US Army Corps
of Engineers

Estimation of Uncertainty in Coastal-Sediment Budgets at Inlets

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PURPOSE: The Coastal Engineering Technical Note (CETN) herein provides information and procedures for estimating uncertainty in coastal-sediment budgets at inlets. Incorporation of uncertainty provides bounds for the sediment budget and serves as an indicator of reliability and possible variability in a sediment budget.

BACKGROUND: A sediment budget is a tally or accounting of all sediment inflows to and outflows from a defined area. At an inlet, a sediment budget typically includes such diverse factors as the longshore sand-transport rate, dredging quantity and placement practice, changes in ebb- and flood-tidal shoal volumes, beach fill, and beach erosion and accretion. Through balancing the sediment budget, littoral- and inlet-sediment processes are related in a consistent way.

A sediment budget gives the pathways and magnitude of sediment transport. Comparing sediment budgets developed for different times often provides an understanding of coastal and inlet changes that occur naturally or in response to engineering actions. Major modifications in the sand-transporting system occur at inlets, where jetties are constructed and channels are maintained through dredging.

Formulation of a sediment budget typically requires estimation of quantities that are not well known. Assignment of "best estimates" for needed values requires considerable experience to derive a balanced and integrated picture of the budget. Usually, the best estimate of a quantity is either an average value or a representative value based on experience and common sense.

At inlets, sediment budgets are particularly difficult to formulate because the paths for sediment movement are complex and are not well known nor directly measurable. Sediment paths at inlets split into two or three routes, and the apportionment of material flowing along them is a matter of judgment. A sediment budget at inlets necessarily involves substantial unknowns, and this CETN describes a methodology to quantify the uncertainty in commonly occurring variables. In the following, a mathematical framework is given to provide a systematic means of including uncertainty with best estimates. The procedures are illustrated through examples, and then the analysis procedure is applied to a simple sediment budget.

Basic understanding of sediment budgets is assumed and can be reviewed in the *Shore Protection Manual* (SPM 1984), Jarrett (1977, 1991), Dolan et al. (1987), Headland, Vallianos, and Shelden (1987), and Komar (1998). Companion Technical Note CETN IV-15 (Rosati and Kraus 1998) describes a sediment-budget methodology specifically for inlets.

ERROR AND UNCERTAINTY: Every measurement has limitations in accuracy and contains a certain error. In coastal engineering, often no direct measurement of a quantity can even be made, such as of the longshore sand-transport rate or of the amount of material bypassing a jetty. Values of such quantities are obtained with predictive formulas or through estimates based on experience and judgment. Therefore, any measured or estimated value can be considered as consisting of two terms, expressed schematically as

$$\text{Reported Value} = \text{Best Estimate} \pm \text{uncertainty} \tag{1}$$

Uncertainty consists of error and true uncertainty. A main general source of error is limitation in the measurement process or instrument. True uncertainty is the error contributed by unknowns that may not be directly related to the measurement process.

In coastal processes, significant contributors to true uncertainty enter through natural variability. Such variability includes (a) temporal variability (daily, seasonal, and annual beach change), (b) spatial variability (alongshore and across shore), (c) selection of definitions (e.g., shoreline orientation, direction of random seas), and (d) unknowns such as grain size and porosity of the sediment (especially true in placement of dredged material). For example, a survey of the beach profile is capable of specifying the horizontal position of the mean high-water shoreline with an error less than a few centimeters with respect to a local benchmark (measurement error). However, a measurement made days before or after the original measurement or 50 m upcoast or downcoast may record a shoreline position differing by several meters from the original measurement (true uncertainty), creating ambiguity about the representative or true value. Error and uncertainty themselves are typically best estimates, leading to the concept of uncertainty in uncertainty, discussed below.

In inlet processes, uncertainty enters several ways. Two prominent ways are through limited knowledge of (a) changes in ebb- and flood-tidal delta sand volumes and (b) the paths and relative magnitudes of transport, such as transport through and around jetties and to the tidal shoals.

In the following, the term "uncertainty" incorporates both measurement error and true uncertainty.

BASICS OF UNCERTAINTY ANALYSIS: Let X denote a coastal engineering quantity to be estimated for a sediment budget, and suppose X is a function of several independent variables or measurements. For example, X might be the longshore sand-transport rate given by the Coastal Engineering Research Center (CERC) formula (SPM 1984), which is a function of wave height, period, and direction. Alternatively, X might be the change in beach volume accompanying updrift impoundment or downdrift erosion at an inlet. In this case, X is expressed as the product of the distance alongshore over which the change occurred, the depth of active sediment movement, and the change in shoreline position.

