Geostatistical Analysis of Sediment Deposition in Two Small Tidal Wetlands, Norfolk, U.K.

J.R. French†, T. Spencer‡, A.L. Murray‡ and N.S. Arnold‡

†Department of Geography
University College London
26 Bedford Way
London WC1H 0AP, U.K.

‡Department of Geography
Cambridge University
Downing Place
Cambridge CB2 3EN, U.K.

Abstract

FRENCH, J.R.; SPENCER, T.; MURRAY, A.L., and ARNOLD, N.S., 1995. Geostatistical analysis of sediment deposition in two small tidal wetlands, Norfolk, U.K. *Journal of Coastal Research*, 11(2), 308–321. Fort Lauderdale (Florida), ISSN 0749-0208.

Attempts to assess the sedimentary status of coastal wetlands have typically utilized either residual sediment transport via major drainage channels ('creeks') or the rate of vertical substrate accretion. The first method neglects the interaction between channel and surface sedimentation and may be inappropriate where significant water movement occurs across wetland margins. The second method requires areal interpolation from a limited number of cores, sediment traps or marker horizons, yet the effects of different spatial and temporal sampling strategies are rarely considered.

This paper presents an analysis of spatial patterns of sediment deposition within two tidal wetlands on the eastern coast of England. Extensive deployments of surface-mounted sediment traps over individual tidal cycles provide new insights into the spatial scales over which particle settling varies. Sedimentation is appropriately considered as a regionalized variable and estimation of 2-dimensional semivariograms allows the spatial scale of variability to be incorporated into interpolated 'sedimentation surfaces'. This enables more accurate estimation of mass fluxes than is possible from conventional arithmetic averaging or measurements of mass flux via drainage creeks. Rapid particle settling during lateral and apical overtopping of the creeks results in coherent patterns of sedimentation at spatial scales of the order 20–200 m, depending on the developmental stage of the wetland surface-channel system. Comparison of these findings with vertical accretion averaged over several years indicates an increasing dependence of sedimentation rate upon inundation frequency (and therefore elevation) as the time-averaging period is lengthened.

Failure to consider these spatial and temporal sampling requirements may result in misleading assessments of wetland vulnerability to future accelerated sea-level rise or to changes in sediment supply.

ADDITIONAL INDEX WORDS: *Tidal wetlands, sedimentation, geostatistics, sea-level, Norfolk, U.K.*

INTRODUCTION

Recently, considerable concern has been expressed in respect to the likely response of coastal wetlands to potential accelerated sea-level rise associated with global climate and ocean warming. Wetlands in areas already subject to high rates of sea-level rise, as a result of regional subsidence and adverse coastal zone exploitation, frequently exhibit measurable differences between local sea-level rise and vertical accretion (STEVENSON *et al.*, 1986; DeLAUNE *et al.*, 1992). In some wetland areas, these and potential future 'sedimentary deficits' translate into major areal losses of valuable habitats, from both marginal erosion (HARMSWORTH and LONG, 1986; PHILLIPS, 1986) and in-place drowning and open water pool coalescence

(WALKER *et al.*, 1987). In the rapidly subsiding Mississippi deltaic plain, for example, wetland loss rates of the order 100 km^2 a^{-1} have been reported (TEMPLET and MEYER-ARENDT, 1988).

Contemporary and future wetland status is not easy to predict with any certainty. Eustatic sea-level variation may result in non-linear changes in tidal range (see, for example, WOODWORTH *et al.*, 1991) and, therefore, wetland hydroperiod. Marsh vertical accretion is further determined by the relative importance of *in situ* organic and externally derived inorganic material supply, autocompaction in above-basement sediments and subsidence effects resulting from regional patterns of sedimentation and/or continued responses to Pleistocene glacio- and hydro-isostatic processes (*e.g.,* CLARK *et al.*, 1978). Different combinations of these factors give rise to different modes of marsh response to eustatic sea-level rise (ALLEN, 1990; FRENCH, 1993).

Several difficulties arise in empirical studies which aim to identify these categories of marsh response and thus current and likely future accretionary balance. Three methods of establishing wetland sedimentary status can be identified.

First, sediment flux measurements in marsh drainage channels (or 'creeks') over individual tidal cycles have been extrapolated to establish annual or longer-term sediment budgets for whole marsh systems (for a review, see STEVENSON et al., 1988). In such programmes, relatively coarse temporal sampling (> 15–30 minute intervals) may inadequately characterize high frequency stage-dependent variations in discharge and sediment load; the resulting errors are magnified where small residual sediment transports are computed from the difference of very large total flood and ebb transports (REED, 1987). Also, a simple input–output approach to marsh sedimentary function is inappropriate where i) sediment storage occurs *within* extensive channel systems; and/or ii) a significant proportion of tidal exchange is *not* routed via the creek system. For example in a North Norfolk (U.K.) salt marsh, FRENCH and STODDART (1992) demonstrated that, over 4 spring tidal cycles, sheetflow across the edge of the marsh (*i.e.*, by-passing the creek system) accounted for up to 39% of total water movement on the flood, and up to 47% on the ebb. The errors induced in residual sediment fluxes computed from creek discharge measurements alone are correspondingly large.

Second, geological studies have used dated horizons or radionuclide profiles within marsh stratigraphic sequences to establish time-averaged rates of substrate accumulation. This approach may be unsatisfactory where rates of vertical accretion are strongly time-dependent. This is the case in tide-dominated systems comprised largely of inorganic sediments, where vertical accretion rates are initially rapid following the establishment of a continuous halophyte cover, but decline rapidly thereafter as surfaces are raised towards a level constrained by the upper limit of the tidal frame (PETHICK, 1981; FRENCH, 1991). As a result, the apparently clear relationships between tidal range and accretionary balance established for many North American wetlands (STEVENSON et al., 1986) cannot be readily extended to the predominantly inorganic coastal marshes of NW Europe (FRENCH, 1993).

Finally, many studies have documented short-term rates of either vertical accretion or mass ac-

cumulation by repeated levelling, monitoring the burial of artificial markers, or surface sediment traps (see FRENCH and SPENCER, 1993 for a review). Although all these techniques over-estimate actual changes in surface elevation where rates of autocompaction are high (STEVENSON et al., 1986), this objection is less sustainable within highly inorganic substrates. Importantly, such short-term measurements offer useful insights in the spatial variability in mass accumulation and into the problems likely to be encountered in the estimation of wetland sedimentary status from other methods.

In this paper we: i) report a technique, with preliminary illustrative field datasets, for the detection of spatial variations in marsh surface sedimentation; ii) examine the utility of standard geostatistical measures for the analysis of sedimentation patterns and the evaluation of marsh sedimentary status; and iii) discuss explanations for the patterns of sedimentation observed and their relation to longer-term (*i.e.*, > 5 yr) accretion rates.

STUDY LOCATION

The salt marshes studied here are situated landward of a shingle and dune barrier island system on the North Norfolk coast of eastern England (Figure 1). Stratigraphic studies show marsh development associated with the Holocene transgression from before 6,500 yr BP, with the most recent phase of major sedimentation dating from 2,750 yr BP (FUNNELL and PEARSON, 1989). This coastline experiences a macrotidal, semi-diurnal tidal regime with a mean range at neap and spring tides of 3.2 and 6.4 m respectively (HYDROGRAPHIC OFFICE, 1992). The salt marsh surfaces lie at 2.0–3.2 m O.D. (Ordnance Datum) while the highest dune-topped barriers reach 15–20 m above sea level. Highest astronomical tides (HAT) reach 3.8–4.0 m O.D., although storm surges, to which the southern North Sea is susceptible, can elevate water levels to over 5.0 m O.D. under particular combinations of wind and tide.

