Draft Report

A SEDIMENT TREND ANALYSIS (STA®) OF THE LOWER WILLAMETTE RIVER

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April 2001

Privileged and Confidential: Attorney/Client Work Product

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1 INTRODUCTION

1.1 Background

The Willamette River rises in the Cascade Range in western Oregon, flows northerly, and empties into the Columbia River about 160 km from the sea. It is a major tributary of the Columbia River and the tenth largest river in the United States based on average annual flow: its watershed covers an area of approximately 30,409 km^2, or about 12 percent of the land area of Oregon.

Located on the Lower Willamette River just above its confluence with the Columbia River, Portland Harbor has been a working harbor for well over 100 years. Over the past century a great number of industrial facilities have been located on the shores of the Willamette River. The Port of Portland currently operates four terminals consisting of 20 berths equipped to handle general cargo, bulk cargo, lumber, automobiles, lift-on-lift-off and roll-on-roll-off containers, and breakbulk vessels. Also present in the harbor area are privately operated facilities for ship repair and for receiving, storing and out-loading petroleum, wood chips, grain, logs, sand and gravel, cement, and steel products. The manufacturing and ship building/repair history dates back more than a century. Within Portland Harbor are several active, land-based cleanup projects dealing with site contaminants including but not limited to wood preservatives, pesticides, and metals: proximity of these sites to the Willamette River led to concerns about possible impacts on the river sediments. In 1997, a joint Department of Environmental Quality (DEQ) and U.S. Environmental Protection Agency (EPA) study identified elevated levels of a variety of contaminants in shallow, near-shore sediments, in parts of Portland Harbor.

DEQ, with funding from the Portland Harbor Group, developed the Portland Harbor Sediment Management Plan (PHSMP), which presented the technical approach for investigating the nature and extent of contamination and assessing risk to human health and the environment from contaminated sediments in Portland Harbor. More recently, DEQ and a number of potentially responsible parties (PRPs) collaborated in an effort to maintain state control of the upcoming sediment investigations and possible sediment remediation. However, on December 1, 2000, EPA placed the Portland Harbor on the Superfund cleanup list, resulting in EPA Region 10 becoming responsible for the in-water sediment cleanup in the harbor.

DEQ had identified the need for a Sediment Trend Analysis (STA®)[1] study in the lower Willamette River. The Port of Portland initially contracted with GeoSea Consulting Ltd. to initiate a Sediment Trend Analysis of the Willamette River, including a part of the Columbia River near its confluence with the Willamette (Figure 1). This work was completed by the Lower Willamette Group, which is the group of PRPs that is undertaking the remedial investigation for the site.

[1] STA is a unique technique developed by GeoSea whereby patterns of net sediment transport are determined from relative changes in the grain-size distributions of bottom sediments. In addition the technique enables the dynamic behavior of the bottom sediments to be determined (i.e., net erosion, net accretion, dynamic equilibrium etc.).

The original theory that is required to carry out STA was first published in McLaren and Bowles (1985). Since that time, however, there have been various refinements in the methodology. A short summary of the theory is contained in Section 2.0 (to allow most readers to follow the findings of the report), and a full, recently revised version of the mathematics and derivation of sediment trends is provided in Appendix I.

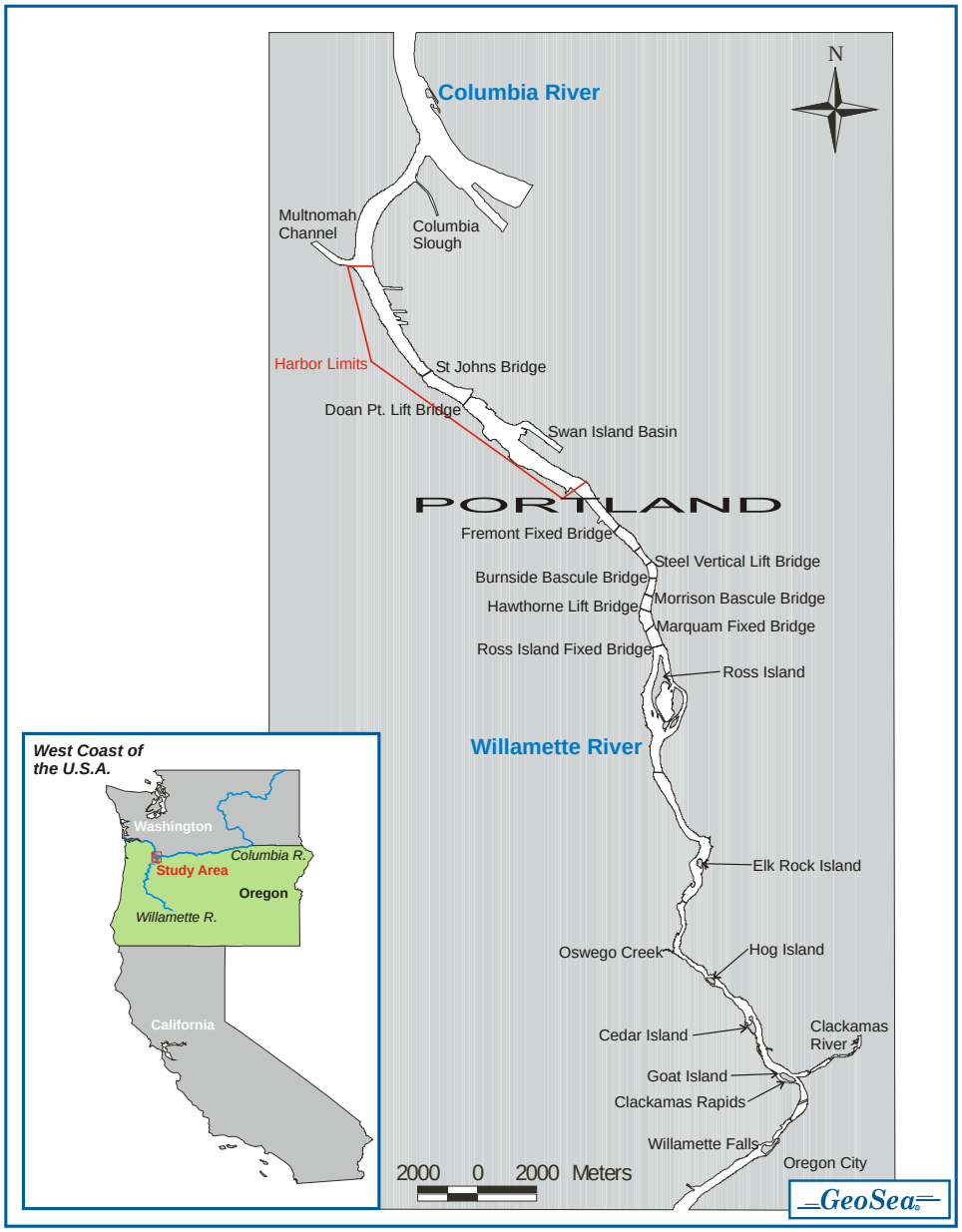

Figure 1: Names and locations contained in the report.

1.2 Objectives

The specific objectives of this study are the following:

1) Collect about 850 sediment grab samples from the Willamette River from the mouth to the Willamette Falls, and a portion of the Columbia River near its confluence with the Willamette.
2) Analyze each of the samples for its complete grain-size distribution and establish, using the technique of sediment trends, the present patterns of transport.
3) Determine areas of erosion, stability (dynamic equilibrium), and deposition.

1.3 Field Methods

Sediment grab samples were collected during the period September 15, 2000 through September 29, 2000 using a van Veen type grab sampler. This device samples the top 10 to 15 cm of sediment. All samples were collected from a 12-foot, hard-bottom inflatable speedboat equipped with a depth sounder, a small electric winch, and grab sampler. Positions were obtained using a portable DGPS system (Garmin GPS75 and Garmin GBR21 differential receiver), providing a typical accuracy of ±2.0 m. In most instances, samples were obtained at predetermined locations; however, where shoreline structures (e.g. docks and marinas) and moored vessels interfered with navigation, samples were collected as close as practicable to the planned position. Representative samples from each successful grab were stored in plastic bags and transported to the GeoSea laboratory in Brentwood Bay, BC, for grain-size analyses.

Samples were collected on a regular hexagonal grid with a spacing of 200m in the Columbia River and from the mouth of the Willamette to approximately River Mile 3.0. Inter-sample spacing was decreased to 150m from River Mile 3.0 to River Mile 9.6, and returned to a spacing of 200m from River Mile 9.6 to the Willamette Falls. In the upper portion of the river where it narrows, sample positions deviated from the regular grid spacing in order to cover more fully the required area. A total of 935 sample sites were visited, of which 99 were found to be “hard ground” (i.e., cobbles or bigger, or scoured bottom, or wood debris covering the bottom) and no sample could be taken. A site was designated as hard ground after three separate drops of the grab sampler failed to retrieve sediment.

1.4 Grain-Size Analysis

All samples were analyzed for their complete grain-size distribution using a Malvern MasterSizer 2000 laser particle sizer. The laser-derived distributions were combined sieve data for particles larger than 1500 microns in diameter using a merging algorithm developed by GeoSea Consulting[2]. The size distributions were entered into a computer equipped with proprietary software to establish sediment trends and transport functions.

[2] The grain-size data (listed in Appendix II) are supplied on a disk as an Excel worksheet containing sample locations and the complete phi distributions of the sediments.

A more complete description of the grain-size analytical technique is provided in Appendix II.

2 BASIC THEORY

The technique to determine the sediment transport regime utilizes the relative changes in grain-size distributions of the bottom sediments. The derived patterns of transport are, in effect, an integration of all processes responsible for the transport and deposition of the bottom sediments. However, the time scale over which this integration occurs is unknown. The bottom sediment may be considered as a facies that is defined by its grain-size distribution. Details of the theory are described in Appendix I; however, the approach is summarized here.

Suppose two sediment samples (D_1 and D_2)[3] are taken sequentially in a known transport direction (for example from a river bed where D_1 is the up-current sample and D_2 is the down-current sample). The theory shows that the sediment distribution of D_2 may become finer (Case B) or coarser (Case C) than D_1: if it becomes finer, the skewness of the distribution must become more negative. Conversely, if D_2 is coarser than D_1, the skewness must become more positive. The sorting will become better (i.e., the value for variance will become less) for both Case B and C. If either of these two trends is observed, we can infer that sediment transport is occurring from D_1 to D_2. If the trend is different from the two acceptable trends (e.g. if D_2 is finer, better sorted and more positively skewed than D_1), the trend is unacceptable and we cannot suppose that transport between the two samples has taken place.

In the above example, where we are already sure of the transport direction, $D_2(s)$ can be related to $D_1(s)$ by a function X(s) where 's' is the grain size. The distribution of X(s) may be determined by:

$$X(s)= D_2(s)/ D_1(s)$$

X(s) provides the statistical relationship between the two deposits and its distribution defines the relative probability of each particular grain size being eroded, transported and deposited from D_1 to D_2.

2.1 Interpretation of the X-Distribution

Empirical examination of X-distributions from a large number of different environments has shown that five basic shapes are most common when compared to the D_1 and D_2

[3] A sample is considered to provide a representation of a sediment type (or facies). There is no direct time connotation, nor does the depth to which the sample was taken contain any significance (provided, of course, that the sample does, in fact, accurately represent the facies). For example, D_1 may be a sample of a facies that represents an accumulation over several tidal cycles, and D_2 represents several years of deposition. The trend analysis simply provides the sedimentological relationship between the two. It is unable to determine the rate of deposition at either locality, but frequently the derived patterns of transport do provide an indication of the probable processes that are responsible in producing the observed sediment types.

distributions (Fig.A-6; Appendix I). These X-distributions are diagnostic of six different transport behaviors described as follows:

1) **Dynamic Equilibrium**: The shape of the X-distribution closely resembles the D_1 and D_2 distributions. The relative probability of grains being transported, therefore, is a similar distribution to the actual deposits. This suggests that the probability of finding a particular grain in the deposit is equal to the probability of its transport and re-deposition (i.e., there is a grain by grain replacement along the transport path). The bed is neither accreting nor eroding and is, therefore, in dynamic equilibrium.

2) **Net Accretion**: The shapes of the three distributions are similar, but the mode of X is finer than the modes of D_1 and D_2. Sediment must become finer in the direction of transport; however, more fine grains are deposited along the transport path than are eroded, with the result that the bed, though mobile, is accreting.

3) **Net Erosion**: Again the shapes of the three distributions are similar, but the mode of X is coarser than the D_1 and D_2 modes. Sediment coarsens along the transport path, more grains are eroded than deposited, and the bed is undergoing net erosion.

4) **Mixed Case**: A Mixed Case trend is one where the sequence of samples produces significantly acceptable statistics for both Net Erosion and Net Accretion. Such a finding is usually taken to be analogous to the case of Dynamic Equilibrium, but it may be more correctly interpreted to mean that the environment undergoes periodic accretion followed by periodic erosion, and both events have been “captured” in the samples used to make up the trend.