Let δX denote an uncertainty in X. The uncertainty δX is considered to be an extreme plausible error[1] and carries a sign, that is,

$$\delta X = \pm|\delta X| \tag{2}$$

If X is a function of the independent variables x, y, and z, by assuming the uncertainty in each variable is reasonably small, a Taylor series gives to lowest order,

$$X_{\text{best}} + \delta X \approx X_{\text{best}} + \frac{\partial X}{\partial x}\delta x + \frac{\partial X}{\partial y}\delta y + \frac{\partial X}{\partial z}\delta z \tag{3}$$

so that the maximum uncertainty in X is

$$\delta X_{\max} \approx \frac{\partial X}{\partial x}\delta x + \frac{\partial X}{\partial y}\delta y + \frac{\partial X}{\partial z}\delta z \tag{4}$$

to lowest order. Because the δx, δy, δz, etc., each contain a sign ($\pm$), the partial derivatives in Equations 3 and 4 are interpreted as absolute (positive) values. That is, in uncertainty analysis one forms extreme values by consistently applying ($\pm$) to each term to avoid cancellation between and among terms.

From Equations 3 and 4 and other assumptions (see Taylor 1997), results given in the following are found.

Uncertainty in a Sum or Difference. Suppose the variable X is a sum or difference of several independent parameters as $X = x + y - z + \ldots - \ldots$, then the two common estimates for the uncertainty are

$$\delta X_{\max} = \delta x + \delta y + \delta z + \ldots \tag{5a}$$

and

$$\delta X_{\text{best}} = \sqrt{(\delta x)^2 + (\delta y)^2 + (\delta z)^2 + \ldots} \tag{5b}$$

Note that in both expressions, the errors add, whether or not the variables enter the quantity being reported as a sum or difference. Equation 5a represents an extreme of bound for the possible error. Equation 5b is the root-mean-square (rms) error. The validity of this expression rests on the assumptions that the individual uncertainties are independent and random. The rms error accounts for the uncertainty in uncertainty by giving a value that is not an extreme, such as $\delta X_{\max}$.

[1] One might wish to define an extreme probable error, which would have a meaning in statistics. However, many variables entering coastal-sediment budgets, such as the amount of material dredged, do not have known distributions from which to derive statistical values. Therefore, the heuristic expression "extreme plausible error" is coined here.

Example 1: The depth of active transport D_A is expressed as

$$D_A = B + D_C \tag{6}$$

in which B is the elevation of the berm from some datum (for example, the National Geodetic Vertical Datum, mean high water, mean low water), and D_C is the depth of closure measured from the same datum. The depth of active transport is assumed representative of a stretch of beach, and the berm elevation and depth of closure are approximately known but carry some uncertainty. The best estimates are B = 2 m, and D_C = 7 m. Based on beach-profile survey data, it is also estimated that the associated uncertainties are δB = 0.3 m, and δD_C = 0.6 m. Then $(\delta D_A)_{\max}$ = 0.3 + 0.6 = 0.9 m, and $(\delta D_A)_{\text{best}} = \sqrt{(0.3)^2 + (0.6)^2} = 0.67$ m.

Uncertainty in a Power. Suppose $X = a\,x^n$, where a is a constant and has no uncertainty. Then, from Equation 4

$$\frac{\delta X}{|X|} = |n|\frac{\delta x}{|x|} \tag{7}$$

Equation 7 conveniently expresses error as a fractional uncertainty or percentage ratio of uncertainty.

Example 2: The breaking wave height H_b enters the CERC formula to the 5/2 power. Denoting the uncertainty in measured or hindcast breaking wave height as δH_b and setting $X = H_b^{5/2}$ in Equation 7, one has (omitting absolute value symbols because wave height is always positive),

$$\frac{\delta X}{X} = \frac{5}{2}\frac{H_b^{3/2}}{H_b^{5/2}}\delta H_b = \frac{5}{2}\frac{\delta H_b}{H_b} \tag{8}$$

For example, if the error in measurement of wave height or in a wave hindcast is ±0.1 m, then for a 1-m breaking wave, the uncertainty is ± 5/2 × 0.1/1 = ± 25%. For a fixed measurement error, as the magnitude of the best estimate increases, the relative error decreases. For example, in the present situation, if storm waves occur with H_b = 3 m, then the uncertainty associated with wave height in the CERC formula is about 8 percent. Because of the 5/2 power, uncertainty is increased as compared with a linear function. Wang and Kraus (1998) give an analysis of all uncertainties in the CERC formula.