Ages of the contemporary marshes vary considerably and relate to the episodic development of the barrier system (PETHICK, 1980). Individual marshes initially experience rapid vertical growth which then slows as the tidal prism is infilled. In time, surfaces track towards an equilibrium height which represents a balance between tidal sedimentation, fossilization of *in situ* plant production and local relative sea-level rise. At the present
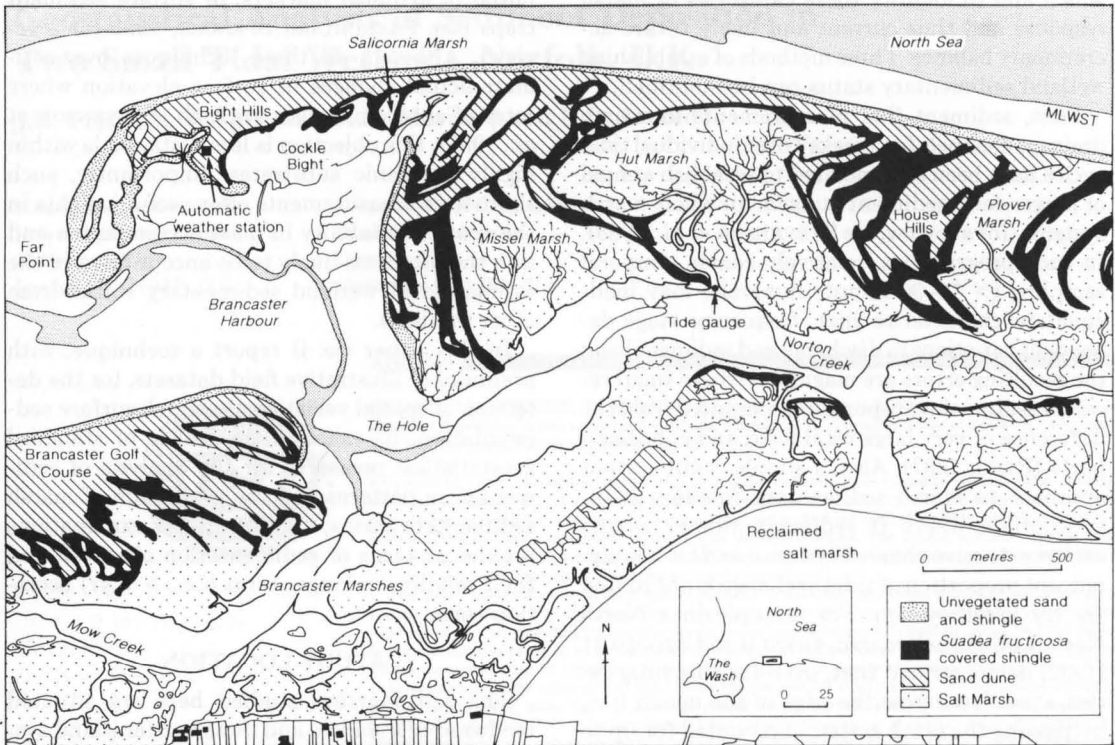
Figure 1.   Location of experimental marshes, Salicornia Marsh and Hut Marsh, at Scolt Head Island, North Norfolk and configuration of back-barrier environments.

time, relative sea-level rise is ca. 2 mm yr^{-1}, being comprised of 1 mm yr^{-1} regional subsidence (WOODWORTH, 1987; SHENNAN, 1989) and an estimated 0.9 mm yr^{-1} eustatic component (PIRAZZOLI, 1989). The marsh substrates are highly inorganic, with typical organic matter contents of 11–14.5% by weight (FRENCH and SPENCER, 1993). The source of the inorganic sediment has been assumed to be readily-erodible Quaternary cliffs, both locally, to the southeast, and to the north along the Yorkshire Holderness coast (see McCAVE, 1987).

Data presented in this paper come from two marshes located within the Scolt Head Island barrier island complex (Figure 1) (FRENCH *et al.,* 1990). As examples of marshes with 'near natural' vegetation, they are of conservation significance, particularly as they are internationally important sites for migratory birds in the winter months (SEAGO, 1989). Salicornia Marsh is a small (0.018 km²) marsh backed by the main shingle ridge of

the island and developed in the last 50 years between two low shingle spit recurvatures ('laterals') on the margin of a large intertidal mudflat, Cockle Bight. It has a single, central creek system. The marsh surface is at 2.5–2.6 m O.D. and is flooded by 370 tides a year (52% of all tides). To the east, Hut Marsh is ca. 0.54 km² in area and ca. 100 years old (ALLISON, 1985). Its northern margin is also enclosed by the main barrier spine and its eastern and western sides are flanked by high shingle/dune laterals which record earlier western limits to the island prior to its present extension. The western lateral is recurved towards the east and shelters the marsh except when overtopped on the highest spring tides. The marsh surface lies between 2.6 and 3.2 m O.D.; the mean height of 2.8 m is flooded by ca. 200 tides a year (27% of the total). Tidal exchange with Norton Creek and the Brancaster Harbour inlet is effected through two major creek systems.

On both marshes, low and intermediate sur-

faces are characterized by the marsh halophytes *Salicornia* spp., *Aster tripolium, Triglochin maritima, Spergularia marginata* and the grasses *Puccinellia maritima* and *Spartina anglica*. High marsh surfaces support a species-rich 'General Salt Marsh' community (after CHAPMAN, 1960) including *Limonium* spp. *Armeria maritima, T. maritima, S. marginata* and *P. maritima*. Woody bushes of *Suaeda fruticosa*, flooded on only high spring tides, characterise the shingle laterals and the northern margins of both marshes. Shrubby *Halimione portulacoides* typically fringes the creek networks of both marshes; in addition, on Salicornia Marsh it forms a band between *S. fruticosa* and the other salt marsh communities and on Hut Marsh it covers extensive areas of the central marsh.

RESEARCH DESIGN

Sedimentation Monitoring

Spatial patterns of marsh surface sedimentation were assessed over single tides (pm tide, 12 December 1992 at Salicornia Marsh; am tide, 10 February 1993 at Hut Marsh) using extensive deployments of surface-mounted sediment traps. At Salicornia Marsh, 150 traps were positioned randomly, whereas at Hut Marsh, 117 traps were placed randomly around a further 83 traps at the sites of buried medium sand marker horizons (organized as a series of intersecting transects). Since 1983, annual sampling of micro-cores from this last set of 83 sites has been used to infer rates and patterns of annual accretion; preliminary results reported by STODDART et al. (1989) have recently been extended by FRENCH and SPENCER (1993).

The sediment traps comprised pre-weighed glassfibre filter papers (4.7 cm diameter Whatman GF/C) placed on plastic petri dish lids (rim downwards). These were held flush with the marsh surface by small metal pins. Particular care was taken to minimize disturbance of the surrounding vegetation cover. Positions and heights of traps on both marshes were surveyed by electronic theodolite and engineer's level. Positions were converted to an island co-ordinate system (accuracy better than ± 0.5 m) and heights to O.D. via local benchmark networks (closure accuracy better than ± 0.01 m).

