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Validation of WeBS Methodology - The Relationship Between Waterfowl Counts Carried Out at High and Low Tide

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to the WeBS partners

British Trust for Ornithology, The Nunnery, Thetford, Norfolk, IP24 2PU
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British Trust for Ornithology

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- The Relationship Between Waterfowl Counts
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ABSTRACT

Population estimates of estuarine waterfowl in the UK are mostly derived from WeBS Core Counts (which are predominantly carried out at high tide), with further detail about feeding distribution within estuaries gathered by WeBS Low Tide Counts. This report compares the numbers of birds recorded by the two types of counts, in order to quantify the relationship between the data gathered by the two schemes.

The high tide and low tide count data for selected winters for a set of 39 estuaries were analysed. For all species combined, the low tide counts recorded about 79% of the total noted at high tide. A similar proportion (85%) was noted for all waders combined, but for the combined estuarine wildfowl, the low tide count total was only 48% of the high tide count.

The amount of agreement between high tide and low tide counts varied between individual species. From a total of 39 species analysed, eight showed no significant relationship between high and low tide counts, although these species were uncommon estuarine species. Four species (Grey Plover, Purple Sandpiper, Dunlin and Bar-tailed Godwit) showed regression coefficients which were not significantly different to one, implying that there was no overall difference between high and low tide counts for these species. Two species (Knot and Greenshank) were counted in significantly higher numbers at low tide than at high tide. For the remainder (25 species), counts were significantly higher at high tide than at low tide.

Analysis of the relationship between the difference in low tide and high tide counts, and a range of external estuarine variables (including measures of estuary size, geographical location and climatic variation) revealed that the difference in counts was related most strongly to the intertidal area. The larger the intertidal area of an estuary, the greater the discrepancy between high tide and low tide counts, presumably due to the difficulties of detecting estuarine birds at greater distances. Correlations of the differences in counts with the length of the shoreline and with the number of days with snow on the ground were also found, but ceased to be significant after application of a Bonferroni correction. However, since these two variables were found to be important for a well-defined group of species (principally sea-duck), the effect may perhaps have been a real one.

It was concluded that WeBS Low Tide Counts should not currently take the place of WeBS Core Counts for the purposes of monitoring the size of waterfowl populations on estuaries (obviously, WeBS Core Counts are not capable of replacing WeBS Low Tide Counts because they do not address within-estuary waterfowl distribution). This is because the difference between low tide and high tide counts depends most strongly on the intertidal area of an estuary, which implies that the smaller numbers of birds counted at low tide are mostly due to detectability and not to birds moving in and out of a site. If all of the UK's larger estuaries had been counted at low tide the discrepancy between low tide and high tide totals would be expected to be far greater than seen in the present study. However, it is quite possible that with a longer run of data, WeBS Low Tide Counts could be used to monitor trends in population sizes of estuarine birds.

1. INTRODUCTION

The Wetland Bird Survey (WeBS) is organised and funded jointly by the British Trust for Ornithology (BTO), The Wildfowl & Wetlands Trust (WWT), the Royal Society for the Protection of Birds (RSPB) and the Joint Nature Conservation Committee (JNCC), the latter on behalf of English Nature, Scottish Natural Heritage, the Countryside Council for Wales and the Environment and Heritage Service in Northern Ireland. WeBS makes use of two principal methods for recording the waterfowl populations on the UK's estuaries. The WeBS Core Counts are a combination of the BTO's Birds of Estuaries Enquiry (BOEE), started in 1969, and the WWT's National Wildfowl Counts, which have been running since 1947. The WeBS Core Counts mostly take place at or around the high tide, since it is usually easier to count estuarine birds when they are concentrated into a few localised high tide roosts along the shore. Such counts enable population estimates to be made and fluctuations in these populations to be investigated (Kirby 1995, Cayford & Waters 1996, Stone *et al.* 1997). Secondly, the more recent WeBS Low Tide Counts look at individual estuaries in more detail in order to establish the feeding distribution of birds at low tide. These counts are designed to determine the relative importance of different parts of estuaries and, as such, place less emphasis on the actual numbers of birds present (Clark & Pr_s-Jones 1994, Cranswick *et al.* 1995). Both of these schemes are of great value in the effective conservation of the UK's estuaries (Davidson & Stroud 1996). This research report assesses the relationship between the numbers of birds counted during high tide WeBS Core Counts and WeBS Low Tide Counts, and explores some of the factors that may help to explain these relationships.

