
Yates, M. G.; Goss-Custard, J. D.. 1997 The development of a correlative approach relating bird distribution and remotely sensed sediment distribution to predict the consequences to shorebirds of habitat change and loss. In: Goss-Custard, J. D.; Rufino, R.; Luis, A., (eds.) *Effect of habitat loss and change on waterbirds.* London, The Stationery Office, 138-144, 144pp. (ITE Symposium, 30).

The development of a correlative approach relating bird distribution and remotely sensed sediment distribution to predict the consequences to shorebirds of habitat change and loss

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SUMMARY
The development of a model to predict the consequences to shorebirds (Charadrii) of habitat change and loss is described and discussed. The approach was based on two correlative relationships. The first related the distribution of shorebirds on their intertidal feeding areas to that of the sediments. The second related sediment distribution to those physical features of the estuary, such as shore width, which are directly influenced by natural or man-made change. In both relationships, the sediment distribution was determined by classifying remotely sensed images of the intertidal area.

INTRODUCTION

Each autumn, winter and spring, internationally important numbers of shorebirds (Charadrii) are dependent for their survival on the intertidal areas of Britain's estuaries where they feed on the benthic invertebrates. This paper describes and discusses the development of a methodology for predicting the numbers of shorebirds that would be affected by the change or loss of those intertidal feeding areas.

The study described here tested whether, in principle, it is possible to predict changes in bird numbers from physical features of intertidal areas, any change in which is usually predictable after habitat is lost or changed. First, the constancy of the bird's intertidal feeding areas between seasons and years was established, because it would be more difficult to devise a predictive methodology without some degree of constancy. Next, having tested the efficacy of using satellite images to map and quantify the distribution of intertidal surface sediments, the study then established that bird distribution in an area was related to the intertidal sediments. In turn, the sediments themselves could be related to physical features of the intertidal area so any change in those features had predictable consequences for the bird through their influence on the sediments.

THE FORM AND BIOLOGICAL BASIS OF THE METHODOLOGY

In the initial stages of its development, the aim of our work was to predict the consequence of change in a single physical variable, the shore width of intertidal areas of the Wash, east England, brought about by saltmarsh reclamation (Goss-Custard & Yates 1992). Ideally, this prediction would have been done using a dynamic approach in which the functional relationship for each of the links in the following causal chain would have been determined:

Shore width $\rightarrow$ sediment characteristics (particle size distribution and shore profile) $\rightarrow$ invertebrate densities $\rightarrow$ bird densities

The quantitative relationships between sediment characteristics, invertebrate densities and bird densities can be determined by field studies (Bryant 1979; Yates *et al.* 1993a). However, their use in predicting to the post-reclamation situation is problematical because the effects of shore