After recovery, filters were placed in Millipore holders, rinsed with distilled water (3 × 100 ml washes) to remove excess salt, dried at 35 °C and

re-weighed to 10^{-4} g precision. The Salicornia Marsh samples were ashed (400 °C for 3 hours) and re-weighed to permit the separation of total sedimentation into inorganic and organic fractions.

Meteorological data for both tidal cycles were obtained from an Automatic Weather Station sited at the Far Point of Scolt Head Island. Tidal data were recorded at 5 minute intervals from a permanently-mounted pressure transducer near the mouth of Hut Creek (Figure 1). In conjunction with the sedimentation study on Salicornia Marsh, additional measurements were made of local water level and creek flow velocities (synchronized 5 minute intervals) and within-creek suspended sediment samples (15 minute intervals).

Geostatistical Analysis

Sediment trap datasets were carefully screened to exclude measurements obviously influenced by contamination (for example, by large fragments of plant detritus). The spatial dependence of sedimentation rate was then investigated with reference to the theory of regionalized variables (CLARK, 1979; MATHERON, 1971; ISAAKS and SRIVASTAVA, 1989), which is finding increasing application within many areas of the earth sciences (see, for example, DAVIS, 1986; OLIVER, 1987). In common with many natural phenomena that have geographic distributions, sedimentation on wetland surfaces can be considered as a continuous variable but one which exhibits sufficient spatial complexity to render it intractable by a deterministic function. One of the basic measures of geostatistics is the semivariance, used to express the rate of change of a regionalized variable (*i.e.*, the spatial dependence between samples) along a specific orientation (DAVIS, 1986, p. 240). In the simple case of N uniformly spaced linear samples, the semivariance can be defined as

$$\gamma_h = \frac{1}{2(N - h)} \sum_{i=1}^{N-h} (X_i - X_{i+h})^2 \qquad (1)$$

where X_i is a measurement of the regionalized variable made at location i and X_{i+h} is another measurement made h intervals (or 'lags') away. If the semivariance is computed for different values of h, the results can be plotted in the form of a semivariogram. Equation 1 is readily modified for the more usual case of irregular sampling intervals, in which case the intervals are grouped into classes, and can also be extended to 2 and 3 di-

mensions (WEBSTER, 1985; OLIVER, 1987). When
the distance between sample points is zero, γ_h
should also be zero (points are being compared
with themselves). In practice the semivariogram
usually intercepts the ordinate at a positive value,
known as the 'nugget' variance. This is essentially
due to random variation and/or spatially depen-
dent variation over distances smaller than the
minimum sampling interval. When h is very small,
the points compared tend to be similar, resulting
in a low value of γ_h. As h is increased, γ_h increases,
up to a point (the 'range') where it approaches
the overall sample variance, σ^2 (termed the 'sill').
Here, the range defines a neighborhood within
which all samples are related to each other, and
outside of which, assuming the regionalized vari-
able is stationary (or has the sample average value
everywhere), samples are statistically indepen-
dent of the central point within the neighborhood
considered.

Estimated semivariograms can be approximat-
ed by fitted continuous functions (see below), and
as such, constitute an extremely useful tool for
the investigation of wetland sedimentation prob-
lems. First, they provide an indication of the spa-
tial scale of the dominant processes of particle
settling over wetland surfaces. Second, they pro-
vide a statistically optimal set of spatial weight-
ings that can be used in connection with kriging
techniques (DAVIS, 1986; ISAAKS and SRIVASTAVA,
1989) to estimate the rate of sedimentation at
unsampled locations. Kriging techniques can be
used to interpolate surfaces and contour maps
which can in turn yield improved estimates of
surface sediment budgets.

In this study, the UNIRAS 2000 package
(mounted on a DEC VaxStation) was used to es-
timate and model omnidirectional semivario-
grams (*i.e.,* considering all possible pairs of ran-
domly located sample points regardless of direction
and grouped into distance classes) prior to surface
fitting by 2-dimensional kriging. Surfaces were
then contoured to visualize the spatial variability
in sedimentation, and numerically integrated to
estimate the total mass of sediment introduced
to the wetland during the tides monitored. The
number and configuration of the 83 long-term ac-
cretion measurement sites did not permit a full
geostatistical analysis; instead a conventional
contouring algorithm (bilinear interpolation)
available within the UNIRAS package was used
to produce contours of mean annual accretion over
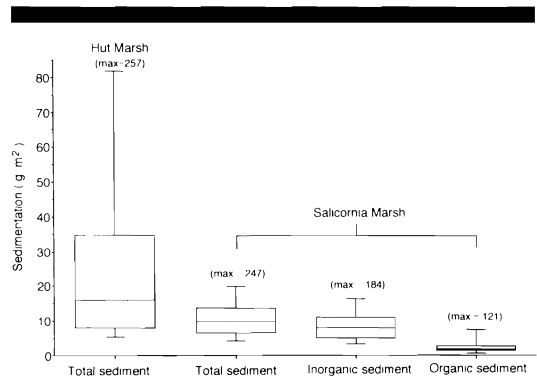the interval 1986–1991.

Figure 2. Schematic "box-whisker" plots of sedimentation da-
taset by site, date and sediment type (all plots refer to g dry
weight m^{-2}). The 'whiskers' show the 10 and 90th percentiles
of each distribution, whilst the boxes represent the 25th, 50th
and 75th percentiles. No breakdown into inorganic and organic
fractions was performed for the Hut Marsh samples.

RESULTS

Exploratory Data Analysis

Hut Marsh

Data for five sites had to be excluded due to
obvious contamination, leaving a total of 195 sam-
ples. The distribution of sedimentation amounts
(all reduced to g dry weight m^{-2}) is summarized
by boxplots in Figure 2. Note that sedimentation
amount varies over 2 orders of magnitude, from
2 to 250 g m^{-2}. The distribution is highly skewed
($\beta_1 = 4.43$), indicating that the arithmetic mean
is likely to be a poor estimator. Figure 3a shows
the same data plotted against sitè elevation. Al-
though the variance in sedimentation is higher at
low elevations, the relationship with elevation is
much weaker than previously reported for annual
accretion (FRENCH and SPENCER, 1993; see also
Figure 3c)—indeed the largest sedimentation val-
ues occur within the middle of the elevation range.
This is consistent with our earlier findings that
factors associated with the supply of sediment
from the creeks override local topographic con-
trols at the timescale of single inundations
(STODDART *et al.,* 1989; FRENCH and SPENCER,
1993).