Uncertainty in Products and Quotients. Suppose the quantity entering the budget is expressed as a product or quotient of independent variables as $X = xyz$ or as xy/z. In either case, the uncertainty in X is

$$\left(\frac{\delta X}{X}\right)_{\max} = \frac{\delta x}{x} + \frac{\delta y}{y} + \frac{\delta z}{z} \tag{9a}$$

and

$$\left(\frac{\delta X}{X}\right)_{\text{best}} = \sqrt{\left(\frac{\delta x}{x}\right)^2 + \left(\frac{\delta y}{y}\right)^2 + \left(\frac{\delta z}{z}\right)^2} \tag{9b}$$

and it is seen that the errors are additive whether a variable enters as a product or quotient. These equations state that the relative uncertainty of a product or quotient is equal to the sum of relative uncertainties of each term forming the product or quotient.

Example 3: Estimate the uncertainty in volume change for a beach segment 1 km long that recedes an average of 10 m based on surveys of the shoreline taken in February 1990 and August 2000. The depth of active transport on this beach has been estimated as 9 m from top of the berm to the depth of closure, as described in Example 1.

Solution. One can assume that the beach profile maintains the same shape over the longshore extent L = 1,000 m. Then with D_A = 9 m, and the best estimate of shoreline recession as Δy = 10 m, the best estimate of the total volume change as erosion ΔV is

$$\Delta V = L\, D_A\, \Delta y = 1{,}000 \times 9 \times 10 = 90{,}000 \text{ cu m} \tag{10}$$

Horizontal survey accuracy is high (say, 0.01 m), so the term $\delta L/L$ is expected to be negligible. The depth of active longshore sediment transport has a relatively large uncertainty because of variable height of the berm alongshore and variability in the depth of closure. From Example 1, $\delta(D_A)/D_A = 0.9/9 = 0.10$. Survey accuracy for the shoreline position is high (subcentimeter), but seasonal variability in waves and water level, as well as difference in seasons in which the two surveys were taken, introduces a large uncertainty to the representative value of the 10-m shoreline recession. Based on available data, the uncertainty is estimated as 3 m, so $\delta(\Delta y)/\Delta y$ = 0.30. The total uncertainty in the volume change becomes

$$\left(\frac{\delta V}{V}\right)_{\max} = \frac{\delta L}{L} + \frac{\delta D_A}{D_A} + \frac{\delta(\Delta y)}{\Delta y} = 0.01 + 0.10 + 0.30 = 0.41 \tag{11a}$$

and

$$\left(\frac{\delta V}{V}\right)_{\text{best}} = \sqrt{\left(\frac{\delta L}{L}\right)^2 + \left(\frac{\delta D_A}{D_A}\right)^2 + \left(\frac{\delta(\Delta y)}{\Delta y}\right)^2} = 0.32 \tag{11b}$$

Therefore, in a sediment budget, the volume of erosion should be reported as 90,000 cu m plus or minus either 32 or 41 percent, depending on the viewpoint taken on the uncertainty or the objective of the analysis.

Uncertainty in Dredging Quantities. Inlet channel dredging, dredged-material disposal, beach-fill placement must be quantified within a sediment budget that encompasses the inlet and adjacent beaches. In this section, methods for obtaining these estimates are discussed, and guidance is given for assigning associated uncertainties. The uncertainties are representative values and should be modified as necessary using engineering judgment and knowledge of the site. For example, bathymetric surveys on the coast of south Florida, where the wave climate is relatively mild and the tidal range is small, can be expected to provide more accurate best estimates with less uncertainty of the volume of material removed from a channel or of ebb-shoal volume than a survey on the north-Pacific coast, where the waves are much higher all year and the tidal range is also larger.