5) **Total Deposition (I)**: Regardless of the shapes of D_1 and D_2, the X-distribution more or less increases monotonically over the complete size range of the deposits. Sediment must fine in the direction of transport; however, the bed is no longer mobile. Rather, it is accreting under a "rain" of sediment that fines with distance from the source. Once deposited, there is no further transport.

6) **Total Deposition (II)**: Recently, a fifth form of the X-distribution has been discovered. Occurring only in extremely fine sediments when the mean grain-size is very fine silt or clay, the X-distribution may be essentially horizontal. Such sediments are usually found far from their source (compared with Deposition (I) sediments in which size-sorting of the fine particles is taking place, and therefore the source is relatively close). The horizontal nature of the X-distribution suggests that their deposition is no longer related strictly to size sorting. In other words, there is now an equal probability of all sizes being deposited. This form of the X-distribution was first observed in the muddy deposits of a British Columbia fjord and is described in McLaren et al. (1993). No Total Deposition (II)-type dynamic behavior was observed for the sediments in the Willamette River.

2.2 Interpretation of a Trend

In reality, a perfect sequence of progressive changes in grain-size distributions is seldom observed in a line of samples, even when the transport direction is clearly known. This is due to complicating factors such as variation in the grain-size distributions of source material, local and temporal variability in the X(s) function, and a variety of sediment sampling difficulties (e.g., sample doesn't adequately describe the deposit; it's taken too deeply or not deep enough).

Initially, a trend is easily determined using a statistical approach whereby, instead of searching for "perfect" changes in a sample sequence, all possible pairs contained in the sequence are assessed for possible transport direction. When one of the trends exceeds random probability within the sample sequence, we infer the direction of transport and calculate X(s). The precise statistical technique is described more fully in Appendix I.

Despite the initial use of a statistical test, various other qualitative assessments must be made in the final acceptance or rejection of a trend. Included is an evaluation of R^2, a multiple linear correlation coefficient defining the relationship among the mean, sorting and skewness in the sample sequence. If a given sample sequence follows a transport path perfectly, R^2 will approach 1.0 (i.e., the sediments are perfectly "transport-related"). A low R^2 may occur, even when a trend is statistically acceptable for the following reasons: (i) sediments on a presumed transport path are, in reality, from different facies, and valid trend statistics occurred accidentally; (ii) the sediments are from a single facies, but the chosen sequence is only a poor approximation of the actual transport path, and (iii) extraneous sediments have been introduced into the natural transport regime, as in the case of dredged material disposal. R^2, therefore, is assessed qualitatively, and when low, statistically accepted trends must be treated with caution.

To analyze for sediment transport directions over 2-dimensions, a grid of samples is required. Each sample is analyzed for its complete grain-size distribution and these are entered into a microcomputer equipped with appropriate software to “explore” for statistically acceptable trends. The technique to explore for transport pathways is undertaken randomly[4] (i.e., up and down the river, across the river, lines of samples running east-west, north-south). As familiarity with the data increases, exploration becomes less and less random until a single and final coherent pattern of transport is

[4] The term “random” is used loosely in that it is not strictly possible to remove the element of human decision-making entirely. The important aspect of the initial search for sediment trends is that it is undertaken with no preconceived concept of transport directions. It is, however, assumed that there will be a net sediment transport pattern and that changes in the grain-size distributions throughout the study area will not be random. The derivation of the final patterns may be likened to communication theory which, in the case of extremely noisy signals, requires the "discovery" of a “message” as the proof that the message does indeed exist.

obtained[5]. On completion of an interpretation, each transport line may then be used to derive a corresponding X-function from which the behavior of the bed material on the transport path is inferred.

The transport patterns discovered in this way are valid only for the facies sampled, which is the upper few centimeters of bottom sediment. If an event occurred which completely replaced the bottom sediments in the study area, either by removing them to expose a lower layer or completely covering them up to a depth of several centimeters, then a subsequent STA might not result in the same transport patterns.

3 PHYSICAL SETTING

Much of the information in this Section of the report was extracted from various websites, including but not limited to those of the US Army Corps of Engineers, the Port of Portland, and the US Geological Survey.

3.1 Climate and Rainfall

The study area is situated about 105 km inland from the Pacific Coast and midway between the northerly oriented low Coast Range on the west and the higher Cascade Range on the east, each about 48 km distant. The Coast Range provides limited shielding from the Pacific Ocean, whereas the steep slopes of the Cascade Range results in orographic lift of moisture-laden westerly winds and consequent moderate rainfall; it also forms a barrier from continental air-masses originating over the interior Columbia Basin. Airflow is usually northwesterly in spring and summer and southeasterly in fall and winter, interrupted infrequently by outbreaks of dry continental air moving westward through the Cascade passes.

Approximately 88 percent of the annual total precipitation occurs in the months of October through May, 9 percent in June and September, while only 3 percent comes in July and August. Precipitation is mostly rain, as on the average there are only 5 days each year with measurable snow. Relatively mild temperatures, cloudy skies and rain with southeasterly surface winds predominating, mark the winter season. Summer temperatures are also mild, with northwesterly winds and very little precipitation. Temperatures below freezing are very infrequent, as are temperatures above 100° F. Outbreaks of continental high pressure from east of the Cascade Mountains produce strong flow from the east through the Columbia Gorge into the Portland area. In winter this flow brings the coldest weather, and in summer the hot, dry continental air brings the highest temperatures.

[5] At present, the approach of obtaining the final derivation of the net sediment transport pathways relies on assessing and removing "noise" qualitatively. The GeoSea trend programming is specifically designed to do this in that all sample distributions may be readily compared with one and other (and excessively noisy distributions discarded), the best sediment types can be determined for the analysis, and the relationships among all the sample pairs may be assessed. Because we are unable to know the exact nature of the "noise" that we may be confronted with, it is difficult at this stage to devise a quantitative technique to eliminate it. To do so is the subject of much on-going research both by GeoSea and at various universities.

3.2 Geology

Major uplifting of the Cascades began in the Miocene: this period of uplift was accompanied by huge outpourings of basalt, extending from Idaho to the Oregon coast. Known as the Columbia River Basalt Group (CRB), it consists of several distinct flows and ranges in thickness to 1,000 feet depending on the variability of the paleotopography. The river flows through these exposed basalts from the Willamette Falls to approximately River Mile (RM) 18, and they are often exposed close to the west bank of the river downriver to Ross Island.

The Willamette Silt, an extensive layer of sand and silt with some thin layers of clay, was deposited over much of the Willamette Valley, probably by the Missoula Floods, during the late Pleistocene. The present Willamette River and its tributaries has subsequently eroded the Willamette Silt along their flood plains and deposited a layer of Recent alluvium up to 90 feet thick at the lower end of the Willamette Valley. The river flows through Pleistocene deposits from approximately RM 18 to RM 12, where deposits of Recent alluvium begin and persist to the confluence with the Columbia. The western bank of the river is again close to exposed basalt around RM 5. Descriptions of the geology of the lower Willamette Valley in the following sections are based on the 1991 Geologic Map of Oregon by G.W. Walker and N.S. MacLeod, available from the US Geological Survey and on the web at “http://nwdata.geol.pdx.edu/OR-Geology/”

3.3 Hydrology

The Willamette River originates within Oregon in the Cascade Mountain Range and flows approximately 300 km north to its confluence with the Columbia River. The Lower Reach of the Willamette River from River Mile (RM) 0 to approximately RM 26.5 at the Willamette Falls is a wide, shallow, slow moving segment that is tidally influenced with tidal reversals occurring during low flow periods as far upstream as RM 15. This Reach has been extensively dredged to maintain a 40-foot deep navigation channel from RM 0 to RM 14. The mean water surface elevation of the Willamette River at its confluence with the Columbia River is about 3m above sea level.

Major floods in the Willamette Valley have resulted from significant rainfall events combined with snowmelt in late fall through early spring when intensive, continuous warm rain falls on saturated or frozen ground, and from high water levels on the Columbia River. The first documented flood on the Willamette River was in January 1814. The Willamette Watershed includes 13 major dams, 11 of which were built primarily for flood and erosion control, hydropower, and summer water supplies, and two others for supplementary uses. In spite of these efforts to control the river, flooding still occurs: the last major flood was in 1996. In addition, dams on the Columbia control that river’s flow. In times of major water releases from those dams into the Columbia, water levels and current flow in the lower Willamette can be highly modified from “normal”.

3.4 Streamflow

Historical daily mean streamflow data for the period 1972 through 1999 were obtained from the U.S. Geological Survey, for stream gauge #14211720, located in Portland at the

Morrison Bridge. Stage and discharge data at this location at 15-minute intervals were also obtained for water years 1992 and 1993. These data should be useful in characterizing the stage versus flow for the river, but it should be noted that the location at which the data were collected is well upriver from the Harbor area, and in a narrower, highly channelized part of the river.

The summary data shown in Table 1 clearly demonstrate the variability in the flow of the river (e.g., there is a ratio of about 100 between the maximum and minimum flow, and the maximum flow is about 12 times greater than the mean).

Daily average streamflow (derived from USGS data 1972 through 1999)						
Average Daily Discharge (m^3/s)[1]	Maximum Discharge, February 1996[1] (m^3/s)	Minimum Discharge (m^3/s)	Surface Area of Tidal River (ha)	Average Volume of Tidal River ($m^3 \times 10^6$)	Average Tidal Volume ($m^3 \times 10^6$)	Average Tidal Range (m)
958	11,893	119	2,395	335	9	0.75

[1] *Maximum discharge associated with the last major flood.*

Table 1: Summary of river flow characteristics (Morrison bridge, Portland)

3.5 Tides and currents

Tides in the Willamette are semi-diurnal, with a typical range of about 0.75m at low and medium stages of the river. Table 1 gives an estimate of river volume and tidal volume a stage of zero, based on the cross-sectional area of the river referred to datum, and using an average river depth of 14m, also referred to datum. The tidal volume was computed assuming a tidal prism thickness varying linearly from the full tidal range at the mouth to zero at Willamette Falls. These figures are rough estimates, but they give a sense of the relative importance of tidal flow in the river. For example, the average tidal volume, which flows into and out of the river twice a day, is roughly equivalent to about a tenth of the average daily discharge, but is less than one percent of the maximum.

Flow values and river stage values at 15-minute intervals were used to examine time series of currents and streamflow at differing river stages. Figure 2 shows the currents measured in 1992: the plot shows the great variability in the currents and the many instances of upstream flow. Some typical currents at low and high river stage are shown in Figure 3 and Figure 4. At low stage, upstream currents are common with the semi-diurnal flood tide. These currents are strong but short-lived, lasting for roughly 1/5 of time that currents are directed downstream. When the river is high, there are no upstream currents, and the tidal signal is not apparent in the currents. This is because as the river rises, the tidal volume becomes an ever-smaller fraction of the total volume of water in the river, and the influence of the tide is thus suppressed.

Analysis of the data over the entire period available revealed that there are occasions when the river stage is very high, but the currents, while remaining unidirectional downstream, are considerably less than those at lower river stages. These occasions probably occur when there is a release of water into the Columbia River from upstream

dams, and Columbia River water is backing up into the Willamette River, causing it to rise.

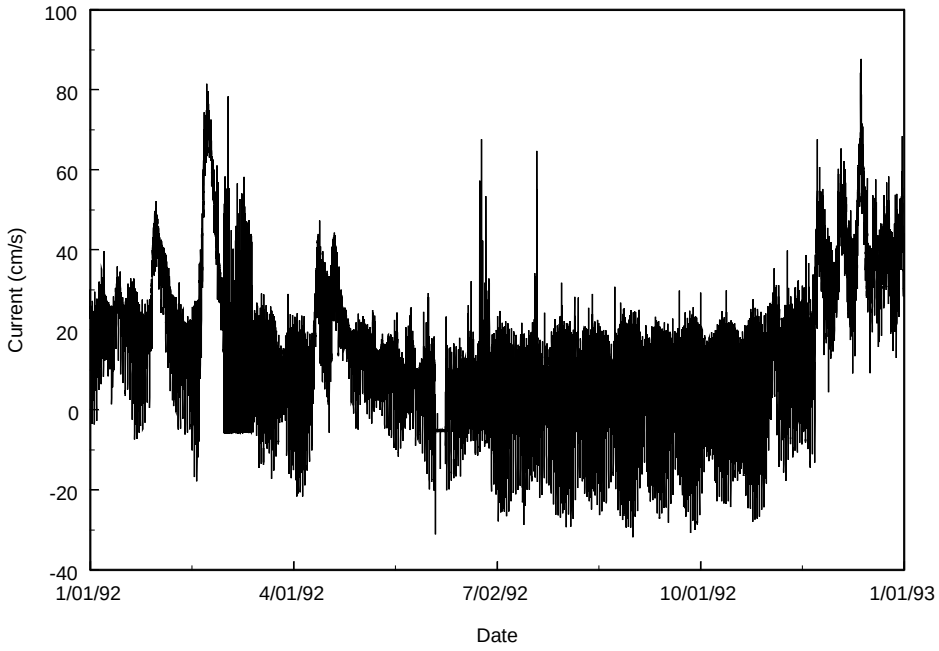

Figure 2: Currents at the Morrison Bridge in 1992.