Salicornia Marsh

Of the traps deployed on Salicornia Marsh, 147
yielded apparently reliable estimates of sedimen-
tation, with a range similar to Hut Marsh. Again,
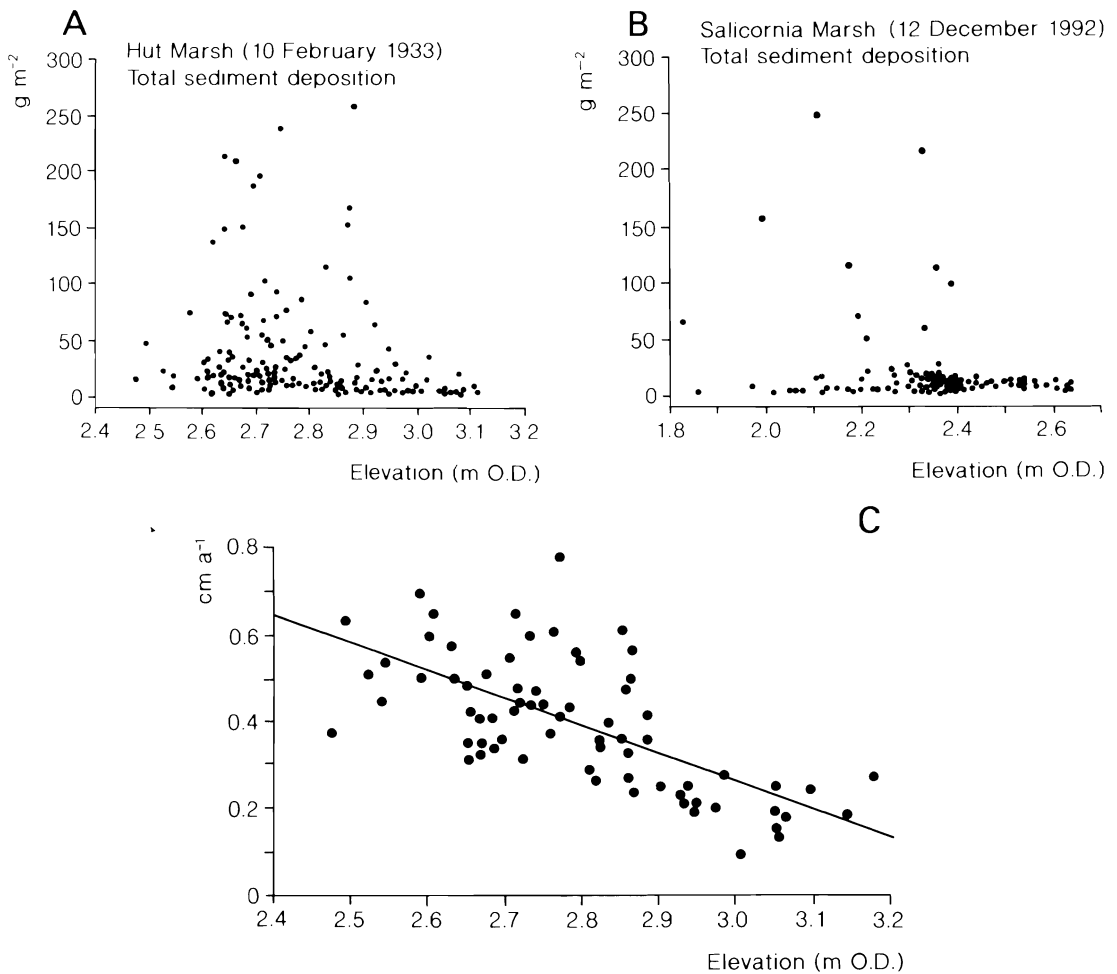there was no discernible relationship between to-

Figure 3. Total sediment trap deposition (g dry weight m $^{-2}$) plotted against elevation (m O.D.). (a) Hut Marsh, 10 February 1993. (b) Salicornia Marsh, 12 December 1992. (c) Hut Marsh, five year mean annual accretion (1986–1991; mm yr $^{-1}$). Regression equation: $y = 2.17 - 0.635x$; $r^2 = 0.45$.

tal sedimentation and elevation, although the highest sedimentation amounts tended to lie within the middle elevation range (Figure 3b). The distributions of total, inorganic and organic sedimentation amount were all highly skewed (Figure 2; $\beta_1 = 4.97$, 5.71 and 5.80 respectively).

Geostatistical Analysis

Figure 4a shows the omnidirectional semivariogram for the Hut Marsh total sedimentation samples (solid circles), plotted for lags up to half the maximum distance between samples (confidence limits increase rapidly as the lag increases). The form of semivariogram is indicative of reasonable continuity between samples, with only a small 'nugget' variance, σ^2_0. The minimum sampling interval was about 8 m. The range of 200 m is consistent with earlier observations of rapid particle settling in the vicinity of the major creeks, such that sedimentation declines towards a negligible rate at between 100 and 250 m from a source creek (FRENCH and SPENCER, 1993).

For interpolation and contouring purposes the experimental semivariogram needs to be approximated by a suitable model. Whilst the type of model required can provide additional insights into the underlying process (OLIVER and WEBSTER, 1986), the models used here were selected purely
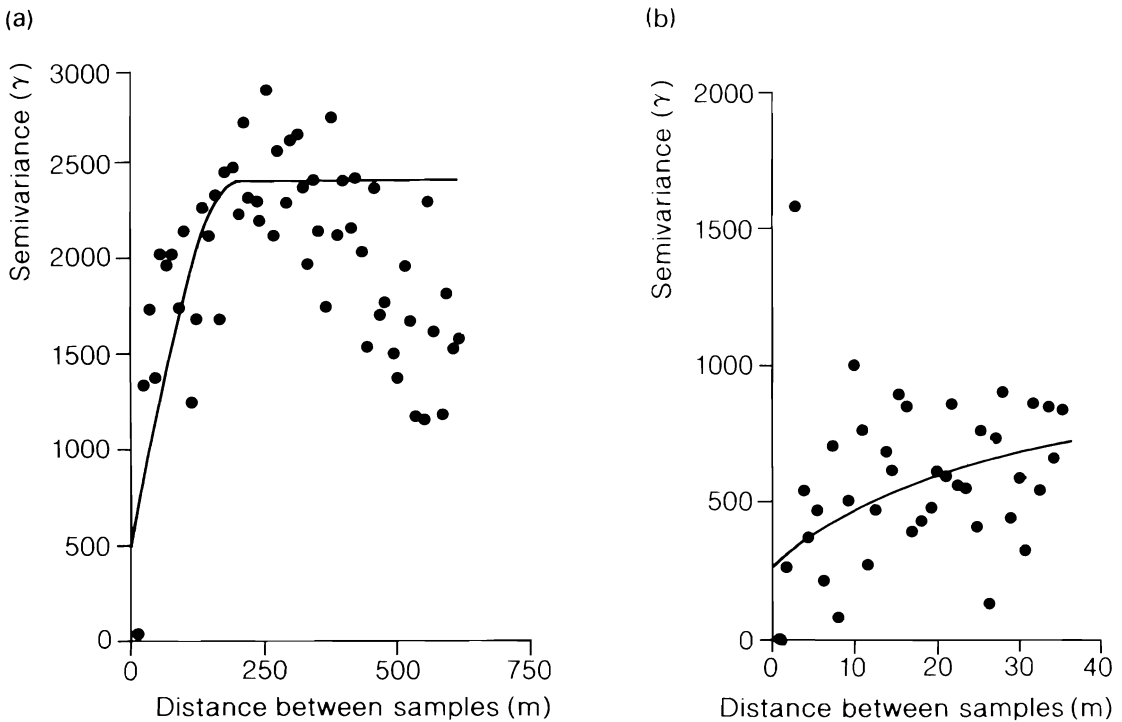
(a)

(b)

Figure 4. Omnidirectional semivariogram plotted for lags up to half maximum distance between samples. (a) Hut Marsh, 10 February 1993, fitted with a spherical model (see text for details). (b) Salicornia Marsh, 12 December 1992, fitted with an exponential model (see text for details).

on the basis of simplicity and goodness of fit. For Hut Marsh, a spherical model was used. This is defined as:

$$\gamma_h = \sigma^2_0 + \sigma^2\left(\frac{3h}{2a} - \frac{h^3}{2a^3}\right) \quad \text{for } 0 < h \leq a \quad (2)$$

$$\gamma_h = \sigma^2_0 + \sigma^2 \quad \text{for } h > a$$

where a is the range and $\sigma^2_0 + \sigma^2$ defines the sill. Note that the fitted model (solid line in Figure 4a) incorporates a larger (though still relatively small) nugget variance, largely due to the low statistical weight assigned to the very few pairs of closely spaced samples.