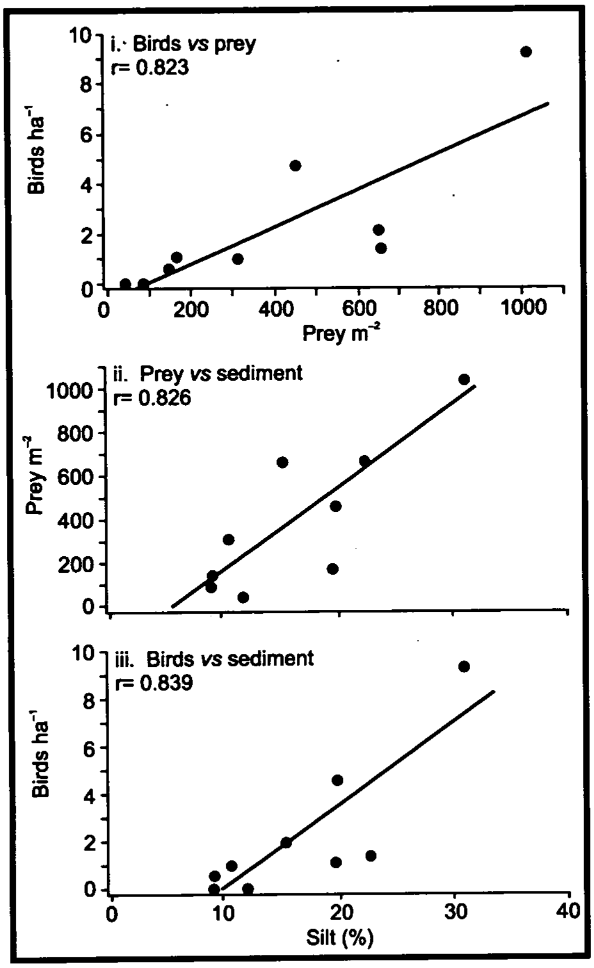

Figure 1. Relationships between (i) knot (*Calidris canutus*) density and that of its prey *Macoma baltbica*, (ii) *Macoma* density and the proportion of silt in the sediment, and (iii) knot density and the proportion of silt in the south-east shore of the Wash (source: Yates *et al.* 1993a)

width on the sediments' particle size distribution and on the shore profile are difficult to predict in sufficient detail for them to be used in predicting invertebrate densities. Instead, the approach we developed used a correlative model that simply relates bird distribution directly to sediments:

Shore width → broad sediment characteristics (mud, sand) → bird numbers

The biological basis for this model had been established in the Wash for a number of shorebird species (Yates *et al.* 1993a) and elsewhere for dunlin (*Calidris alpina*) (Clark *et al.* 1993). It arises because the distribution of birds on their intertidal feeding areas is related to that of their invertebrate prey, which, in turn, is related to the particle size distribution of the sediments. It follows, then, that bird distribution will also be related to the sediment type in which their prey occurs. Figure 1 illustrates these relationships for knot (*Calidris canutus*), feeding on the Baltic tellin (*Macoma balthica*) on the south-east shore of the Wash.

CONSTANCY IN BIRD DISTRIBUTION

Clearly, it would be difficult to devise a predictive methodology without there being some degree of constancy in the distribution of feeding birds, both between season and year. To assess constancy of distribution, comparisons were made of the numbers of birds feeding in 59 one km broad transects between three seasons – autumn, winter and spring – and over four years. These showed that, in both timescales, bird distribution remained similar. Curlew (*Numenius arquata*), bar-tailed godwit (*Limosa lapponica*), oystercatcher (*Haematopus ostralegus*) and shelduck (*Tadorna tadorna*) showed the highest seasonal similarity in distribution (Goss-Custard & Yates 1992), while grey plover (*Pluvialis squartarola*) and curlew the highest similarity between years (Yates *et al.* 1996b). The distribution of knot was the least constant.

USING REMOTE SENSING TO MAP INTERTIDAL SEDIMENTS

The basic data requirement for the modelling approach was a measure of the distribution of the broad sediment categories, sand and mud, over the entire intertidal area. Mapping sediments by conventional methods needs extensive sampling programmes that are costly in time and labour and can pose problems of access and safety because of the nature and size of many intertidal areas. Furthermore, even with extensive sampling, there is always a source of error involved in extrapolating from sample sites to the whole area. Remote sensing from either aircraft or satellite provides synoptic coverage of large areas, alleviating the problems of safety and access. Image analysis techniques also allow accurate extrapolation from a few carefully selected ground observations to the whole area, provided the surface types to be mapped are spectrally separable. Muddy and sandy sediments are separable because of their surface features. Typically, the large, sandy mid-shore areas retain a film of surface water, some 1–2 cm deep, at low tide, while muddy sediments, though less

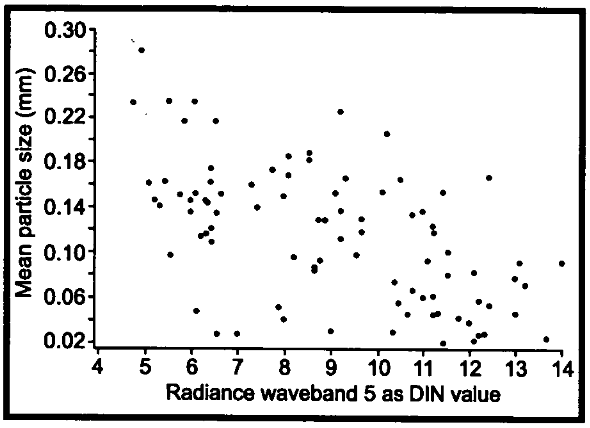

Figure 2. The relationship between the mean particle size of sediments in 192 samples sites in the Wash and the radiance, expressed as a DIN value, of middle-infra-red (Landsat thematic mapper band 5) from the sediment's surface (correlation coefficient, r=–0.552, P<0.0001). Decreasing radiance indicates increasing particle size, ie sandier sediments