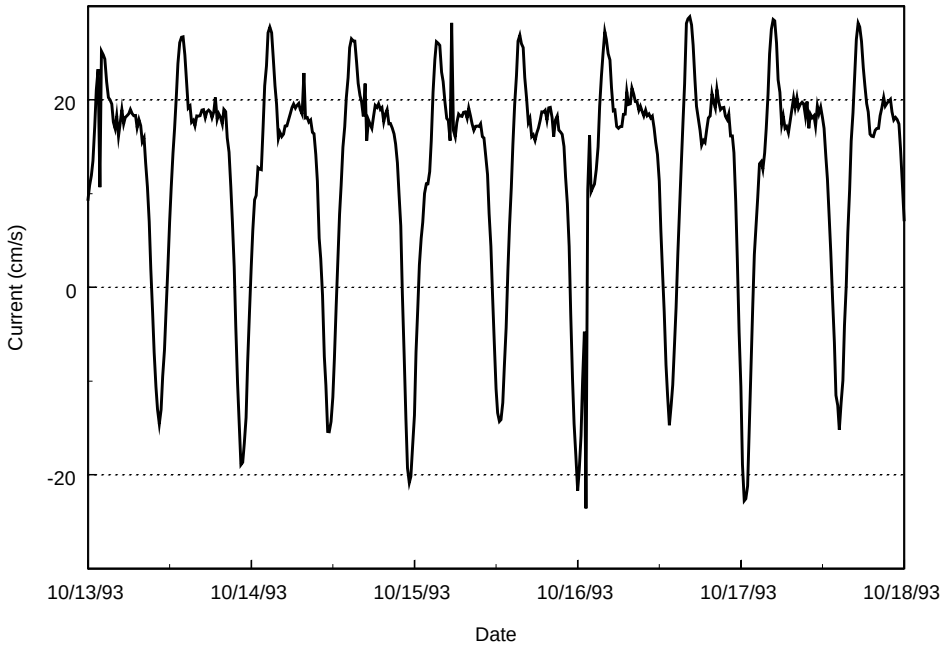

Figure 3: Low stage currents.

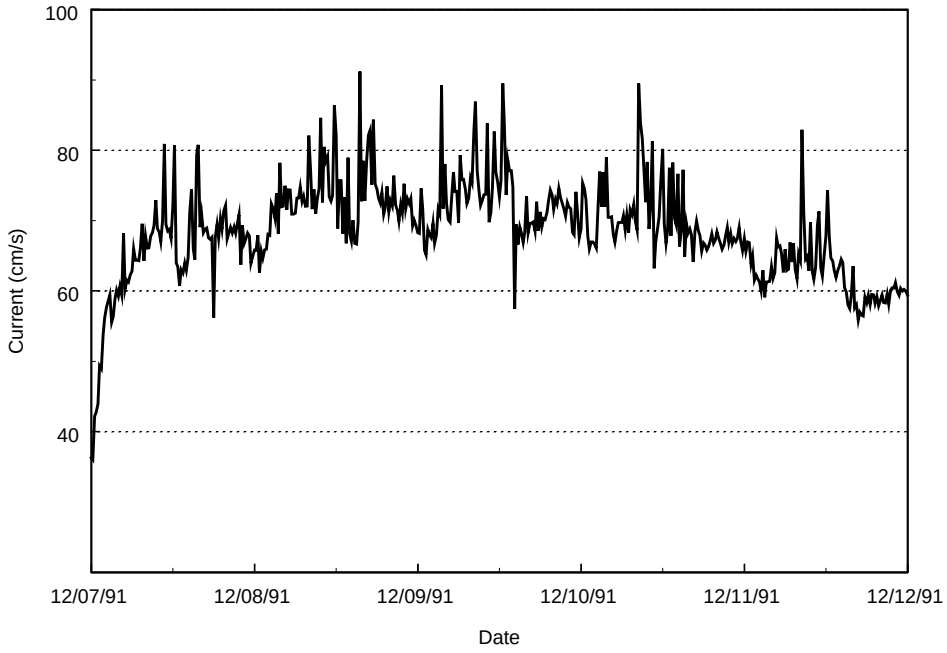

Figure 4: High stage currents.

4 PATTERNS OF SEDIMENT TYPES AND SEDIMENT TRANSPORT

The sediments of the Willamette River (summarized in Table 2) vary widely, from coarse sand in the upstream portions of the river near its' confluence with Clackamas River, to mainly sandy mud near the mouth where it enters the Columbia River. To facilitate presentation and discussion of the results, the river has been divided into seven reaches segments, starting from Reach 1 near Willamette Falls.

SEDIMENT TYPE[6]	# of SAMPLES	PERCENTAGE
Sandy gravel	2	0.2%
Gravelly Sand	16	1.7%
Sand	305	32.6%
Muddy Sand	180	19.3%
Sandy Mud	296	31.6%
Mud	37	4.0%
Hard Ground	99	10.6%
TOTAL	935	100%

Table 2: Summary of sediment types

The most common sediment types are sand, muddy sand and sandy mud, which account for 83.5 per-cent of all the samples (Table 2). Approximately 10 percent of the samples are Hard Ground, where no sample could be obtained after three attempts with the grab. Most of these samples were found in the upstream part of the river, but there were a few locations (e.g., in Multnomah channel) where wood debris covered the bottom.

The best patterns of transport that could be derived were possible only when all samples were used in a single interpretation (i.e., all the samples were treated as a single facies). Because the range of sizes present in each of the samples throughout the study area is relatively constant, the assumption that they are indeed all "transport-related" and can be treated as a single facies is probably correct.

Following the calculation of numerous sample sequences to determine significant trends, a total of 154 transport lines were selected to provide a pattern of transport. For ease of discussion, the transport lines have been grouped into sixteen Transport Environments (TE's), starting from TE1 at the upstream end of the survey area (i.e., near Willamette Falls). A Transport Environment is defined as an area within which transport lines are associated both geographically and "behaviorally". Generally, transport lines cannot be continued from one TE into another, because to do so decreases the statistical significance of the line (samples in the new TE are not related through transport to the samples in the line). Thus a region in which transport lines naturally end (and begin) is a boundary between Transport Environments.

[6] The sediment types use 20% and 50% as "cut-off" limits. For example, pure sand has less than 20% of mud or gravel; sandy mud has greater than 50% mud and more than 20% sand; muddy sand has greater than 50% sand and more than 20% mud. The few samples containing three modes (i.e., a muddy, sandy gravel) although obviously "noisy" distributions, were still successfully included in the STA.

The trend statistics for each line are provided in Appendix III, and a summary table of line statistics is provided at the beginning of the description of each TE. Representative X-distributions[7] to illustrate typical dynamic behaviors derived from transport lines in this study are shown in Appendix IV.

Place names referred to in the following discussion are shown on Figure 1 and are not usually labeled on the Sediment Type and Transport Environment figures.

4.1 Reach 1 (Figure 5 and Figure 6)

Figure 5 shows the sediment types in this reach. Here the river is confined in Tertiary basalt, which outcrops on much of its bottom. The Clackamas River brings some sand into the river, and there are pockets of reworked sand along the margins and in backwaters. There are two transport environments in this Reach: TE1 consisting of 5 lines; and TE2 consisting of 4 lines.

4.1.1 Transport Environment 1

Lines	N	Average R^2	Std. Dev. R^2	Erosion %	Accretion %	Total Depos'n %	Dynamic Equil. %	Mixed Case %
1-5	5	0.998	0.004	0	100	0	0	0

Table 3: Line statistics for TE1.

Most of the bottom is hard ground in this area, and no sediment could be obtained upstream from this environment in either the Willamette or Clackamas Rivers. Based on very few samples, these lines originate in the Clackamas River and the Clackamas Rapids south of Goat Island. That the trends are depositional could be ascribed to a rapid deepening of the river (from 3m to 14m), together with widening immediately downstream from Goat Island. Each of the trend lines is tied into the beach samples; however, the beach samples on their own show no relationships with each other (i.e., downstream transport). Field observations indicate that beach deposits might be simply reworked river bottom sediments deposited during periods of high river flow, and that the reworking is due to local waves and boat wakes, which results in the removal of fines. However, the amount of fine-grained sediment removed is insufficient to provide a noticeable sediment source for the downstream river sediments. All the lines show accretion, and the R^2 values are high.

4.1.2 Transport Environment 2

Lines	N	Average R^2	Std. Dev. R^2	Erosion %	Accretion %	Total Depos'n %	Dynamic Equil. %	Mixed Case %

[7] An X-distribution is a function derived from the grain-size distributions contained in a sample line. It is used to describe the dynamic behavior of the sediments along the transport pathway defined by the sample line. The X-distribution may be thought of as a function that describes the relative probability of each particle being removed from an "up-current" sediment sample, and being deposited in a "down-current" sample. The shape of the X-distribution relative to the distributions of the sediments making up the sample line is used to define dynamic behavior.

6-9	4	0.955	0.048	100	0	0	0	0

Table 4: Line statistics for TE2.

As in TE1, these few lines are based on a very small number of samples due to the lack of sediment in this part of the river. The lines originate in the vicinity of Cedar Island and extend into a narrowing river channel with the result that all the trends indicate Net Erosion. The R^2 values continue to be high.

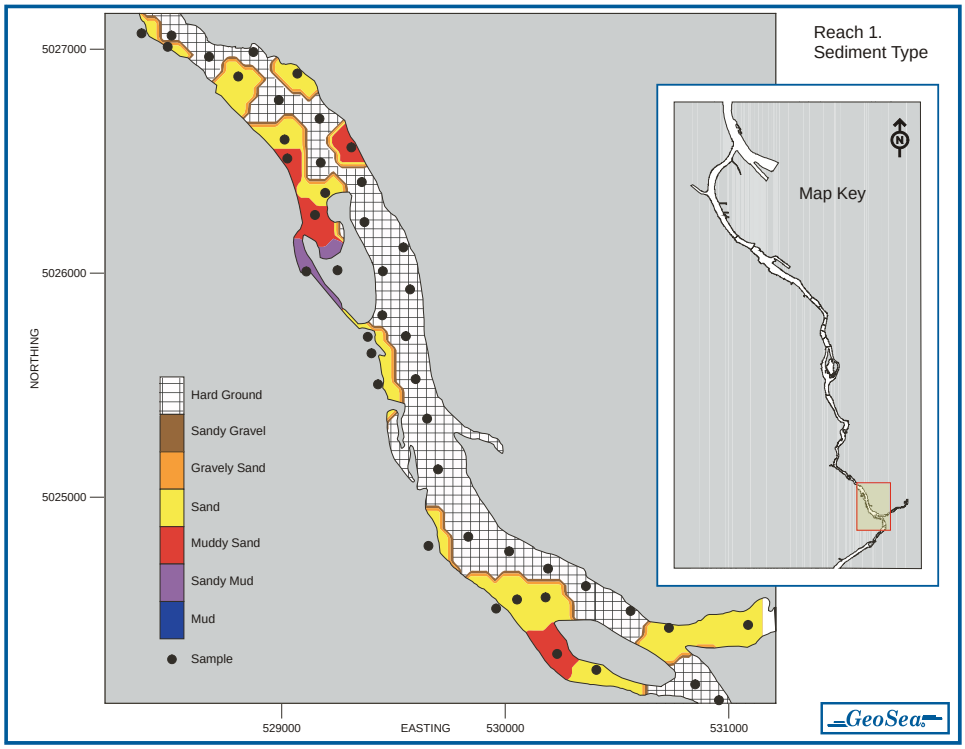

Figure 5: Sediment types in Reach 1.