The experimental semivariogram for the Salicornia Marsh data is 'noisier' than that for Hut Marsh (Figure 4b). Again, the 'nugget' variance is small. Interestingly, the range is reduced to approximately 20 m (the maximum spacing between samples was about 80 m). For contouring purposes, an exponential model was used, of the form

$$\gamma h = \sigma^2_0 + \sigma^2(1 - e^{-h/r}) \quad \text{for } h > 0 \quad (3)$$

where the fitted distance parameter, r, =a/3 and can be considered to represent an 'effective range (see, for example, OLIVER and WEBSTER, 1986).

Contours of sedimentation, produced by 2-dimensional kriging using interpolation weights given by the fitted models are presented in Figure 5. The pattern for Hut Marsh (Figure 5a) is more spatially 'coherent'. The highest sedimentation rates are adjacent to the two major creek systems (see Figure 1), and the lowest are in mid- and back-marsh areas most remote from lateral or apical suspended sediment discharge from the creeks. Spatial variation in sedimentation in Salicornia Marsh (Figure 5b) is more disorganized, although a large area of rapid sedimentation in the centre of the marsh can be attributed to both lateral and apical inundation around the actively eroding head of the main creek. This creek system is 'drowned' out much earlier during the tidal cycle than the better-developed creeks of Hut Marsh. Separa-
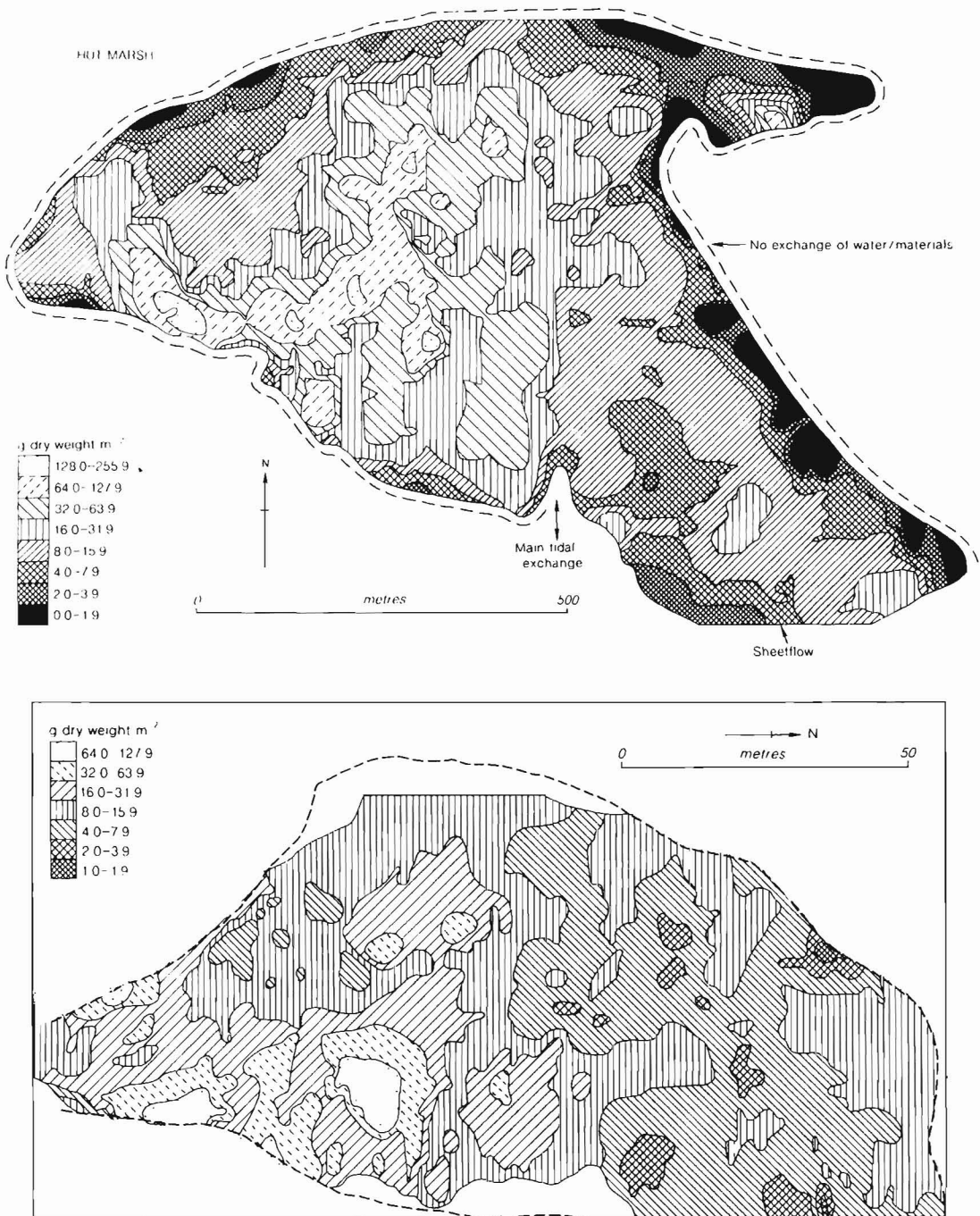
Figure 5. Single tide sedimentation plots produced by 2-D kriging (from sediment trap data). (a) Total sediment deposition (g dry weight m⁻²) at Hut Marsh, 10 February 1993. Broken line represents marsh perimeter where enclosed by dunes or shingle ridges which prevent tidal exchange. (b) Total sediment deposition (g dry weight m⁻²) at Salicornia Marsh, 12 December 1992. Broken line represents perimeter of marsh as defined by the zone of *Suaeda fruticosa*. Some areas along this margin were not sampled in the trap deployments. (c) Inorganic sediment fraction (g dry weight m⁻²) at Salicornia Marsh, 12 December 1992. (d) Organic sediment fraction (g dry weight m⁻²) at Salicornia Marsh, 12 December 1992.
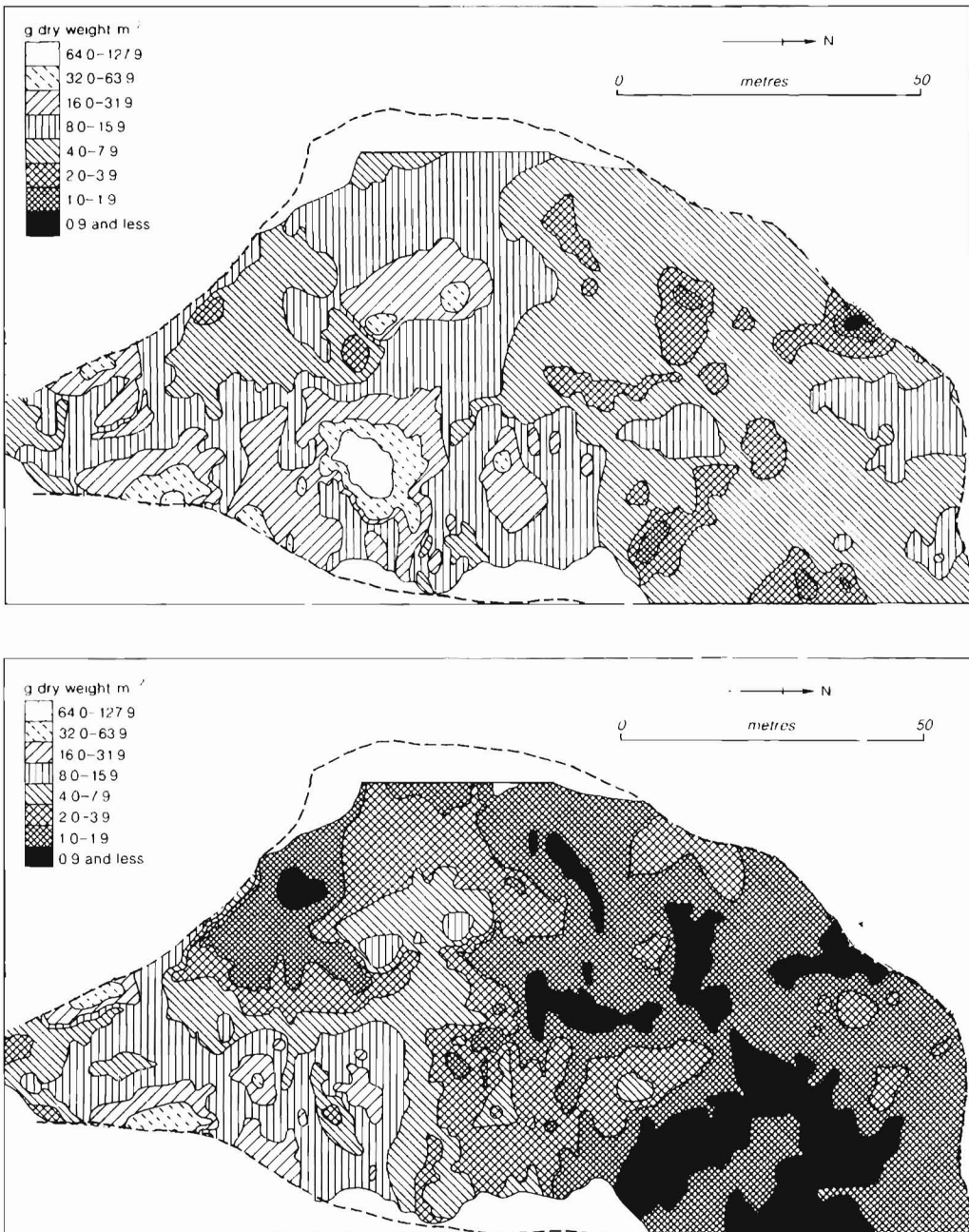
Figure 5.   Continued.