permeable to water, tend to be uneven or elevated and less likely to retain water on their surface. This factor allows the two to be separated because the remote sensing instruments detect (i) visible and near- and (ii) middle-infra-red parts of the spectrum. Infra-red is absorbed by water so the presence of surface water on sandy sediments, and its absence from muddy sediments, means the two are separable by their difference in infra-red reflectance (Figure 2) (Yates *et al.* 1993b). In addition, muddy sediments tend to have higher densities of diatoms and algae on their surface than do sandy sediments. During

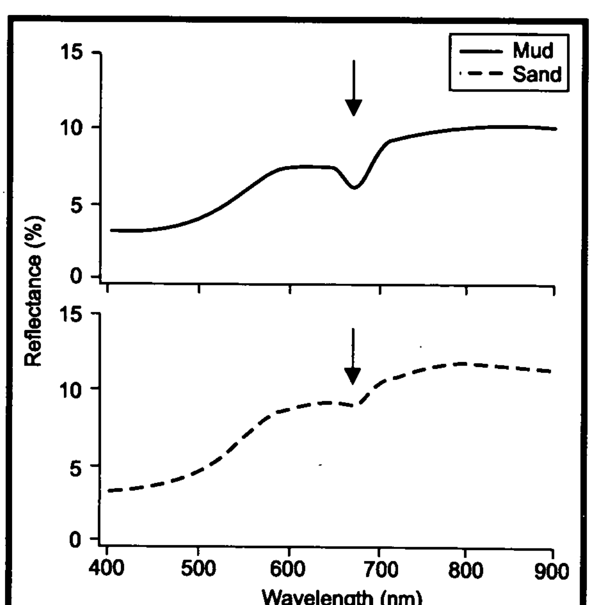

Figure 3. The spectral reflectance from muddy and sandy sediments. Note the reduced reflectance of red light at 670 nm (arrowed) that is due to the presence of higher densities of algae and diatoms on the surface of muddy sediment

photosynthesis, these organisms absorb visible red light. Consequently, muddy sediments are also separable from sandy ones on the basis of their greater absorption of red light (Figure 3).

Sediment distribution of the Wash was mapped by analysing a Landsat 5 remotely sensed image, taken at low tide when the whole intertidal area was exposed. The accuracy of the map was verified by comparison with ground observation data from 192 sample sites: 83% of muddy and 70% of sandy sites were correctly mapped (Yates *et al.* 1993b). This accuracy was considered to be very good compared with any other source of sediment distribution data. However, for further verification, the biological efficacy of the image-derived sediment data was also explored by testing whether the derived data could be substituted for ground-based observations to predict the density of the birds' invertebrate prey.

We had already determined equations that related ground-based sediment data, in addition to other environmental variables such as tidal inundation time, to prey density in 192 sample sites. So we were able to compare equations using sediment values obtained by ground observations with those using image-derived sediment values. This comparison showed that equations in which image-derived sediment values had been used explained the variation in invertebrate density almost as well as those using ground observations (Figure 4). In fact, in some instances, image-derived values improved the explanatory power of the equation (Yates *et al.* 1993c).

THE 'SHORE WIDTH AND SEDIMENT' MODEL

Having established the accuracy of image-derived measures of sediment distribution, the relationships between bird numbers feeding in an area and the sediments in that area, and between the sediments and the width of the shore were formulated by regression analysis. In the 'shore width' model developed for the Wash, the unit areas were contiguous, one km broad transects aligned perpendicular to the high water mark. The length of these transects was, of course, determined by the width of the shore.