Because many sediment budgets are formulated based on historical data, the dredging methods used at the time the data were gathered must be known. For example, a hopper dredge may have been filled to capacity while allowing overflow of fine sediments, which theoretically would be transported away from the channel by the tidal and other currents. In this situation, consideration should be given to the possibility that some littoral material may not have been included in the dredging estimates, or potentially that the material was rehandled if it settled within the channel. The period of the dredging cycle also enters in the uncertainty. If the dredging occurred over several months, seasons, or years, a dredging quantity based on predredging and postdredging bathymetry surveys could represent additional shoaling of the channel after the initial dredging cycle.

One of the more accurate dredging estimates comes from comparison of predredging and postdredging surveys. These surveys meet standard U.S. Army Corps of Engineers' hydrographic survey accuracy requirements and are often the basis for paying the dredging contractor. The estimates can have significantly different degrees of reliability and can vary greatly. For example, a dredging contractor is usually paid only for the volume taken out of the design template. If a dredger digs outside the template (whether too deep or to the side of the template), then the reported pay quantity will be less than the volume removed and placed in the disposal area. In calm seas, the reported pay quantity may be only slightly greater than the pay quantity (~ + 20 percent), whereas in rough seas and intermittent calm and rough seas (when material can move back into the dredging area), the reported quantity might be double the pay quantity (~ +100 percent).

Another method for estimating dredged quantity references the volume of the storage bin or hopper on a hopper dredge. A typical volume is 765 cu m (1,000 cu yd). One method of determining the dredged material volume is to fill the hopper, allow the sediments within the hopper to settle (with excess water spilling over the hopper sides), and measure the vertical distance from the top of the hopper to the sediment surface. The hopper volume can then be calculated with a relatively low uncertainty, estimated at ±10 of the total volume.

A third method of volume calculation is to survey the placed material, whether as an offshore mound or as a beach fill. Uncertainty enters through the in situ voids ratio and whether fine sediments or any of the placed material has run off or slumped beyond the construction template. In this method, the contractor is paid based on surveys aimed to demonstrate that the construction template was filled. Typically, more material must be dredged and placed to meet the survey requirement.

Sidecasting of dredged material is occasionally performed. Typically, an average production rate for the dredge is multiplied by the slurry flow and the time the dredge has operated to obtain a volume. Occasionally, a nuclear-density meter operates on the sidecasting arm and can more accurately estimate the percentage of sediment in the dredged slurry. The uncertainty estimate for these methods is expected to be relatively large, perhaps ±30 percent.

Sometimes the only estimate of dredged volume is the permitted quantity or the design quantity specified to meet depth requirements for navigation, and this "paper" quantity may not provide a good estimate of the actual volume dredged. Typically, the permitted or design quantity will be exceeded, but the amount of exceedance is unknown.

In summary, dredged volume inaccuracies can enter as (a) uncertainty in the predredging condition; (b) uncertainty in the volume-estimation process; (c) unquantified sediment shoaling that occurs between the predredging and postdredging surveys; (d) failure to include nonpay volume (material removed from side slopes beyond the design channel location and unintentional overdepth dredging); and (e) changes in bulk density between the site where the volume was measured and the site or budget compartment where the volume is placed.

Uncertainty in Volume of Beach Fill. Fill can be placed either as an authorized shore-protection (beachfill) project or as a beneficial use of dredged material. For an authorized beachfill project, the fill is surveyed in place to ensure that the design cross section is met along the shore. For a beneficial-uses project, the placed material will typically not be measured in place, and the volume will be estimated as that from the dredging site. In both cases, considerations as discussed above for dredged material will apply.

Uncertainty in Volume Change of Ebb- and Flood-Tidal Shoals. Changes in the volume of material comprising an ebb-tidal shoal are typically based on comparisons between surveys conducted at two different times. The uncertainty in the shoal volume depends on the extent of coverage and accuracy of the survey and the density of points (to ensure capture of the relief of irregular features). Flood shoals are often not surveyed fully, because they are too shallow to allow access by boat. In this situation, aerial photography may delineate the shoal area, which can be multiplied by an average shoal depth to estimate the flood-shoal volume. The SHOALS system (Parson and Lilllycrop 1998) provides unprecedented capability to survey shoals at high resolution (4- by 4-m grid). Where accuracy is essential, bathymetric data for ebb and flood shoals, as well as channel position and shoaling, acquired with the SHOALS is recommended.

Because of the great differences in survey type and resolution, assigning a single value to the uncertainty is not possible. Further information can be found in Hicks and Hume (1997) and in Stauble (CETN-IV-13, 1998).