tion of inorganic and organic fractions (Figure 5c
and d) reveals contrasting patterns of deposition.
Inorganics dominate overall deposition and are
more clearly related to a single ill-defined creek
system that runs up the centre of the marsh. The
pattern of organic accumulation is greatly influ-
enced by a large influx of detritus off the tidal flat
(Cockle Bight in Figure 1) onto the lower marsh.

Table 1. *Summary of sediment flux calculations using different methods.*

a) Hut Marsh

February 10, 1993; tidal height = 3.4 m O.D.

Method	Total sedimentation (tonnes dry weight)
2-D kriging	11.6
2-D bilinear interpolation	12.0
Areal extrapolation of arithmetic mean	17.5

1986–1991 annual average (after French & Spencer, 1993)

Method	Total sedimentation (tonnes dry weight) assuming dry bulk density of 500 kg m^{-3}
2-D bilinear interpolation	747 tonnes yr^{-1} (200 inundations yr^{-1})
'Expected' single tide flux	$\frac{747}{200} = 3.7$ tonnes

b) Salicornia Marsh

December 12, 1992; tidal height = 3.3 m O.D.

	Sedimentation (tonnes dry weight)			%
Method	Total	Inorganic	Organic	Inorganic
2-D kriging	0.148	0.103	0.045	69.6
2-D bilinear interpolation	0.139		—	—
Areal extrapolation of arithmetic mean	0.312	0.221	0.092	70.8
Net flux via creek gauging	0.237	0.200	0.037	84.4

Table 2. *Summary of creek flux measurements for Salicornia Marsh, December 12, 1992. TSS = total sediment deposition; ISS = inorganic sediment deposition; OSS = organic sediment deposition. All measurements in tonnes dry weight.*

	Flood	Ebb	Residual
TSS	0.4579	0.2205	0.2374
ISS	0.4054	0.2048	0.2006
OSS	0.0525	0.0158	0.0367
%ISS	88.5%	92.9%	84.5%

Sediment Flux

Hut Marsh

Table 1a presents the results of mass flux computations using the following procedures: i) 2-dimensional kriging; ii) 2-dimensional contour interpolation using 'conventional' bilinear interpolation; and iii) crude areal extrapolation of the arithmetic mean sedimentation rate. All yield slight over-estimates of the true flux since the averaging incorporates the area occupied by creeks (about 5% of total area). If one accepts that methods i) and ii) are likely to produce the best available estimates, then the crude arithmetic averaging is seen to over-estimate the total sediment input by 45–50%. Interestingly, there is little difference between the estimates obtained by kriging and conventional bilinear interpolation, despite differences in the detail of spatial variation picked out by these methods. The best estimate of 11.6 tonnes is greater than the 'expected' flux of approximately 3.7 tonnes calculated from the previously published annual sediment input of 747 tonnes over 200 tidal cycles (see Table 1a). This is not unexpected since many tides inundating the marsh achieve a much shallower depth and, notably in the summer months, introduce much less sediment (FRENCH and STODDART, 1992; FRENCH and SPENCER, 1993).