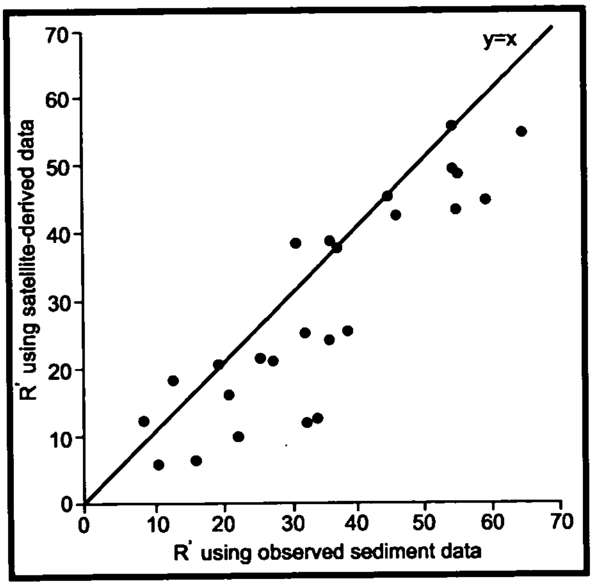

Figure 4. The percentage of the variation (R^2) in macrobenthos density explained by models in which the sediment data were derived from satellite image analysis plotted against the R^2 of models using ground-based observations of sediment. Each point represents a species of macrobenthos (source: Yates *et al.* 1993c)

Between 37% and 58% of the variation in the numbers of the eight shorebird species counted in the 59 transects was accounted for by the area of mud or sandy sediment in a transect. The numbers of four species – knot, bar-tailed godwit, oystercatcher and curlew – were linearly related to the area of mud or sand. The remaining species all showed a quadratic relationship with either mud or sand (Figure 5).

Analysis of the relationship between sediment type and shore width revealed three shore types in the Wash (Figure 6). All shores less than 2 km in width were muddy. Those greater than 2 km were either predominantly muddy or predominantly sandy. On the muddy shores, the area of mud was linearly related to shore width, while on sandy shores the area of mud remained constant so that the area of sand increased linearly with increasing shore width.

We considered the explanatory power of these functional relationships to be sufficiently good for them to be used to predict the consequence of changes in shore width. Predictions of the areas of mud and sand on a shore of a given width were made by solving the equations for the relationships illustrated in Figure 4. In turn, solving the equations illustrated in Figure 3 using the predicted sediment values enabled the number of each bird species to be determined in each transect.

TEST OF THE MODEL

The model's predictions were validated both within the Wash and on the Essex coast of east England, 150 km distant. Validation within the Wash involved using the model based on three years' bird data to predict the numbers of birds occurring in the transects in the fourth year. The precision of the model's predictions, expressed as a percentage of the variation in observed bird numbers that was explained by the model (P^2), increased as the size of the area for which the predictions were made increased (Figure 7). For example, predictions of redshank numbers increased from a P^2 value