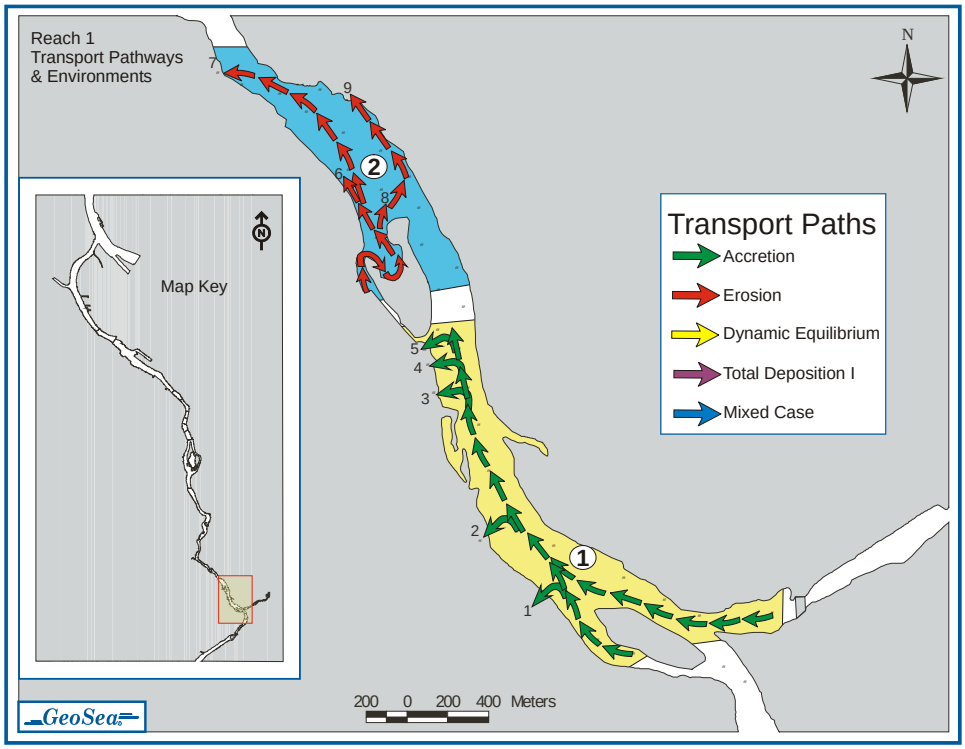

Figure 6: Transport pathways in Reach 1.

4.2 Reach 2 (Figure 7 and Figure 8)

The river is still contained in Tertiary basalt for most of this Reach, and as a result there are many Hard Ground samples. Where sediment is found, it is sand or gravelly sand, although there are pockets of muddy sand near the banks in a few locations.

There are two transport environments in this Reach: TE3 consisting of lines 10 through 18; and TE4 consisting of lines 19 through 28.

4.2.1 Transport Environment 3

Lines	N	Average R^2	Std. Dev. R^2	Erosion %	Accretion %	Total Depos'n %	Dynamic Equil. %	Mixed Case %
10-18	9	0.961	0.058	0	100	0	0	0

Table 5: Line statistics for T.E. 3.

Continuing in coarse sandy sediment, TE3 is also based on only a few samples. Originating at Hog Island, the trends extend beyond Oswego Creek to the next narrows. Compared to TE2, the river becomes somewhat wider, which may account for all the trends showing accretion. The presence of Oswego Creek, which drains Oswego Lake, may also be providing a greater amount of sediment than in the previous environments. Water depths change rapidly in this portion of the river indicating bedrock control of bathymetry. All lines show accretion, and the R^2 values are high.

4.2.2 Transport Environment 4 ~~(Figure 8)~~

Lines	N	Average R^2	Std. Dev. R^2	Erosion %	Accretion %	Total Depos'n %	Dynamic Equil. %	Mixed Case %
19-28	10	0.967	0.081	0	90	10	0	0

Table 6: Line statistics for T.E. 4.

This environment is confined by narrows at each end. Again, a large portion of the river bottom is classified as hard ground, and the bottom is highly irregular. With the exception of Line 19, which shows Dynamic Equilibrium, all the other Lines indicate Net Erosion. The amount of sediment available for transport and deposition is, therefore, relatively small. All lines show either accretion or total deposition, and the R^2 values remain high.

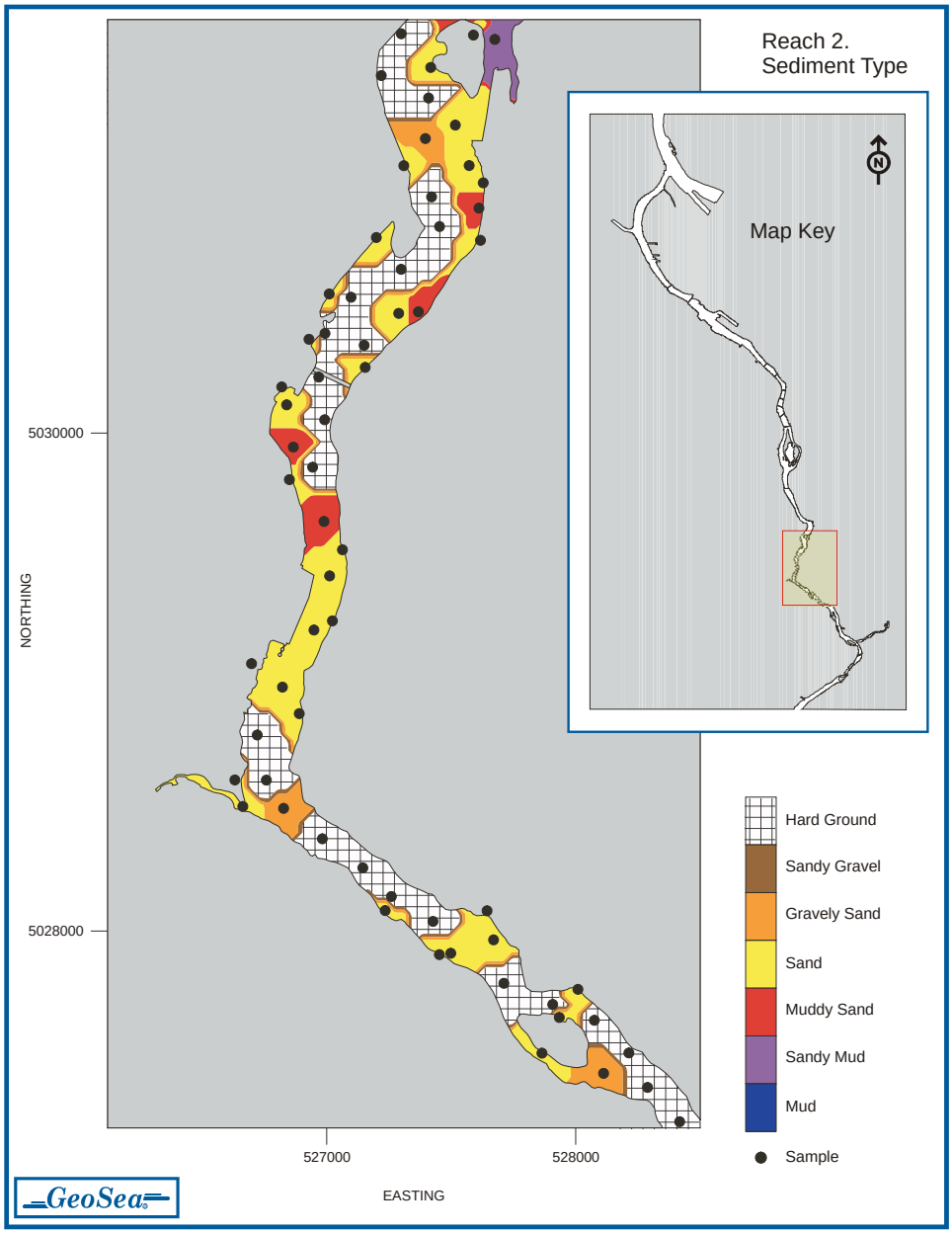

Figure 7: Sediment types in Reach 2.

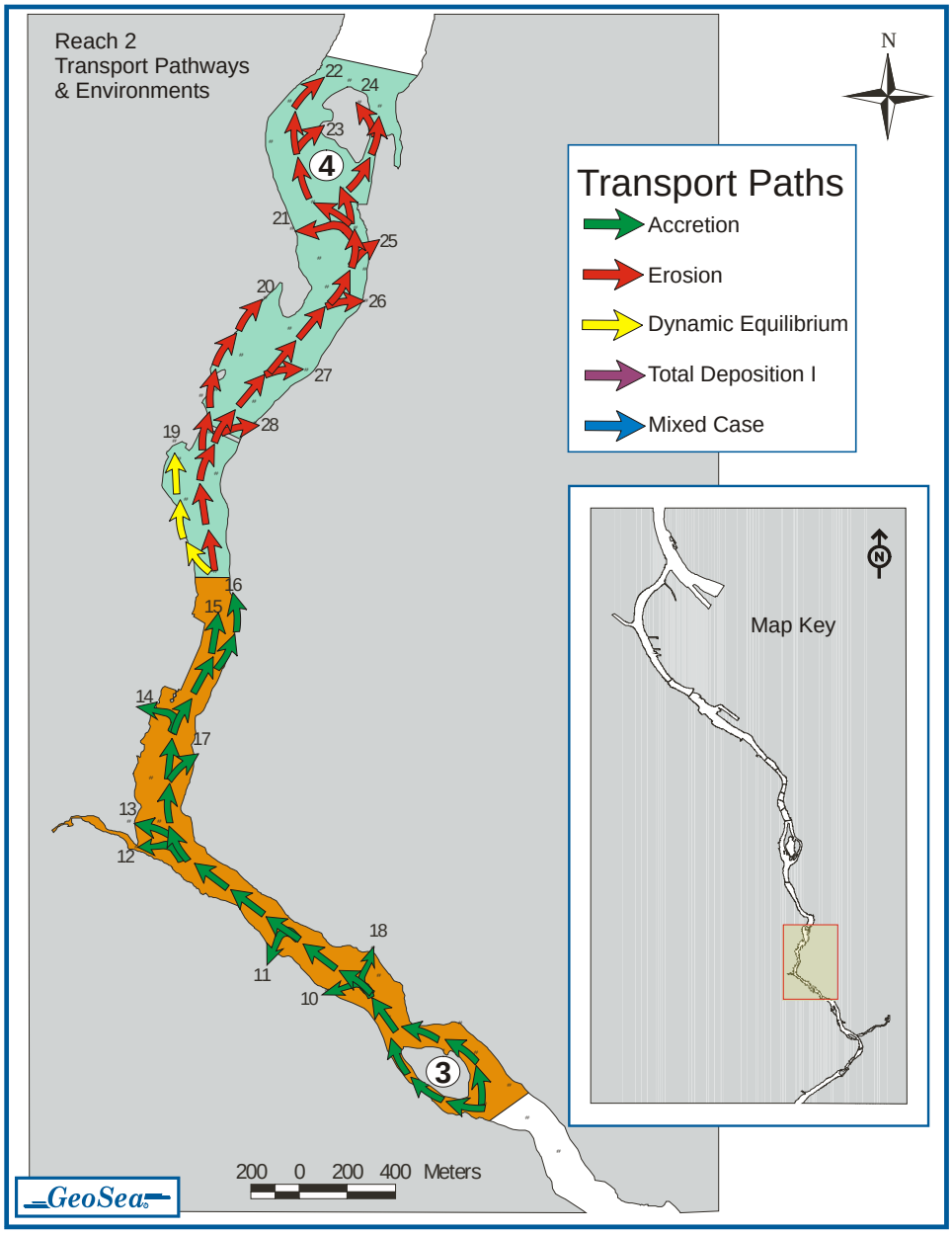

Figure 8: Transport pathways in Reach 2.

4.3 Reach 3 (Figure 9 and Figure 10)

A mix of sediments characterizes Reach 3, but they consist mostly of either sand or muddy sand. Pure mud, which is rare throughout the river, is found along the western margins of the lagoon inside Ross Island, where extensive aggregate mining takes place. Some Hard Ground is also found in this Reach, but now only in more isolated and smaller areas than in the upstream Reaches.

Three Transport Environments are found in this reach: TE5 consisting of 28 lines; TE6 consisting of 8 lines, and TE7 consisting of one line.

4.3.1 Transport Environment 5

Lines	N	Average R^2	Std. Dev. R^2	Erosion %	Accretion %	Total Depos'n %	Dynamic Equil. %	Mixed Case %
29-56	28	0.973	0.027	4	14	10	36	46

Table 7: Line statistics for TE5.

This large group of 28 transport lines extends from Elk Rock Island to the vicinity of the Marquam Fixed Bridge. The river generally widens and flows through Pleistocene sediments, with the result that hard ground is considerably less frequent and sediments contain somewhat more mud than in the previous environments. The river bottom remains highly irregular and contains several deeps with intervening sills. With the exception of three lines close to Elk Rock Island (Lines 30, 53 and 54) that indicate Net Accretion, and one line (55) showing Net Erosion, the remaining 24 lines all produced trends in Dynamic Equilibrium or Mixed Case. Such dynamic behavior is consistent with a relatively small amount of sediment available for transport. The trends bifurcate into the channels on either side of Ross Island. The trend in the eastern channel ends near the entrance into the aggregate mining area located in the excavated lagoon centered on Ross Island. The R^2 values for these lines are high.

4.3.2 Transport Environment 6

Lines	N	Average R^2	Std. Dev. R^2	Erosion %	Accretion %	Total Depos'n %	Dynamic Equil. %	Mixed Case %
57-64	8	0.979	0.026	25	0	75	0	0

Table 8: Line statistics for TE6.