Salicornia Marsh

Table 1b summarizes the results of mass flux computations for Salicornia Marsh. These were performed in the same manner as those for Hut Marsh, with the addition of the net sediment flux estimated from discharge and suspended sediment gauging at the mouth of the creek system. As before, numerical integration of surfaces produced by kriging or bilinear interpolation yields similar estimates that are much lower than that predicted from extrapolation of the arithmetic mean rate—which in this case over-estimates total sedimentation by 110%. Inorganic sediments dominate the overall mass deposition, accounting for between 62 and 71% of the total. These results contrast markedly with those from creek gauging, which indicates a much larger import of inorganic material than can be accounted for by reference to measured surface deposition. A more detailed breakdown of the creek gauging results is given in Table 2, which shows that the discharge closure between flood and ebb transports was extremely good (a small residual water import of only 5.3% of the total flood transport). The large discrepancy between the creek gauging and the marsh surface trap estimates of inorganic sedimentation illustrates the practical problems in using creek residual transports to infer wetland sedimentary status. Here, a large proportion of inorganic sediment imported via the creek system apparently never reaches the marsh surface. In contrast, the residual flux of the more readily transported organic fraction is more accurately represented by the creek measurements.
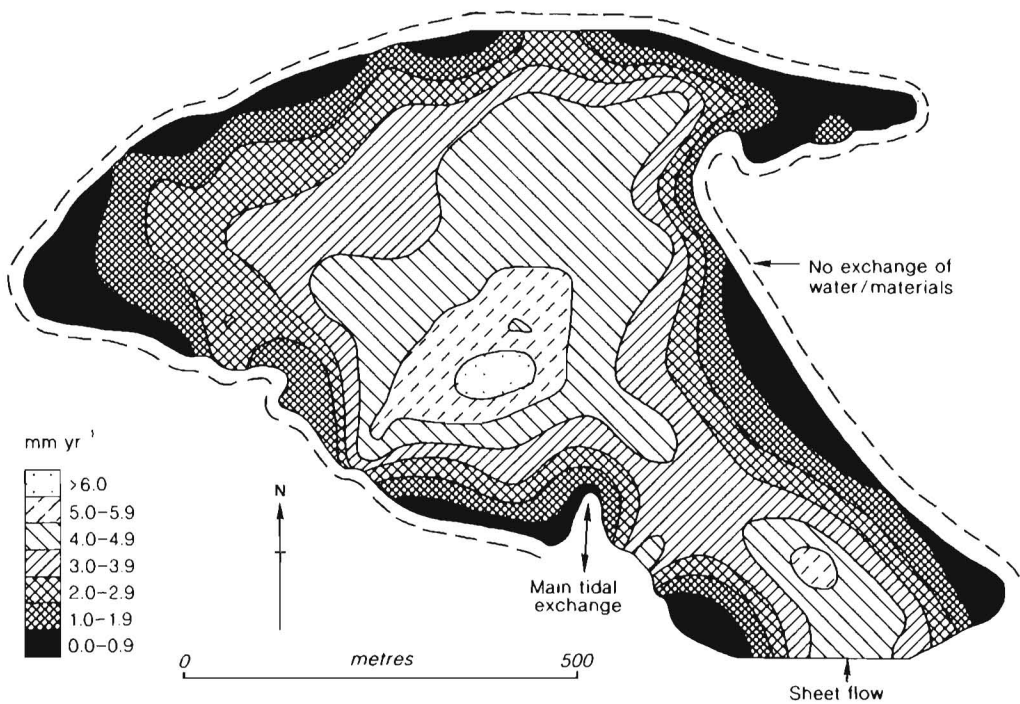
Figure 6.   Five year mean accretion (1986–1991; mm yr⁻¹) at Hut Marsh by conventional bi-linear interpolation procedures (after FRENCH and SPENCER, 1993).

DISCUSSION AND CONCLUSIONS

Mean annual accretion rates for Hut Marsh have been reported by STODDART *et al.* (1989) and FRENCH and SPENCER (1993). Rates vary from approximately 1 mm yr^{-1} in areas of high marsh close to the barrier to almost 8 mm yr⁻¹ in the central area of the marsh where the density of large channels is high (Figure 6). FRENCH and SPENCER (1993) also showed that controls on sedimentation are strongly scale-dependent. There is a negative relationship between accretion and elevation at a marsh-wide scale (several hundreds of metres) but this correlation is reversed at the local scale (tens of metres) where proximity to the creeks control sedimentation, to the extent that it completely overrides the effects of local 'microtopography'. Such local patterns suggest the rapid removal of suspended particulates advected or diffusing across channel margins. Detailed field measurements at this site have shown that although creek suspended sediment concentrations may be as high as 1,000 mg l^{-1}, concentrations are typically in the range 50–150 mg l⁻¹ over immediately

adjacent marsh surfaces, declining to 10–20 mg l⁻¹ at more remote 'interior' locations.

Electron microscopy of suspended particulates from creeks and their margins (FRENCH *et al.*, 1993) indicate an abundance of composite particles which clearly settle more rapidly than their primary constituents. The composites vary from simple clay particle aggregations a few microns in size to complex structures, often bound by organic compounds, up to 1,000 μm in maximum projected diameter. Rapid settling of composites, once transported away from the relatively high intensity creek flows, leads to the superimposition of a single-tide pattern in sedimentation on the larger scale and longer-term patterns of accretion revealed by the marker horizon studies. In the latter case, variability in sedimentation is strongly controlled by elevation-dependent changes in inundation frequency.

Vegetation characteristics (as measured by above-ground biomass) and 'background' suspended sediment concentrations varied little between the December and February sediment trap deployments, and both occasions were character-

ized by calm sea conditions (hourly mean wind-speeds < 25 km hr^{-1}) and no precipitation. Thus, although more comprehensive temporal sampling is required to fully document the interaction of sedimentation with the full range of ecological and environmental forcing effects, these instrumented tides provide an important insight into the processes associated with normal tidal flooding events. Extremely few studies have monitored the sedimentation processes associated with specific tidal cycles (e.g., STUMPF, 1983; FRENCH and SPENCER, 1993). The analysis presented here clearly supports the hypothesis that progressive particle settling along pathways of water movement (possibly aided by diffusion along lateral concentration gradients) imparts a spatially coherent pattern of sedimentation on the marsh surface that contrasts with the more uniform pattern of sedimentation implied by references to 'slack water settling' (e.g., FREY and BASAN, 1985).

Mechanisms of sedimentation are usefully investigated by reference to estimated semivariograms. Whilst these are often used purely as a necessary stage in the process of contour interpolation by kriging, they are valuable in their own right as a guide to the spatial scales at which sedimentation arises. The semivariograms obtained here reveal strongly coherent variability at scales which can be be readily associated with the introduction of rapidly settling particulates during creek overtopping. Of particular interest are the contrasts between semivariograms obtained from the two marsh sites. At the early stages of marsh growth, shortly after the establishment of continuous halophytic cover, Norfolk salt marshes are characterized by shallow channels and broad concave interfluves. Over time, marsh surfaces and creek floors become increasingly differentiated and 'old' marshes exhibit flat or even slightly convex surfaces associated with the development of creek margin levees (FRENCH et al., 1990; FRENCH and STODDART, 1992). The semivariograms (Figure 4) indicate more coherent spatial variability over a larger spatial distance, or range using semivariogram terminology, on older surfaces (Hut Marsh) compared with the much 'noisier' short-range coherence on the younger Salicornia Marsh. It is also interesting that the 'nugget effect' is relatively small, even in the modeled semivariograms. This suggests that physical processes associated with water movement play a greater role in determining spatial patterns of sediment input (and

landform development) than very localized vegetational influences.

Crude arithmetic averages poorly approximate 'true' areally-averaged rates of sedimentation, because the distributions of point sedimentation (or vertical accretion) are highly skewed. When informed by weightings based upon modeled semivariograms, kriging techniques result in statistically optimal contour interpolations that can be used to produce more accurate estimates of total sediment input. Table 1 clearly shows that the arithmetic mean of even a large number of point measurements yields a gross overestimate of the areally-averaged rate. By extension, comparison of similarly averaged vertical accretion with local relative sea-level rise will invite misleading conclusions concerning marsh 'sedimentary status'. More accurate mass fluxes, whether obtained from short-term sediment trap deployments as here, or from densely-spaced marker horizons or sediment cores, would permit testing of the hypothesis that sediment volumes are conserved on marshes experiencing fringe erosion and rapid surface accretion (see, for example PHILLIPS, 1986; REED, 1988). Encouragingly in this instance, conventional computer interpolation algorithms (which are more widely available than kriging packages) yield results very close to those obtained by kriging techniques; however, this may not be true for all possible types of spatial variability in sedimentation, and the estimation and modeling of the semivariogram itself provides important insights into the phenomenon under study.

Extensions of these types of analysis should assist with predictions as to how marsh surfaces might be rejuvenated by changes in tidal flooding on potential future sea-level rise. As topographic changes are accompanied by changes in the distribution of salt marsh vegetation communities, an understanding of sedimentation processes and their spatial variability will have wider conservation and management significance.