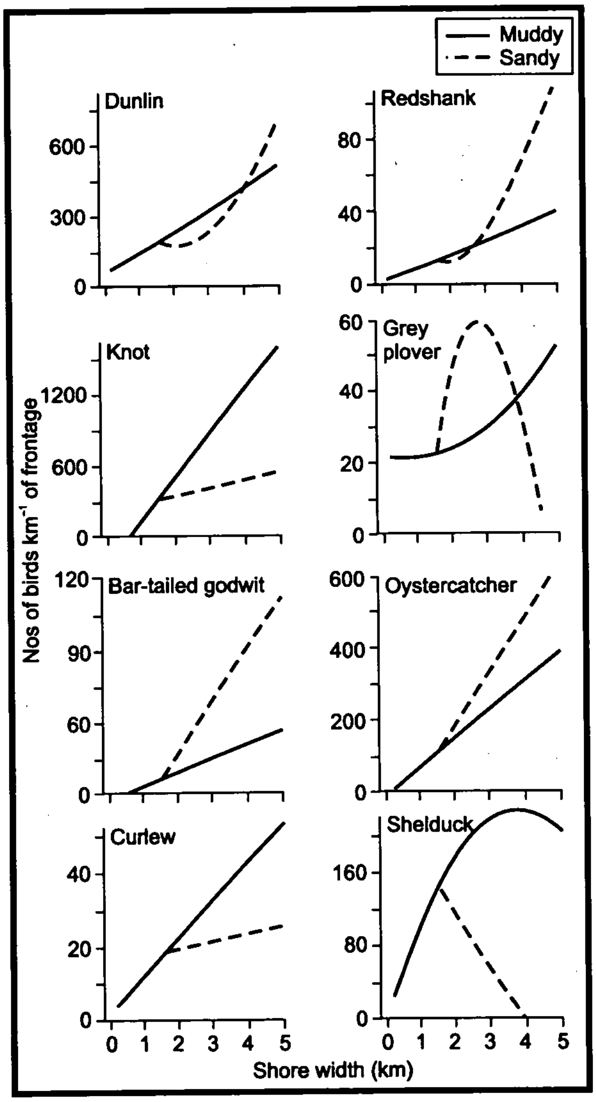

Figure 5. The predictions of the Wash 'shore width' model for the numbers of birds in one km transects in shores of various widths. The solid lines refer to shores that are predominantly muddy, the dashed lines to those that are sandy. Note that all shores less than 1.5 km wide were muddy

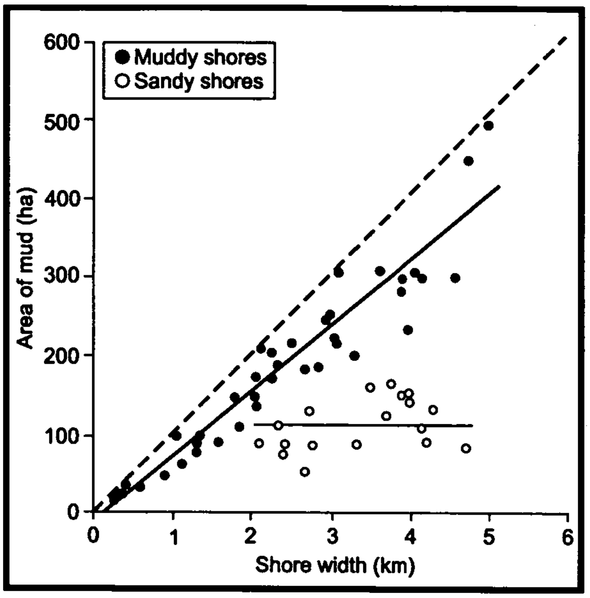

Figure 6. The area of muddy sediments in one km transects in relation to shore width on predominantly muddy shores (•) and predominantly sandy shores (o) of the Wash. The dashed line shows the expected relationship if the shores were completely muddy. The diagonal solid line shows the fitted regression for muddy shores and the horizontal line the mean area of muddy sediments on sandy shores (source: Yates *et al.* 1996b)

of 13% for areas of shore with a one km broad frontage to a value of 70% for an area of shore with a frontage of 7–11 km. In most species, P^2 values reached a maximum for areas with a 7 km broad frontage, though for grey plover and bar-tailed godwit numbers were best predicted for areas with a 3 km frontage. These findings suggested that there may be an optimal scale for the size of area for which predictions are made.

Whereas tests of the model within the Wash served as 'internal' validation of the model, those made using areas on the Essex coast provided a stringent test of the model's utility for other estuarine areas. As in the Wash, analysis of a satellite image taken at low water was used to determine the parameters of the shore width to sediment relationship for an area of the Essex coast that included Canvey Island, Maplin Sands, Dengie Flats and the River Blackwater estuary (Yates *et al.* 1996b). The model, based on bird to sediment relationships determined in the Wash, was then used to predict bird number for that area of the Essex coast. A comparison of the model's predictions with the number of birds observed at roost sites adjacent to that area during Birds of Estuaries Enquiry (BoEE) censuses indicated there was good agreement between predicted and observed numbers (Figure 8). The satisfactory outcome of this test was considered particularly important because it demonstrated the model's ability to predict bird numbers on intertidal areas other than those used to develop the model. Clearly, this suggests that the approach is applicable to other intertidal areas.