Uncertainty in the Sediment Budget. Sediment budgets are developed for a variety of reasons, including management of inlets and the adjacent shores and achievement of a consistent regional picture of sediment-transport processes. The accounting for uncertainty in the various components that comprise the budget yields an indicator of the reliability of the budget, as well as bounds for judging the range of values that might be taken by the more uncertain quantities. A simple example follows that incorporates uncertainty to estimate a range of values for a quantity that is difficult to estimate directly.

Example 4: Determine the volume of sand (and its associated uncertainty) that would be expected to be collected in a proposed deposition basin located on the landward side of an ebb-tidal shoal of a shallow-draft inlet. Assume that the deposition basin can be sized based on the estimated volume transported to the ebb-tidal shoal V_E from the updrift side and its associated uncertainty δV_E (a) immediately after jetty construction in 1971 and (b) after the jetty was fully impounded in 1980 (see Figure 1).

The following information is available. Shoreline change for 2 $\pm$ 0.01 km updrift of the jetty for the time period 1971 to 1980 was $\Delta y_1 = 3.1 \pm 0.4$ m/year, and from 1980 to 1994, $\Delta y_2 = 0.80 \pm 0.1$ m/year. These data were obtained from beach-profile surveys. Analysis of the beach profiles also indicates that the berm crest is at elevation $B = 2 \pm 0.15$ m National Geodetic Vertical Datum (NGVD), and the depth of closure is estimated as $D_c = 6 \pm 0.3$ m NGVD. Based on records of channel dredging, which showed variability because of storms and wave seasonality, the average dredging rate for the 10-year time period 1971 to 1980 was $V_{D1} = 300{,}000 \pm 60{,}000$ cu m, which increased to $V_{D2} = 900{,}000 \pm 200{,}000$ cu m for the 15-year period of 1980 to 1994.

Because of the orientation of the downdrift shoreline and characteristics of wave conditions at the site, all channel shoaling is assumed to originate the updrift beach. The net longshore sand-transport rate entering the area from the updrift side was estimated to be 120,000 ± 60,000 cu m/year based on a 20-year wave hindcast and calculation of the left- and right-moving longshore transport to give the net rate. After establishing a control volume for forming the sediment budget, as shown in Figure 1, the solution incorporating uncertainty is as follows.

