area (USACE, 1988).

Figure G5. Morphology of Willow Bar study area (USACE, 1988).

between RM 96.00 and 97.25. These cross-sections fall into three geomorphic categories as indicated in Table G-1.

Lower Vancouver Bar

Lower Vancouver Bar extends from RM 101.3 to 104.6 (figure G6). Dominant features include the mouth of the Willamette River at the downstream end, a bifurcation at the foot of Oregon Slough at the upstream end. Most of the reach is a sharp river bend. Site for 1987 samples are located at RM 103.10 and 103.27 at the upstream end of the bend. Channel cross-sections have been constructed at approximately 500-foot intervals between RM 102.30 and 104.05. These cross-sections fall into three geomorphic categories as indicated in Table G-1.

Figure G6. Morphology of Lower Vancouver Bar study area (USACE, 1988).

Table G2. Sediment samples by river mile location for all years sampled. Brackets indicate the number of samples at that river mile location.

Reach	1980	1981	1982	1983	1984	1987
Slaughters Bar	64.00		63.11(3)		64.00(3)	
	64.32		64.11(3)			64.52(2)
						65.07
						65.08
						65.12
	65.43	65.37	65.37(2)			
		65.43(2)	65.43			
		66.16	66.16		66.00(3)	
		66.21	66.21			
	66.26					
Lower Dobelbower Bar	67.00(4)		67.00			
	67.05					
			67.11		67.16(3)	
				67.31		
			67.37			
	67.42					
	67.47					
					68.00(3)	
	68.11					
	68.16				68.21(2)	
Upper Dobelbower Bar	68.42(2)					
	69.16(15)					
	69.37					
					70.00(3)	
	70.37					
	71.21					
	71.37				71.45(4)	
						71.46(4)
					72.00(3)	
	72.11					

Table G2 (cont.)

Reach	1980	1981	1982	1983	1984	1987
Kalama Reaches	73.00(9)				73.17(2) 73.27(3) 73.40(3) 74.00(3)	74.35(2) 74.50(2) 75.00 75.05(2)
					76.11(3)	
Willow Bar						96.15(3) 96.25(3) 96.35(3)
Lower Vancouver Bar						103.07 103.27