FURTHER DEVELOPMENTS TO THE METHODOLOGY

Relating within- and between-estuary variation in sediment to physical features

From dealing with changes in a single physical feature, shore width on the east coast of England, the modelling approach was subsequently developed further to include changes in a number of physical features across a range of British estuaries (Yates *et al.* 1996a). The relationship

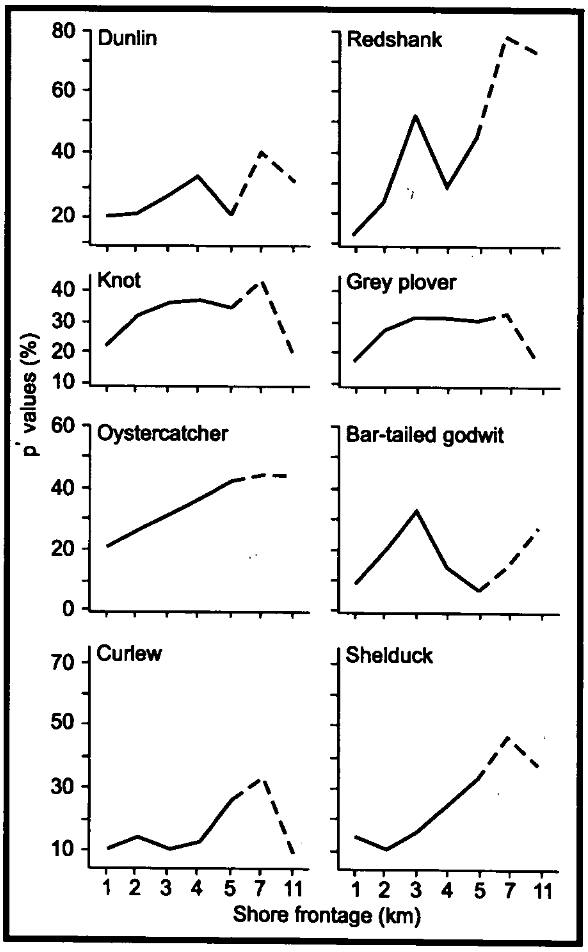

Figure 7. The percentage of variation in observed bird numbers explained by the Wash 'shore width' model's prediction (P^2) plotted against the frontage of the shore to which the predictions apply (source: Yates *et al.* 1996b). In all species the model's predictions improve as the frontage, and thus the area, of the shore increases

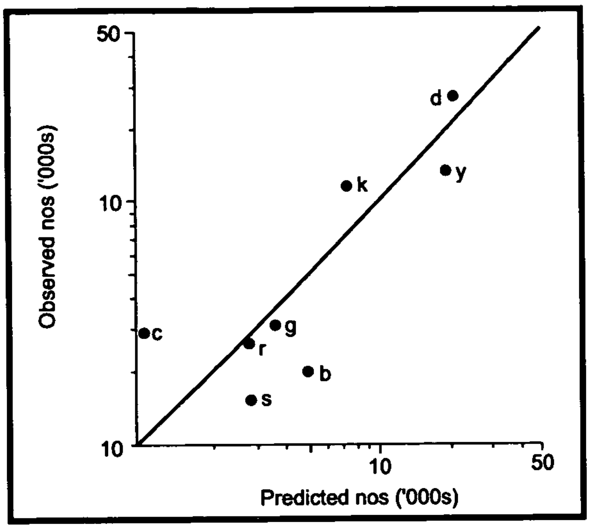

Figure 8. Comparison between the numbers of shorebirds observed on the Essex coast and those predicted by the Wash 'shore width' model. The letter by each point indicates the bird species: b=bar-tailed godwit, c=curlew, d=dunlin, g=grey plover, k=knot, r=redshank, s=shelduck and o=oystercatcher (source: Yates *et al.* 1996b)

between intertidal sediment distribution and environmental characteristics has been determined from a sample of 25 estuaries (see Figure 1 in Rehfisch *et al.*, p117). These variables were selected with two major considerations in mind. First, they were considered likely to influence either:

- within-estuary sediment distribution, eg the distance up the shore; or
- between-estuary differences in sediments, eg estuary size, shape and tidal range.

Second, the effect of natural or man-made environmental changes on these variables is readily predictable; for example, construction of a tidal barrage across an estuary would change the tidal range by a predictable amount.

As before, sediment distribution was determined from remotely sensed images (Yates *et al.* 1996a). The coarser resolution of satellite imagery was sufficient for sediment mapping in larger estuaries or embayments like the Wash, that have vast intertidal areas. For estuaries with smaller intertidal areas, typically with shores less than 2 km wide, it was more appropriate to use sensors mounted in aircraft to acquire the imagery because the spatial resolution is improved, thus allowing differences in sediments over a smaller spatial scale to be resolved.