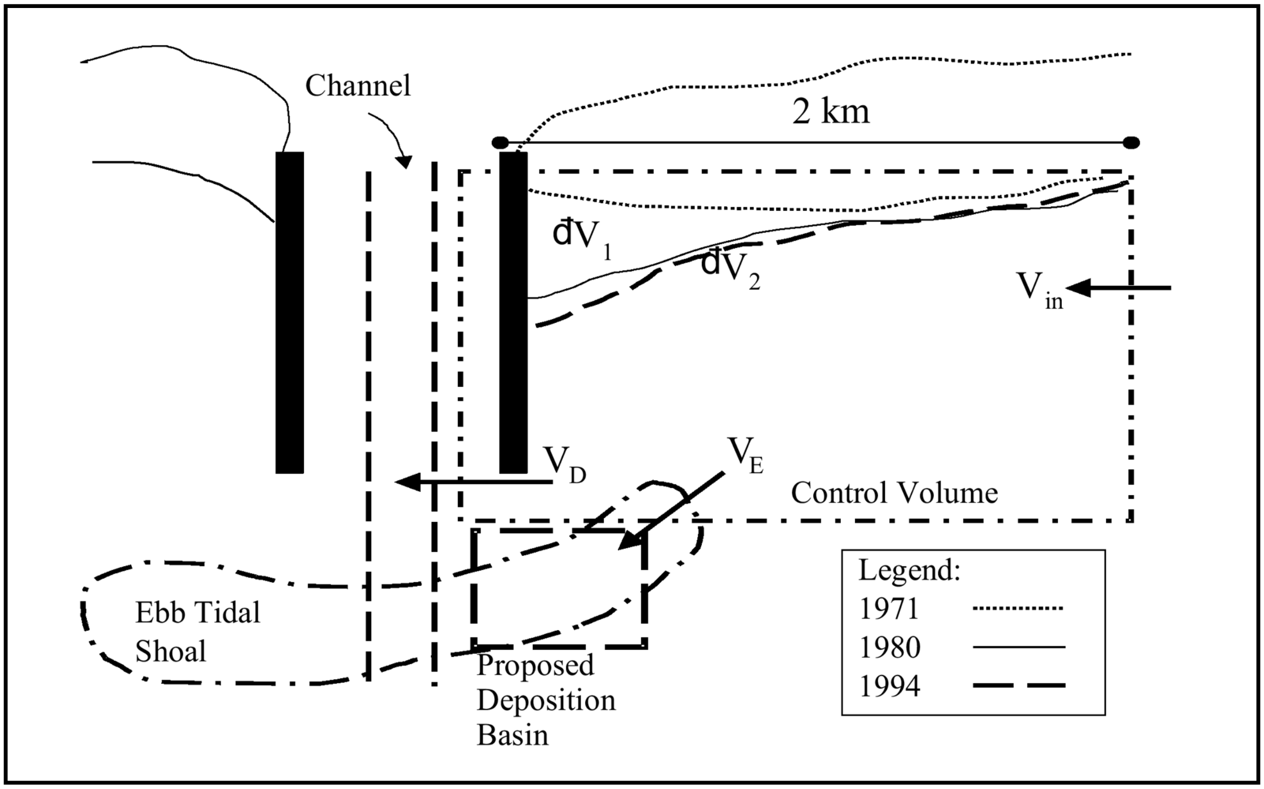

Figure 1. Sketch for Example Problem 4

Solution: ***Step 1:*** From Equation 6, calculate the active depth of transport as $D_A = B + D_C =$ $2 + 6$ m = 8 m. Equation 5a gives the associated maximum uncertainty $(\delta D_A)_{max} = 0.15 + 0.3$ m = 0.45 m, and Equation 5b gives the rms (best estimate) uncertainty as $(\delta D_A)_{best} = [(0.15)^2 + (0.3)^2]^{1/2}$ m = 0.33 m.

Step 2: Calculate the change in beach volume and its associated uncertainty for both time periods. For the first period (1971 to1980), Equation 10 gives $\Delta V_1 = (\Delta y_1)(D_A)(L) =$ (3.1)(8)(2,000) = 49,600 cu m/year, or 496,000 cu m for the 10-year time period. From Equation 11a, $(\delta V_1)_{max}/\Delta V_1 = \delta y_1/\Delta y_1 + \delta D_A/D_A + \delta L/L = 0.4/3.1 + 0.45/8 + 0.01/2 = 0.19$, giving $(\delta V_1)_{max} =$ (0.19)(496,000) = 94,000 cu m as an expected maximum error in volume of beach accretion. The rms error is similarly calculated from Equation 11b as $(\delta V_1)_{best}/\Delta V_1 = [(\delta y_1/\Delta y_1)^2 + (\delta D_A/D_A)^2 + (\delta L/L)^2]^{1/2} = [(0.4/3.1)^2 + (0.33/8)^2 + (0.01/2)^2]^{1/2} = 0.13$, and therefore $(\delta V_1)_{best} =$ (0.13)(496,000) = 67,000 cu m.

For the second period (1980 to 1994), Equation 10 gives $\Delta V_2 = (\Delta y_2)(D_A)(L) = (0.80)(8)(2{,}000) =$ 12,800 cu m/year, or 192,000 cu m for the 15-year time period. From Equation 11a, $(\delta V_2)_{max}/\Delta V_2 = \delta y_2/\Delta y_2 + \delta D_A/D_A + \delta L/L = 0.1/0.8 + 0.45/8 + 0.01/2 = 0.18$, giving $(\delta V_2)_{max} = (0.18)$ (192,000) = 36,000 cu m as an expected maximum error in volume in beach accretion. The rms uncertainty is similarly calculated from Equation 11b as $(\delta V_2)_{best}/\Delta V_2 = [(\delta y_2/\Delta y_2)^2 + (\delta D_A/D_A)^2 + (\delta L/L)^2]^{1/2} = [(0.1/0.8)^2 + (0.33/8)^2 + (0.01/2)^2]^{1/2} = 0.13$, and therefore $(\delta V_2)_{best} =$ (0.13)(192,000) = 25,000 cu m.

Step 3: Convert the rate of net longshore sand transport entering the area from the updrift side to a volume as follows: V_{in1} = (120,000 cu m/year) (10 years) ± (60,000 cu m/year) (10 years) = 1,200,000 ± 600,000 cu m, and V_{in2} = (120,000 cu m/year) (15 years) ± (60,000 cu m/year) (15 years) = 1,800,000 ± 900,000 cu m.