Taken from inside the lagoon in Ross Island, these samples are generally much muddier than the sediments in the adjacent channel. For this reason, trends were not brought in from the outside, but rather examined separately inside the lagoon. With the exception of two lines on the eastern margin showing Net Erosion, the remaining lines all indicate Total Deposition-Type I dynamic behavior. Any fine sediment entering the lagoon from upstream is able to settle inside the lagoon, although there is constant human activity taking place. The R^2 values for these short lines are also high.

4.3.3 Transport Environment 7

Lines	N	Average R^2	Std. Dev. R^2	Erosion %	Accretion %	Total Depos'n %	Dynamic Equil. %	Mixed Case %
65	1	0.85	-	0	0	0	100	0

Table 9: Line statistics for TE7.

Consisting of only one sample sequence, this line originates near the entrance to the aggregate mining lagoon inside Ross Island. Downriver from Ross Island, TE7 merges with TE5, both of which terminate at the start of TE8. The R^2 value is lower than for the previous transport environments.

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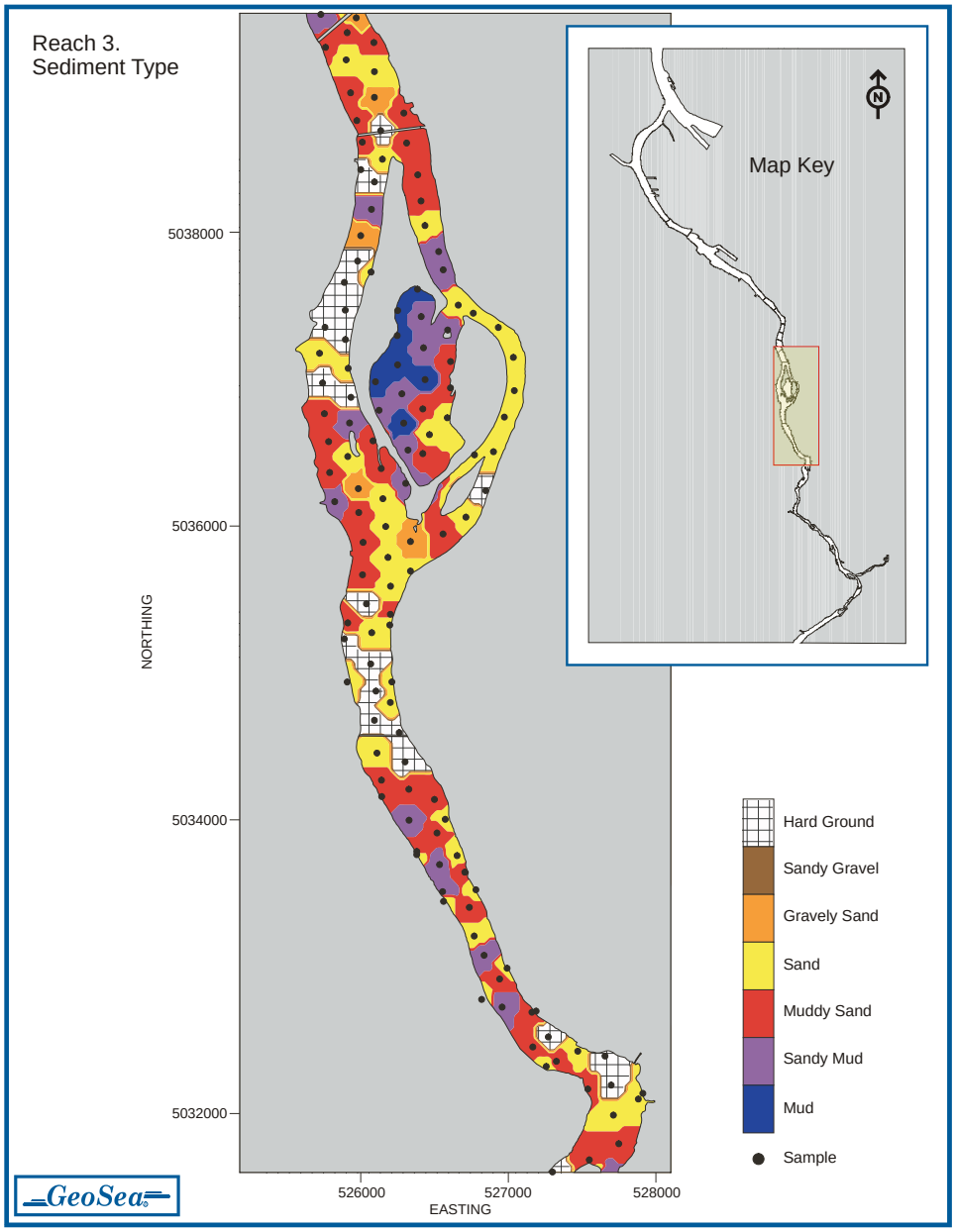

Figure 9: Sediment types in Reach 3.

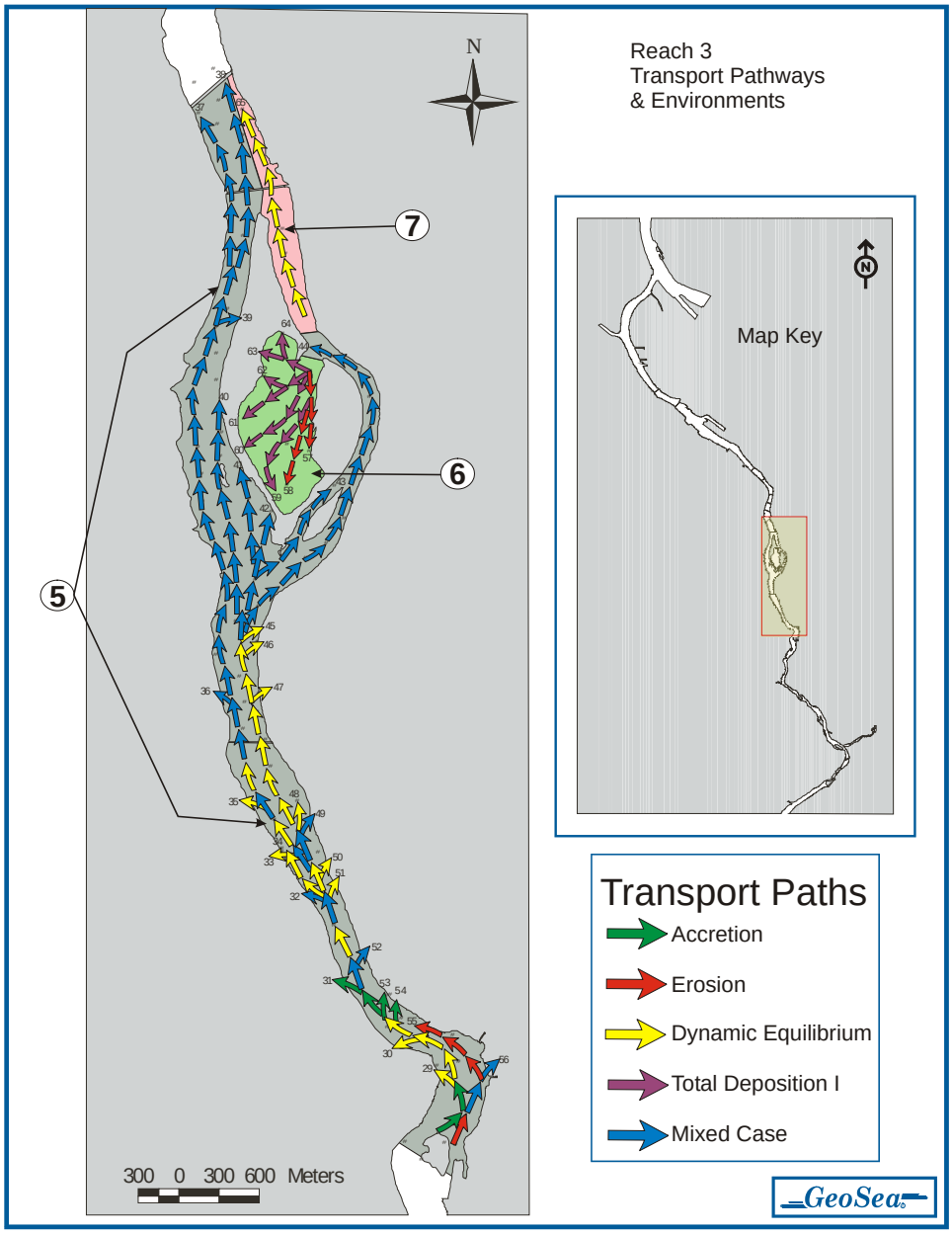

Figure 10: Transport pathways in Reach 3.

4.4 Reach 4 (Figure 11 and Figure 12)

Sediments in this Reach are nearly all sands or muddy sands. There are occasionally both finer and coarser sediments, but they are relatively rare. Hard Ground samples are also present, but they are nearly all found close to bridges, where the presence of bridge support structures may give rise to local scouring.

There is only one Transport Environment in this part of the river: TE 8, consisting of three lines (66 through 68).

4.4.1 Transport Environment 8

Lines	N	Average R^2	Std. Dev. R^2	Erosion %	Accretion %	Total Depos'n %	Dynamic Equil. %	Mixed Case %
66-68	3	0.787	0.185	33	0	0	33	33

Table 10: Line statistics for TE8.

These three lines are confined to a narrow portion of the river roughly between the Marquam and Fremont Fixed Bridges. One line (66) shows Net Erosion, one (67) shows Mixed Case transport and the last (68) is in Dynamic Equilibrium. Velocities are evidently high through the narrows and Hard Ground was commonly found, usually near bridges. This environment terminates where the river once again begins to widen. R^2 values are somewhat lower than those for the previous environments. A decrease in R^2 in a region often indicates the presence of new sediment sources.

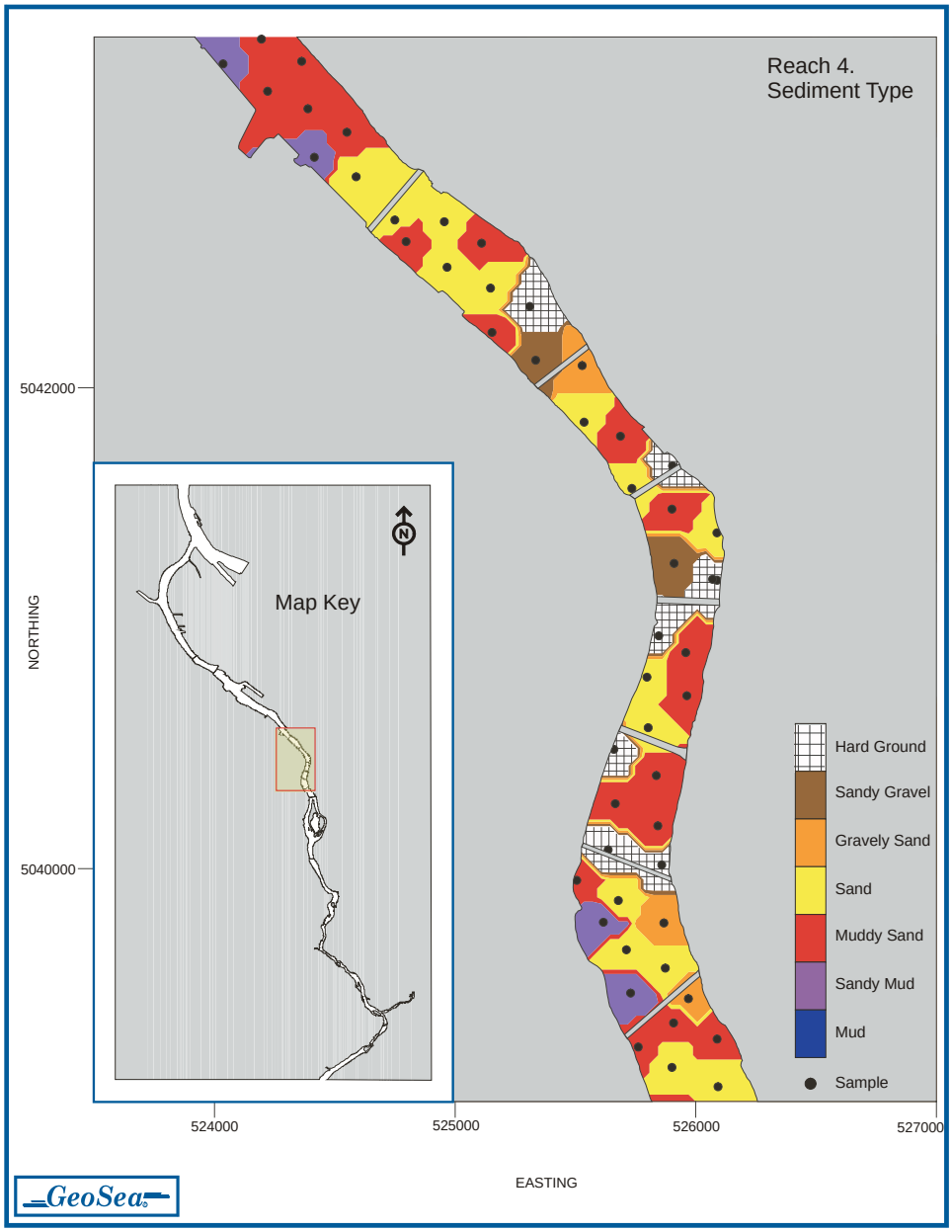

Figure 11: Sediment types in Reach 4.