Seventy-one per cent of the variation in the area of muddy sediments between estuaries was explained by two physical variables of the estuaries. One was the shape, defined as the estuary length divided by its maximum width. The other was the tidal range (Yates *et al.* 1996a). The proportion of the variation these two variables explained was increased to 91% if estuary location, on the east or west coast of Britain, was also taken into account.

Within an estuary, sediment distribution within a selected area of the shore was related to:

- the distance of the area along the estuary's longitudinal axis;
- its distance from the low-water mark; and
- its exposure to wave action measured as the maximum fetch (Yates *et al.* 1996).

Sediments were muddier farther up an estuary, on the upper parts of the shore and on shores with less exposure to wave action. Together, these variables explained 34% of the variation in the within-estuary distribution of muddy sediments.

Relating within- and between-estuary variation in bird numbers to sediments and physical features

Having established that within- and between-estuary variation in sediments could be predicted from environmental variables, the relationships between shorebird distribution and the sediments, and the environmental variables that explained sediment distribution were determined in the same sample of British estuaries. This study was done by the British Trust for Ornithology in conjunction with ourselves (Austen *et al.* 1996) and part of that study is described by Rehfisch *et al.* (pp116–126). It established that the proportion of the intertidal area covered by a particular sediment was indeed an important predictor of whole-estuary bird density. The predictive power of the relationship was further increased by the inclusion of estuary morphology variables. In particular, whole-estuary densities of oystercatcher, dunlin and redshank were predicted well, with 75%, 84% and 86% of the variation explained, respectively (Austen *et al.* 1996). As an example, the densities of redshank predicted by the relationship between birds and estuary morphology are compared with the actual densities observed in the sample estuaries in Figure 9.

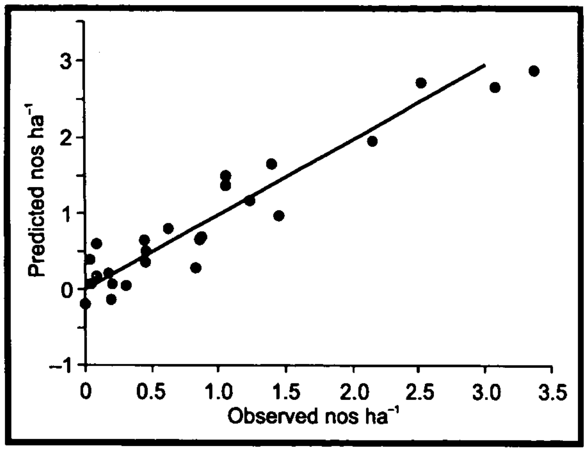

Figure 9. The densities of redshank in 25 British estuaries predicted by the relationship between the birds and the shape, tidal range and longitude of the estuary, plotted against the observed bird density. The diagonal line indicates exact correspondence between predicted and observed densities (source: Austen *et al.* 1996)

Though a full analysis of the data from this study is yet to be completed, the results emphasise further the value of a modelling approach that predicts bird numbers from estuary sediments and other physical variables influencing sediments, particularly on a whole-estuary scale.

CONCLUSIONS

The development of this modelling approach has demonstrated the value of using intertidal sediment distribution as a predictor of shorebird numbers on an intertidal area. Combined with studies on the influence of environmental and physical variables on sediments, the relationships provide a means of predicting the effect of habitat change or loss on shorebird numbers. However, the equations derived this way may only be reliable more generally if all intertidal areas are at carrying capacity in terms of the numbers of birds they can support. Birds may, however, be able to feed at higher densities than at present, in which case the predictions derived from the approach must be considered to be pessimistic; if birds can feed at densities higher than those yet observed, fewer would be influenced than the predictions suggest. Nevertheless, models developed using this approach provide an extremely useful, though perhaps conservative, tool for predicting shorebird densities on estuaries and how they might be expected to respond to man-made or natural changes to the physical features of estuaries.

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Printed in the United Kingdom for The Stationery Office
ISBN 011 702171 7 C6 8/97