ACKNOWLEDGEMENTS

LITERATURE CITED

ALLEN, J.R.L., 1990. Salt-marsh growth and stratification: A numerical model with special reference to the Severn Estuary, southwest Britain. *Marine Geology,* 95, 77–96.

ALLISON, H.M., 1985. The Holocene Evolution of Scolt Head Island. Unpubl. Ph.D. Thesis, University of Cambridge.

CHAPMAN, V.J., 1960. *Salt Marshes and Salt Deserts of the World.* London: Hill, pp. ??

CLARK, I., 1979. *Practical Geostatistics.* London: Applied Science Publishers.

CLARK, J.A.; FARRELL, W.E., and PELTIER, W.R., 1978. Global changes in post-glacial sea level: A numerical calculation. *Quaternary Research,* 9, 265–287.

DAVIS, J.C., 1986. *Statistics and Data Analysis in Geology.* 2nd ed. New York: Wiley.

DELAUNE, R.D.; PATRICK, W.H., and SMITH, C.J., 1992. Marsh aggradation and sediment redistribution along rapidly submerging Louisiana Gulf Coast. *Environmental Geology and Water Science,* 20, 57–64.

FRENCH, J.R., 1991. Eustatic and netectonic controls on salt marsh sedimentation. *In:* KRAUS, N.C.; GINGERICH, K.J., and KRIEBEL, D.L. (eds.), *Coastal Sediments '91,* New York: American Society of Engineers, pp. 1223–1236.

FRENCH, J.R., 1993. Numerical simulation of vertical marsh growth and adjustment to accelerated sea-level rise, North Norfolk, UK. *Earth Surface Processes and Landforms,* 18, 63–81.

FRENCH, J.R.; CLIFFORD, N.J., and SPENCER, T., 1993. High frequency flow and suspended sediment measurements in a tidal wetland channel. *In:* CLIFFORD, N.J.; FRENCH, J.R., and HARDISTY, J. (eds.), *Turbulence: Perspectives on Flow and Sediment Transport.* Chichester: Wiley, pp. 249–277.

FRENCH, J.R. and SPENCER, T., 1993. Dynamics of sedimentation in a tide-dominated backbarrier salt marsh, Norfolk, UK. *Marine Geology,* 111, 315–331.

FRENCH, J.R.; SPENCER, T., and STODDART, D.R., 1990. Backbarrier marshes of the north Norfolk coast: Geomorphic development and response to rising sea levels. *University College London Discussion Papers in Conservation* 54. 35p.

FRENCH, J.R. and STODDART, D.R., 1992. Hydrodynamics of saltmarsh creek systems: Implications for marsh morphological development and material exchange. *Earth Surface Processes and Landforms,* 17, 235–252.

FREY, R.W. and BASAN, P.B., 1985. Coastal salt marshes. *In:* DAVIS, R.A. (ed.), *Coastal Sedimentary Environments.* New York: Springer, 2nd ed., pp. 225–301.

FUNNELL, B.M. and PEARSON, I., 1989. Holocene sedimentation on the north Norfolk barrier coast in relation to relative sea-level change. *Journal of Quaternary Science,* 4, 25–36.

HARMSWORTH, G.C. and LONG, S.P., 1986. An assessment of saltmarsh erosion in Essex, England, with reference to the Dengie Peninsula. *Biological Conservation,* 35, 377–387.

HYDROGRAPHIC OFFICE, 1992. *Tide Tables, Vol. 1: European Waters.* Taunton: Hydrographer of the Navy.

ISAAKS, E.H. and SRIVASTAVA, R.M., 1989. *An Introduction to Applied Geostatistics.* Oxford: Oxford University Press.

McCAVE, I.N., 1987. Fine sediment sources and sinks around the East Anglian coast, UK. *Journal of the Geological Society of London,* 144, 149–152.

MATHERON, G., 1971. *The Theory of regionalized Variables and its Applications.* Fontainebleau: Cahiers du Centre de Morphologie Mathématique Number 1.

OLIVER, M.A., 1987. Geostatistics and its application to soil science. *Soil Use and Management,* 3, 8–20.

OLIVER, M.A. and WEBSTER, R. 1986. Semi-variograms for modeling the spatial pattern of landform and soil properties. *Earth Surface Processes and Landforms,* 11, 491–504.

PETHICK, J.S., 1980. Salt marsh initiation during the Holocene transgression: The example of the north Norfolk marshes. *Journal of Biogeography,* 7, 1–9.

PETHICK, J.S., 1981. Long-term accretion rates on tidal marshes. *Journal of Sedimentary Petrology,* 61, 571–577.

PHILLIPS, J.D., 1986. Coastal submergence and marsh fringe erosion. *Journal of Coastal Research,* 2, 427–436.

PIRAZZOLI, P.A., 1989. Present and near-future global sea-level changes. *Palaeogeography, Palaeoclimatology, Palaeoecology,* 75, 241–258.

REED, D.J., 1987. Temporal sampling and discharge asymmetry in salt marsh creeks. *Estuarine and Coastal Shelf Science,* 25, 459–466.

REED, D.J., 1988. Sediment dynamics and deposition in a retreating coastal salt marsh. *Estuarine Coastal and Shelf Science,* 26, 67–79.

SEAGO, M.J., 1989. Birds of Blakeney Point and Scolt Head Island. *In:* ALLISON, H. and MORLEY, J. (eds.), *Blakeney Point and Scolt Head Island.* Norfolk: National Trust, pp. 87–108.

SHENNAN, I., 1989. Holocene crustal movements and sea-level changes in Great Britain. *Journal of Quaternary Science,* 4, 77–89.

STEVENSON, J.C.; WARD, L.G., and KEARNEY, M.S., 1986. Vertical accretion in marshes with varying rates of sea level rise. *In:* WOLFE, D.A. (ed.), *Estuarine Variability.* Orlando: Academic Press, pp. 241–260.

STEVENSON, J.C.; WARD, L.G., and KEARNEY, M.S., 1988. Sediment transport and trapping in salt marsh systems: Implications of tidal flux studies. *Marine Geology,* 80, 37–59.

STODDART, D.R.; REED, D.J., and FRENCH, J.R., 1989. Understanding salt marsh accretion, Scolt Head Island, Norfolk, England. *Estuaries,* 12, 228–236.

STUMPF, R.P., 1983. The process of sedimentation on the surface of a salt marsh. *Estuarine Coastal and Shelf Science,* 17, 495–508.

TEMPLET, P.H. and MEYER-ARENDT, K.J., 1988. Loui-

siana wetland loss: Regional water management approach to the problem. *Environmental Management,* 12, 181–192.

WALKER, H.J.; COLEMAN, J.M.; ROBERTS, H.H., and TYE, R.S., 1987. Wetland loss in Louisiana. *Geografiska Annaler,* 69A, 189–200.

WEBSTER, R., 1985. Quantitative spatial analysis of soil in the field. *Advances in Soil Science,* 3, 1–70.

WOODWORTH, P.L., 1987. Trends in UK mean sea level. *Marine Geodesy,* 11, 57–87.

WOODWORTH, P.L.; SHAW, S.M., and BLACKMAN, D.I., 1991. Secular trends in mean tidal range around the British Isles and along the adjacent European coastline. *Geophysical Journal International,* 104, 593–609.