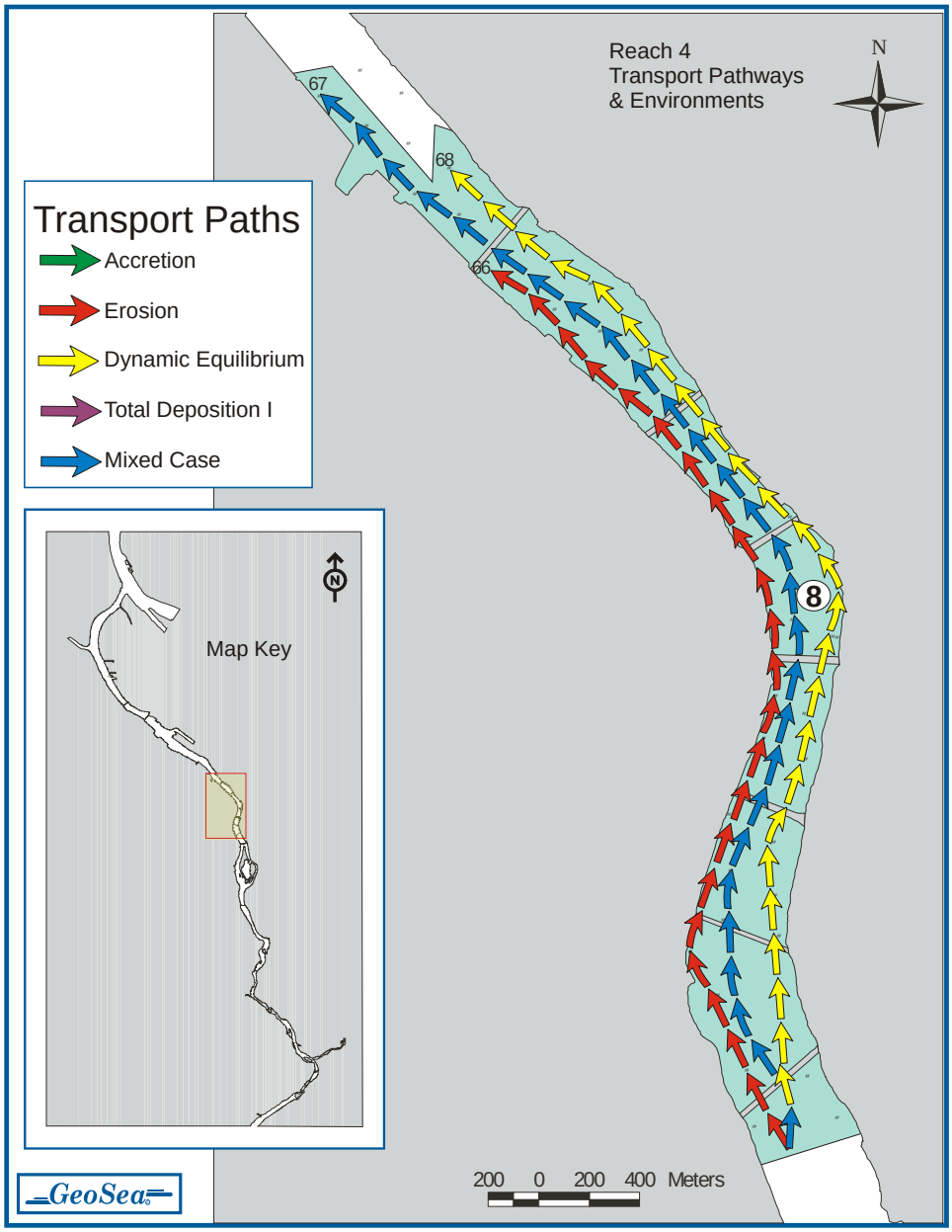

Figure 12: Transport pathways in Reach 4

4.5 Reach 5 (Figure 13 and Figure 14)

The river widens in this Reach, and as a result the sediment type changes from sand at the upstream end, through muddy sand to sandy mud in the main part of the Reach. Exceptions to this are pure mud samples in Swan Island Lagoon, and coarser sediments found near the center of the river downstream of Swan Island.

This reach has three Transport Environments: TE9, consisting of 5 lines; TE10, consisting of 30 lines; and TE11, consisting of 2 lines.

4.5.1 Transport Environment 9

Lines	N	Average R^2	Std. Dev. R^2	Erosion %	Accretion %	Total Depos'n %	Dynamic Equil. %	Mixed Case %
69-73	5	0.932	0.029	0	0	60	40	0

Table 11: Line statistics for TE9.

This TE originates from the narrows at the Fremont Fixed Bridge and enters into a widening river. The quantity of mud rapidly increases and for the first time Total Deposition Type I trends occur. Two of the lines remain in Dynamic Equilibrium. The environment, however, terminates abruptly, suggesting a significant new source of sediment in this area. The R^2 values are high, although somewhat lower than those farther upstream.

4.5.2 Transport Environment 10

Lines	N	Average R^2	Std. Dev. R^2	Erosion %	Accretion %	Total Depos'n %	Dynamic Equil. %	Mixed Case %
74-103	30	0.976	0.023	0	17	53	20	10

Table 12: Line statistics for TE10.

Originating on the north side of the river next to Swan Island, it appears likely that there is a major new source of sediment in this area. The environment can be traced to the next narrows in the vicinity of Doane Point. Most of the lines show Total Deposition Type I dynamic behavior. Along the north bank, transport circulates into the Swan Island Lagoon, and the trends change from Net Accretion to Total Deposition-Type I. The north side of Swan Island Lagoon appears to have a coarse sediment source resulting in Dynamic Equilibrium in this area. The trends entering Swan Island Lagoon meet an out-flowing transport regime (TE11). As the narrows near Doane Point are approached, transport behavior changes to Net Accretion, Mixed Case, and Dynamic Equilibrium, presumably as current velocities increase. The R^2 values for this environment are high.

4.5.3 Transport Environment 11

Lines	N	Average R^2	Std. Dev. R^2	Erosion %	Accretion %	Total Depos'n %	Dynamic Equil. %	Mixed Case %
104-105	2	0.980	0.028	0	0	100	0	0

Table 13: Line statistics for TE11.

Inside Swan Island Lagoon there appears to be a source of fine sediments that are in Deposition Type I transport. These transport lines meet with incoming sediments out of TE10 in the vicinity of the bend. The R^2 values are high.

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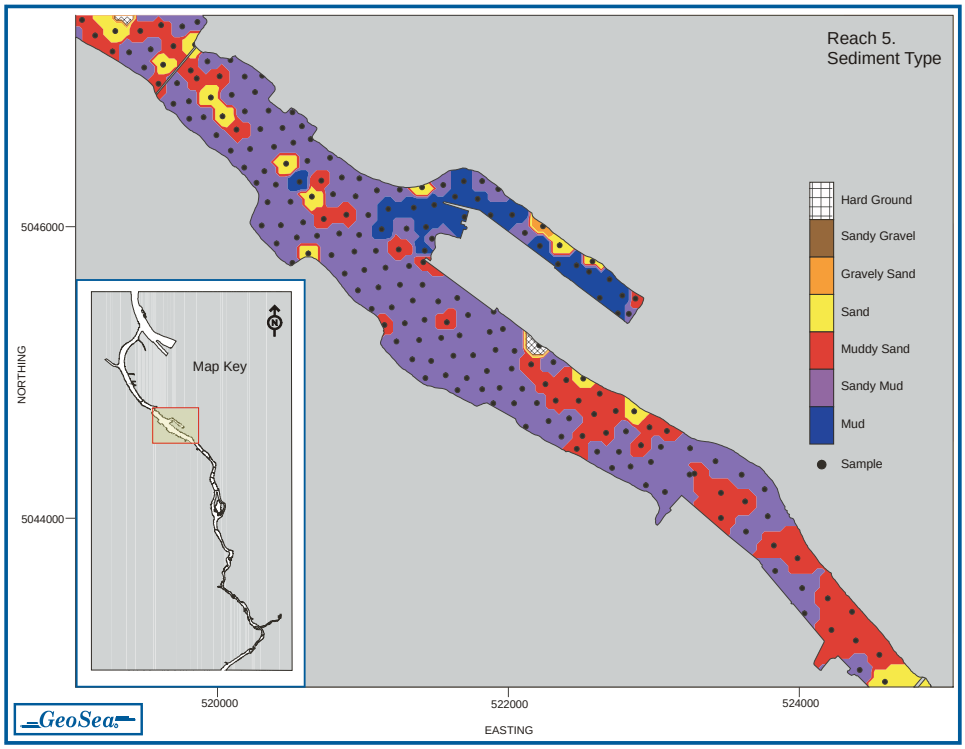

Figure 13: Sediment types in Reach 5.

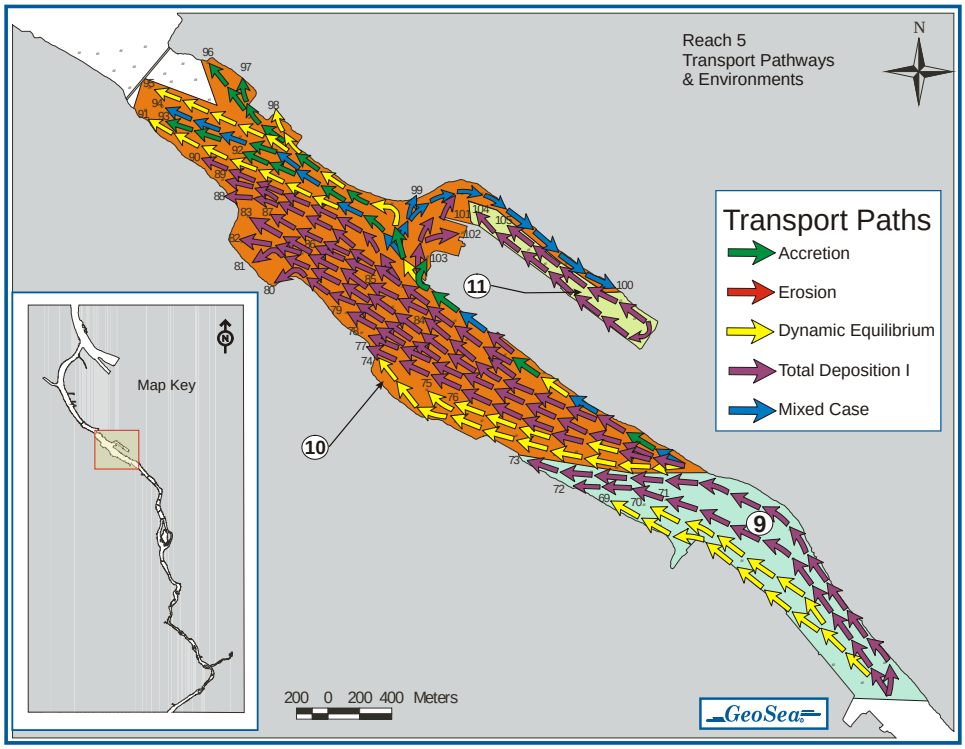

Figure 14: Transport pathways in Reach 5.

4.6 Reach 6 (Figure 15and Figure 16)

Sediments in this reach, which includes the downstream portion of the river up to Columbia Slough and part of Multnomah Channel, are nearly all muddy sand. Similar to Reach 5, there are some coarser sediments near the center of the river and in the Multnomah Channel, together with several, randomly scattered, mud samples.

There are three Transport Environments contained in this Reach: TE12 consisting of 6 lines; TE13 consisting of 24 lines; and TE14 consisting of 2 lines.

4.6.1 Transport Environment 12

Lines	N	Average R^2	Std. Dev. R^2	Erosion %	Accretion %	Total Depos'n %	Dynamic Equil. %	Mixed Case %
106-111	6	0.982	0.026	0	0	0	100	0

Table 14: Line statistics for TE12.

This small group of lines lies roughly between Doane Point and the St. Johns Fixed Bridge. It is thought that they make a separate environment because of the bridge pylons and the resultant scour and current eddies. All the lines show Dynamic Equilibrium, and the R^2 values are high.

4.6.2 Transport Environment 13

Lines	N	Average R^2	Std. Dev. R^2	Erosion %	Accretion %	Total Depos'n %	Dynamic Equil. %	Mixed Case %
112-135	24	0.973	0.009	0	0	0	54	46

Table 15: Line statistics for TE13.

Despite the river widening, and the presence of muddy sediments, all trends in this environment stay in either Dynamic Equilibrium or Mixed Case. The trends can be traced down the Multnomah Channel, and into each of the three slips on the right bank of the river. The presence of mud at the end of the middle slip (Line 134) indicates deposition, however the number of samples was insufficient to change the trend from dynamic equilibrium. The R^2 values are high.