Step 4: Calculate the volume of sand transported to the ebb-tidal shoal from the updrift side and its associated uncertainty, V_E and δV_E , by forming a control volume as shown in Figure 1 and using a sediment-budget relationship such that the sum of the sediment sources, or inputs, to a control volume minus the sum of the sinks, or outputs, from that same volume, must equal the volume change in that control volume,

$$\sum Sources - \sum Sinks = \sum \Delta V \tag{12}$$

For the first period (1971 to 1980), Equation 12 is represented as $V_{in1} - (V_{D1} + V_{E1}) = \Delta V_1$, or $V_{E1} = V_{in1} - V_{D1} - \Delta V_1$ = 1,200,000 – 300,000 – 496,000 = 404,000 cu m. The associated maximum uncertainty is $(\delta V_{E1})_{max} = \delta V_{in1} + \delta V_{D1} + (\delta V_1)_{max}$ = 600,000 + 60,000 + 94,000 = 754,000 cu m. The rms uncertainty is $(\delta V_{E1})_{best}/V_{E1} = [(\delta V_{in1}/V_{in1})^2 + (\delta V_{D1}/V_{D1})^2 + (\delta V_1/V_1)^2]^{1/2} = [(600{,}000/1{,}200{,}000)^2 + (60{,}000/300{,}000)^2 + (67{,}000/496{,}000)^2]^{1/2}$ = 0.55, or $(\delta V_{E1})_{best}$ = (0.55)(404,000) = 224,000 cu m. Thus, during the initial 10-year time period after the jetties were constructed, the volume provided to the ebb-tidal shoal was 404,000 ± 754,000 (max) or ± 224,000 (best) cu m, which converts to a volume change rate of 40,400 ± 75,400 (max) or ± 22,400 (best estimate) cu m/year.

For the second period (1980 to 1994), the same procedure is applied. From Equation 12, $V_{in2} - (V_{D2} + V_{E2}) = \Delta V_2$, or $V_{E2} = V_{in2} - V_{D2} - \Delta V_2$ = 1,800,000 – 900,000 – 192,000 = 708,000 cu m. The associated maximum uncertainty is $(\delta V_{E2})_{max} = \delta V_{in2} + \delta V_{D2} + (\delta V_2)_{max}$ = 900,000 + 200,000 + 36,000 = 1,136,000 cu m. The rms uncertainty is $(\delta V_{E2})_{best}/V_{E2} = [(\delta V_{in2}/V_{in2})^2 + (\delta V_{D2}/V_{D2})^2 + (\delta V_2/V_2)^2]^{1/2} = [(900{,}000/1{,}800{,}000)^2 + (200{,}000/900{,}000)^2 + (36{,}000/192{,}000)^2]^{1/2}$ = 0.58, or $(\delta V_{E1})_{best}$ = (0.58)(708,000) = 410,000 cu m. Thus, during the 15-year time period after the updrift shoreline stabilized, the volume provided to the ebb-tidal shoal was 708,000 ± 1,136,000 (max) or ± 410,000 (best) cu m, which converts to a volume change rate of 47,200 ±75,700 (max) or ±27,300 cu m/year (best). Table 1 summarizes the results of these calculations.

Table 1
Example Problem No. 4 Results (cu m/year)

Time Period	V_E	$(\delta V_E)_{max}$	$(\delta V_E)_{best}$
1971 to 1980	40,400	75,400	22,400
1980 to 1994	47,200	75,700	27,300

Discussion: As would be expected, the rate of sediment transported to the ebb-tidal shoal increased in the 1980 to 1994 period, after the updrift beach stabilized. Note that a negative value of the maximum uncertainty implies a loss of material from the ebb-tidal shoal. Given conditions at this inlet, one would not expect this outcome and, therefore, would reduce the maximum uncertainty to equal V_E for these cases. This example illustrates that uncertainty in sediment budgets can be large and is a representative result.

The sediment deposition basin should be sized to accommodate the maximum anticipated deposition, or 47,200 + 75,700 = 122,900 cu m/year. However, it is likely that the volume of material available for dredging and placement on the downdrift beach will range from 47,200 ± 27,300 = 19,900 to 74,500 cu m/year.

ADDITIONAL INFORMATION:

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