4.6.3 Transport Environment 14

Lines	N	Average R^2	Std. Dev. R^2	Erosion %	Accretion %	Total Depos'n %	Dynamic Equil. %	Mixed Case %
136-137	2	0.955	0.064	100	0	0	0	0

Table 16: Line statistics for TE14.

A single sequence of samples taken up the Columbia Slough required two separate transport lines broken more or less at the point where a large outfall on the north side enters the Slough. Both lines show Net Erosion indicating that sands are lost to the Willamette from the Slough: indeed, samples in the Willamette become sandier at the entrance to the Columbia Slough. It is likely that TE13 in the Willamette River terminates because of new sediment being brought in by the Slough. The R^2 values are high.

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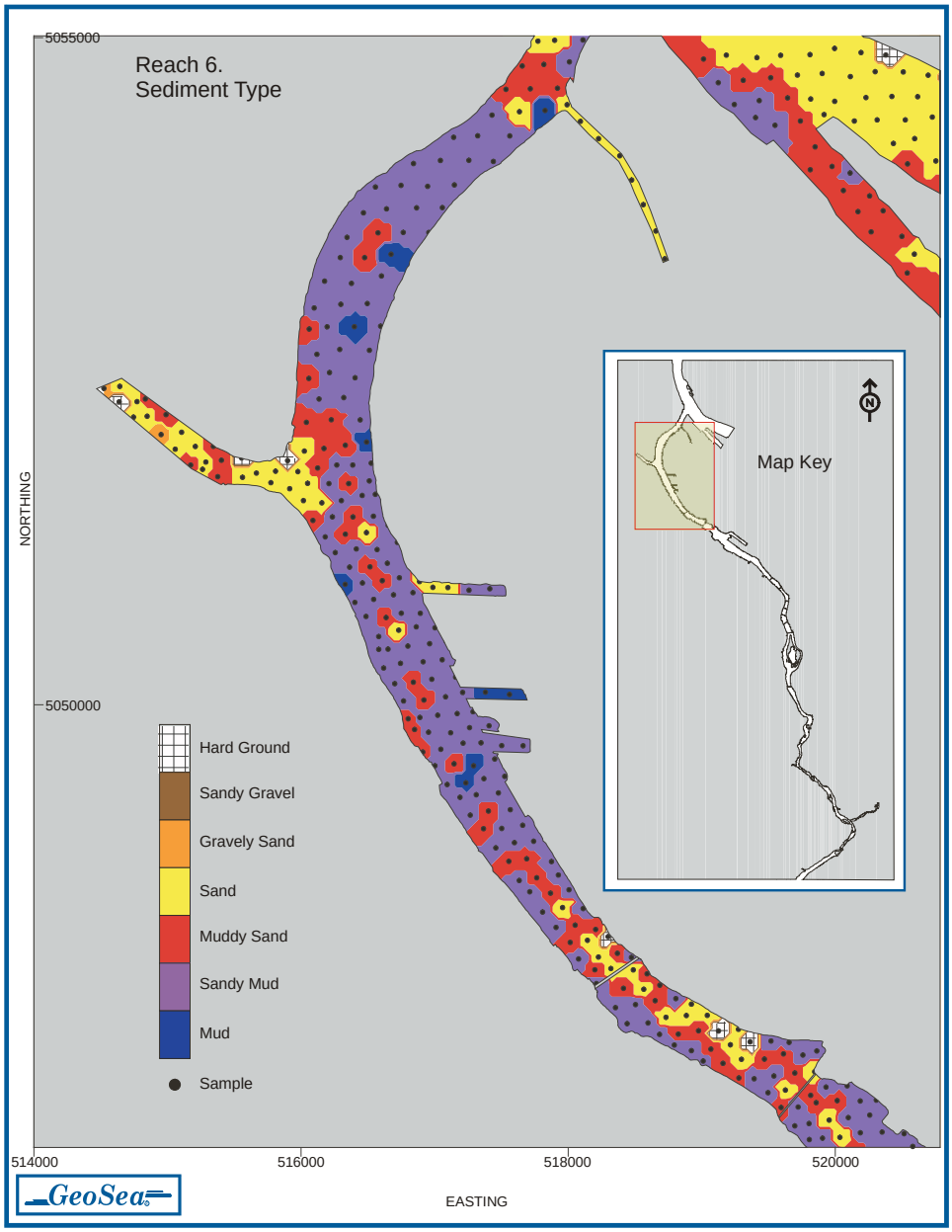

Figure 15: Sediment types in Reach 6.

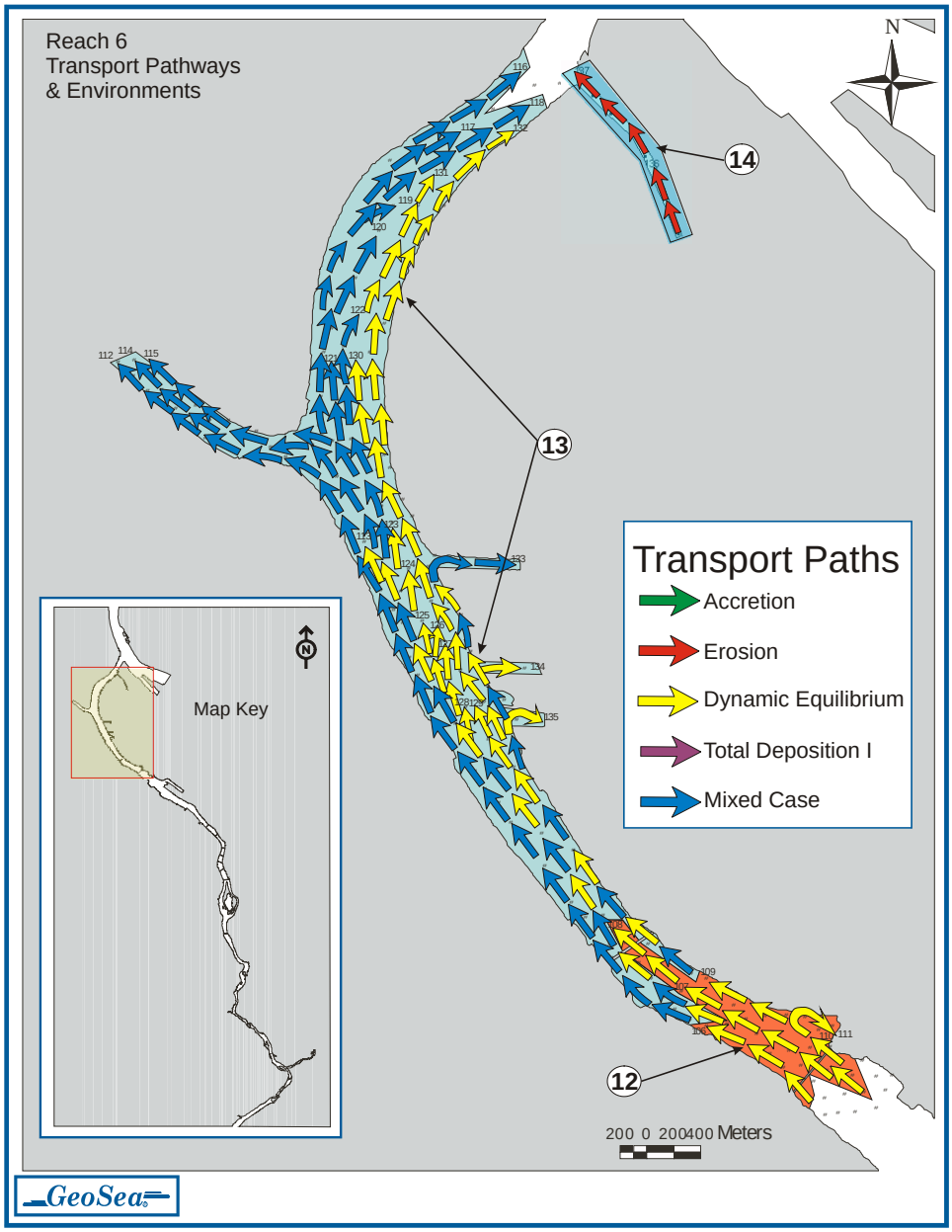

Figure 16: Transport pathways in Reach 6.

4.7 Reach 7 (Figure 17 and Figure 18)

Reach 7 comprises the Willamette River downstream of the Columbia Slough and a portion of the Columbia River near the mouth of the Willamette. Sediments in the Willamette are generally finer than those in the Columbia, which are mostly pure sand. Some finer sediment (muddy sand and sandy mud) is found along the southwest bank of the Columbia.

There are two Transport Environments found in this Reach: TE15, consisting of 5 lines; and TE16, consisting of 12 lines.

4.7.1 Transport Environment 15

Lines	N	Average R^2	Std. Dev. R^2	Erosion %	Accretion %	Total Depos'n %	Dynamic Equil. %	Mixed Case %
138-142	5	0.616	0.278	60	0	0	40	0

Table 17: Line statistics for TE15.

Originating near the Columbia Slough, these lines emanate from the Willamette River into the west side of the Columbia River. Sediments rapidly become coarser and all the trends are either in Dynamic Equilibrium or Net Erosion. The R^2 values are low and variable, probably reflecting the mixture of Willamette and Columbia River sediments at the confluence of the two rivers.

4.7.2 Transport Environment 16

Lines	N	Average R^2	Std. Dev. R^2	Erosion %	Accretion %	Total Depos'n %	Dynamic Equil. %	Mixed Case %
143-154	12	0.556	0.252	100	0	0	0	0

Table 18: Line statistics for TE16.

These lines originate upriver from the mouth of the Willamette River and are “deflected” to the right bank by the Willamette River transport regime. Again, the R^2 values are low and variable, which is explained by the mixing of two sediment sources. All lines show high energy, Net Erosion transport suggesting that fines are being progressively removed from the deposits in a downstream direction. Samples in the region on the northeast bank of the Columbia upriver from this environment could not be associated with transport lines in this environment for reasons that are presently not understood. Sediments in that area tended to be finer and better sorted than those in TE 16.

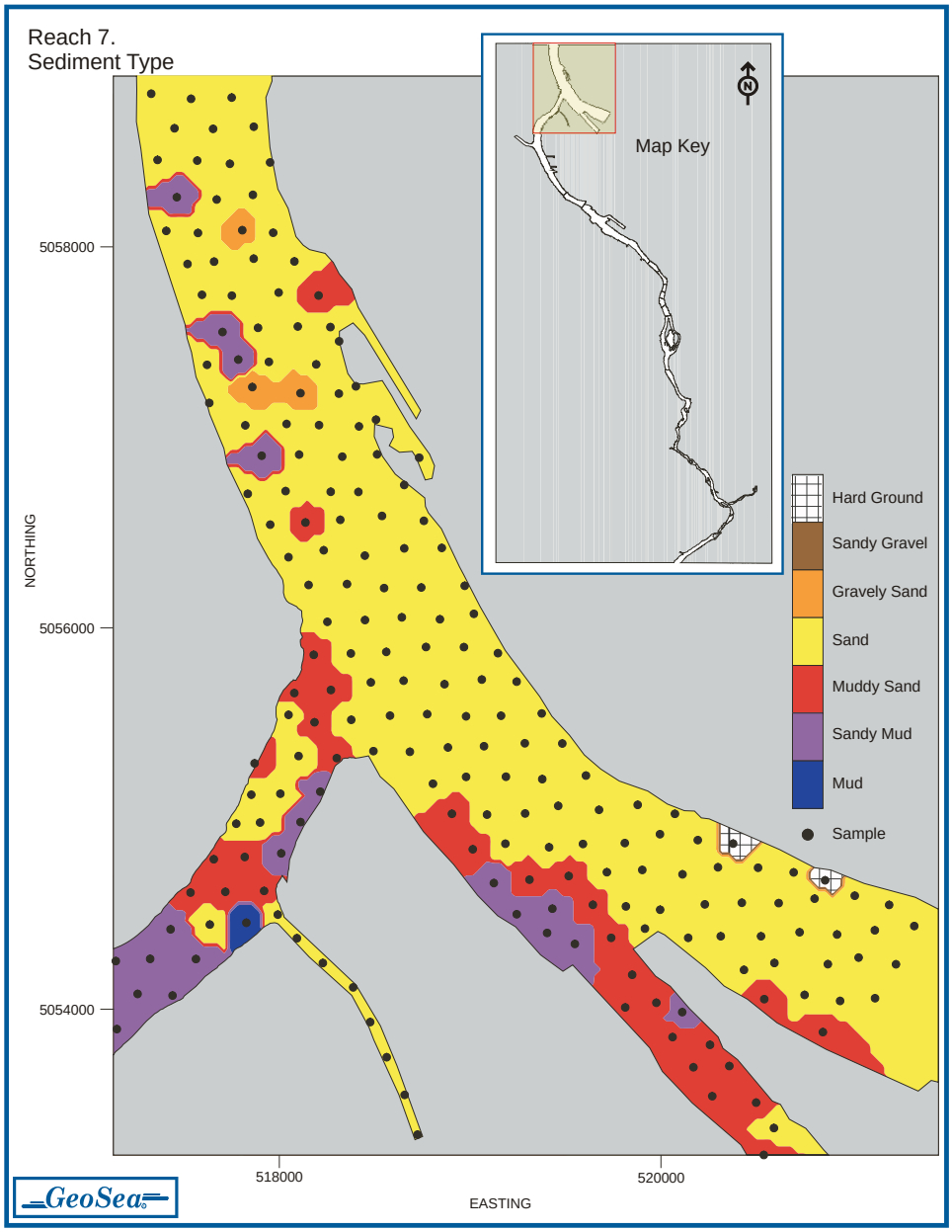

Figure 17: Sediment types in Reach 7.

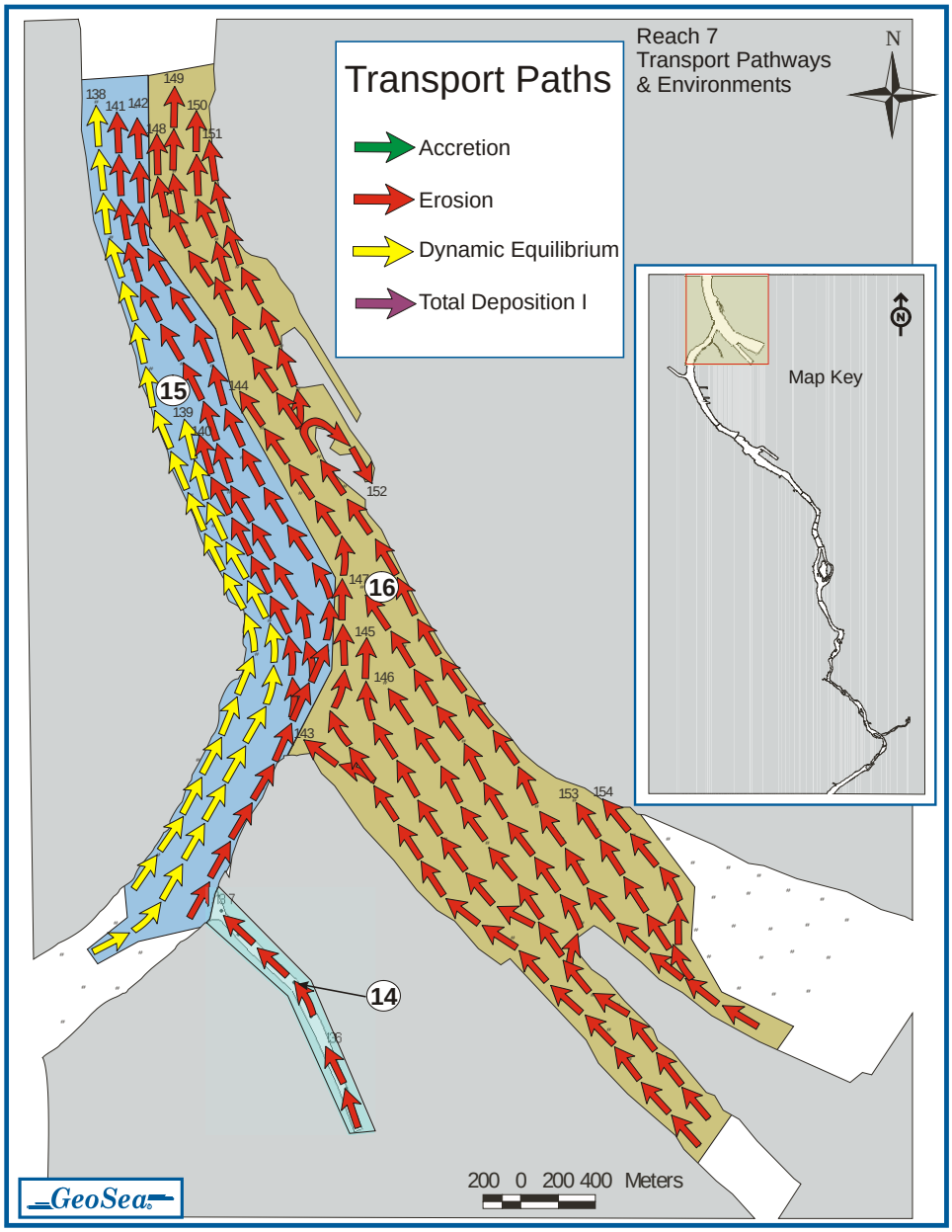

Figure 18: Transport pathways in Reach 7.

5 DISCUSSION

5.1 Process Implications

From TE1 through to TE8 there is a steady decline in the presence of Hard Ground areas. The amount of sediment, therefore, initially entering the study area must be relatively small (i.e., as the amount of sediment available for transport increases, the probability of deposition also increases). Dams, including the Willamette Falls, presumably block sediment potentially available to enter TE1 from farther upriver. Initially, in TE's 1 to 4, the morphology of the river is controlled by bedrock, namely Tertiary basalts, and the dynamic behavior of the sediments appears to be very much controlled by the underlying topography of the riverbed. Where the river widens and deepens, deposition of sand is found; where it narrows and shallows, the flows are consequently higher and erosion results. Thus TE1, receiving a small amount of sand from upriver and from the Clackamas River, is characterized by deposition, followed by erosion in TE2. This same sequence is found in TE3 and TE4.[8]

Progressing beyond TE4, the river becomes less controlled by bedrock as it enters Quaternary deposits and alluvium. More sediment, both from the surrounding geology, minor tributaries and an increasing number of outfalls, is available for deposition, and areas of Hard Ground decrease. Nevertheless much sediment potentially available for transport and deposition is denied to the river because of an increasing abundance of walls and other riparian structures. The present river, therefore, can be regarded as a "chute", most of which is bedrock or anthropogenically controlled. Within the chute, a rather limited amount of sediment is transported, much of it being in Dynamic Equilibrium, somewhat analogous to a conveyor belt continually moving the sediment from upstream to downstream.

The conveyor belt concept of sediment transport is temporarily interrupted in TE's 9, 10 and 11. At the start of TE9, the river emerges from narrows in the area of the Fremont Fixed Bridge. River flow decreases in the wider reaches of the river and for the first time a significant amount of fine-grained material, originally in suspension, is deposited. Its cohesiveness results in Total Deposition-Type I dynamic behavior (i.e., once these fine grained particles are deposited they are not easily moved again). Another factor influencing an increase in deposition may be the effects of the tide in this region of the river. Although no evidence of "tidal pumping"[9] of sediments upstream is observed, it may be that upriver tidal flow helps to slow river velocities sufficiently to allow the deposition of fines, but does not accentuate the downstream flow sufficiently during the ebb to continue the downstream transport of fines.

Sediments in Swan Island Lagoon (TE11) appear to be brought in by sources entering the lagoon at or near its upstream extremity, and are in depositional transport toward the

[8] Although the amount of available sediment is very small, it is still possible to ascertain the transport behavior of that sediment.

[9] Tidal pumping is a common process in estuaries where flood currents are typically faster and of shorter duration than the ebb. For this reason, cohesive sediments can be moved on the flood, but not the ebb, with the result that mud is transported upriver.

river. Downstream of Swan Island in TE10, some coarser sediment is found near the center of the river, and transport changes to Dynamic Equilibrium or Mixed Case. This change may be due to ship and barge traffic causing re-suspension and subsequent transport of fines downstream.

Continuing into TE12 the river once again establishes a "conveyor belt" dynamic behavior, despite the fact that the sediments remain dominantly fine grained. TE12 itself is located in a narrows (at Doane Point) where higher velocities would result in Dynamic Equilibrium. TE13 contains both Dynamic Equilibrium and Mixed Case yet it is contained in a widening river (analogous to TE9), and given the abundance of fine-grained sediment, Total Deposition Type I could reasonably be expected to occur. Its absence requires explanation. First, an increasing amount of vessel traffic is likely to result in re-suspension and transport of fines downstream. The presence of coarser sediments down the center of the TE13 supports this concept since propeller wash would be greatest in mid-channel. A second possibility is that the sediment sinks established in TE's 9,10 and 11 may have significantly decreased the amount of sediment available to TE's 12 and 13. As the amount of sediment available for transport and deposition decreases, the probability of Dynamic Equilibrium and Net Erosion increases. Third, and finally, tidal effects may be increasingly important with distance downstream, with the result that ebb flow dominates over any upstream transport due to the flood. Unfortunately there are no current measurements available to compare with those from the Morrison Bridge to test this hypothesis. Regardless of the process responsible, this portion of the river reestablishes the conveyor belt analogy, taking Willamette sediments downstream to join with those of the Columbia, and also into Multnomah Channel.

As the Columbia River is approached (TE15) and in the Columbia River itself (TE16), sediments once again become predominantly sand. Some coarser sediment enters the Willamette from the Columbia Slough (TE14) just upstream of the mouth, which appears to be responsible for the boundary between TE14 and TE15. Evidently energy levels associated with the lowest part of the Willamette River and the Columbia are too high to allow the deposition of fine-grained material which, if present at all, is now eroded to regions downriver of the study area.

Taken in their entirety, the results of the STA (using samples collected at a low river stage) suggest that during low river stages, very little transport and deposition of sediment takes place at all. There may be some throughput of very fine sediment with re-suspension events occurring because of vessel traffic. But it is unlikely that processes during the low stage flows could be responsible for the observed "sedimentary signatures" used for the STA. If this were not true, the abundance of Hard Ground in the upper reaches of the study area, and the evident scouring associated with nearly all the bridges, would be unlikely. Based on the results presented here, it is possible to speculate on sediment transport processes occurring in the lower Willamette River during high river stages. The following paragraph outlines one possible scenario.

With periodic rises in river stage, velocities increase rapidly together with a supply of new sediment into the system. The "conveyor belt" of sediment movement takes effect with Total Deposition occurring in TE's 9,10 and 11. In the regions of the river dominated by Dynamic Equilibrium and Mixed Case, sediment likely moves rapidly,

although some would accumulate along the margins at locations which are probably back eddies, and these sediments become beaches when the flooding recedes. These beach deposits are subsequently reworked by waves and boat wakes providing a small source of fine sediments for transport downstream. The pulse of new sediment entering the river on a rising stage is likely to be short lived. By the time really high stages are reached, during the subsequent fall, it is unlikely that very much sediment remains for deposition, but the "conveyor belt" transport still operates. As the river stage falls, velocities once again become too low for active transport and associated erosion and depositional there is little new sediment entering the river, and little happens until the next high stage event.

6 SUMMARY AND CONCLUSIONS

STA was performed on about 850 sediment samples taken from the Willamette River and the Columbia River. The samples displayed a large variety of sediment types ranging from sandy gravel to mud, although the majority of the sediments are sands or muddy sands. After considerable experimentation with the analysis parameters, it was found that, in any particular region, all sediments could be treated as a single sediment facies and that it was not possible to perform separate trend analyses on specific sediment types. The derived patterns of transport allowed the study area to be divided into 16 Transport Environments (TE's) based on transport direction, dynamic behavior and, to a lesser extent, grain-size.

In the tidal Willamette River, differences in sediment transport behavior divide the river into four separate regions. Furthest upstream, just downstream of the Willamette Falls, the river flow and sediment transport is bedrock-controlled. It is thought that most of the sediment supply to this part of the river (and therefore downstream portions of the river as well) is due to extreme events such as floods or significant dam releases. The next section of the river is a highly channelized portion of the river flowing through the most highly urbanized part of Portland. Sediments in transport here or those injected into the system from outfalls are essentially on a "conveyor-belt" moving them further downstream. This mode of transport ends just downstream of the Fremont Fixed Bridge, where sediments become finer and transport becomes depositional. This part of the river, which encompasses much of the industrial and Port facilities, is the only part of the lower Willamette that is a sink for sediments. Downstream of this part of the river, sediments in transport enter another "conveyor-belt" transport regime in which they are moved downstream to enter the Columbia River system. The final region is the extreme downstream end of the Willamette and the portion of the Columbia that was sampled; here Net Erosion dominates the sedimentary environment.

7 ACKNOWLEDGEMENTS

Sincere appreciation is expressed to Trey Harbert and the Port of Portland for instigating and managing this project.

Some of the information in the section on "Physical Setting" was obtained from websites of the US Army Corps of Engineers, the Port of Portland, and the US Geological Survey.

8 REFERENCES

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9 APPENDICES

The following appendices will be found as separate Word 2000 documents, named as (for example) *AppendixII.doc*.

Appendix I: Sediment Transport Model.

Appendix II: Sediment Grain Size Analysis and Data.

Appendix III: Sediment Trend Statistics of Selected Sample Lines.

Appendix IV: Selected D_1, D_2, and X Distributions.