2. METHODS

2.1 Count Data

A greater number of estuaries are currently counted for the WeBS Core Counts than have been covered by the WeBS Low Tide Counts. Therefore, the initial choice of estuaries which could be included in the comparisons was limited to those which had been covered by the WeBS Low Tide Counts during the four winters from 1992-93 to 1995-96. For the sites which had been counted more than once at low tide, the winter with the best coverage was selected and the others discarded. This was to ensure that no bias was introduced, particularly by Strangford Lough which was counted at low tide during all four of the winters in question. A factor affecting the relationship between high tide and low tide counts which was peculiar to Strangford Lough could have been misinterpreted as the influence of longitude (since Strangford is much further west than most other sites). Counts for the Inner Thames, the Burry Inlet and Lindisfarne were discarded since only partial coverage of these sites was achieved at low tide. The low tide count data for the Wear Estuary were also left out of the data set since no core count data exist for comparison. This resulted in an initial list of 32 estuaries.

Further low tide count data were available from other BTO commercial projects. The methodology for these projects was very similar to that for the WeBS Low Tide Counts, making it possible to utilise their data to ‘reconstruct’ equivalent low tide counts for a further 22 sites.

The WeBS Core Count data for these 54 estuaries were then examined in more detail. It was found that for a number of sites, mostly small estuaries in the south-west, the WeBS Core Counts were also carried out at low tide. These estuaries would obviously have been unsuitable for comparing high and low tide counts and so were discarded from the set of sites. In two cases (Swale Estuary and Forth Estuary), the sites counted at high tide and low tide differed by quite well-defined geographical areas; the difference in counted areas was satisfactorily dealt with by removing some of the data from one or other scheme. In all other cases, the length of shoreline of the counted sites differed by less than 5% between the two schemes.

Taking all of these factors into account yielded a final set of 39 estuaries which had reasonably comparable high and low tide count data. These are listed in Table 2.1.1.

One of the features of WeBS count data is that months are sometimes missed by counters. In order to ensure that comparisons of high and low tide count data were valid, any months for which either the high tide or low tide count was missing were omitted from the analysis. The months which were used for the comparisons are listed in Table 2.1.1.

Although the priority species were the more common waders and wildfowl, a number of other less numerous species were also included. However, gulls were not included, partly because coverage of these birds by counters is patchy, and partly because the numbers of gulls on an estuary have a stronger dependency on the time of day (rather than tidal state) than do other waterfowl. The 39 species which were included in the final analysis, along with their two-letter codes, are listed in Table 2.1.2.

For each combination of species and site, the mean count of that species for the whole site at low tide over the selected months was required. This was arrived at by summing the mean numbers of each species for each individual mudflat. The high tide counts were also averaged over the relevant number of months. This resulted in two values for each species and site combination, *i.e.* the mean number on the site at high tide and the mean number at low tide, over the months selected. These values are referred to hereafter as HIGHNO and LOWNO respectively. Zero counts were included within the data set when a species was not recorded at low tide and/or high tide.

2.2 Estuarine Variables

As a part of the analysis, the differences between high and low tide counts were compared to a suite of additional variables. These were acquired from a number of sources. The four measures of estuary size, TOTAREA, INTAREA, SHORE and CHANNEL, were derived from Appendix 2a of Davidson *et al.* (1991). It should be noted, however, that the figures do not necessarily correspond exactly to those areas counted for WeBS. In particular, the study areas in Davidson *et al.* (1991) often include intertidal zones that are more riverine than estuarine in character. In these cases (Breydon Water is a particularly good example; see Buck 1997), the figures for SHORE are particularly inaccurate.

Single values for both latitude and longitude of each estuary were determined from maps and referred to a selected 'mid-point' of each site.

The climatic data had been provided by the Meteorological Office and was available for the five years 1989-1993. A total of 10 stations were selected which were considered representative of the weather at the estuarine study sites. Raw weather data were extracted for the five years 1989-1993, from November to February only. The average values for seven weather variables were then calculated. Since meteorological data were not available for the precise dates of counts (and since high tide and low tide counts were not themselves carried out on the same dates at a site), average values for the weather variables over five recent winters were therefore used to describe the long-term climatic influences on each site. Additionally, examining weather on the exact dates of counts would introduce a bias against poor weather conditions since counters are more likely to miss a count if conditions are poor. The weather stations allocated to each of the estuaries are listed in Table 2.2.1 and are illustrated in Figure 2.2.1.

The 13 variables used are listed in Table 2.2.2. Many of these variables were expected to be inter-correlated and thus correlations were run between all pairs of variables; the results are presented in Table 2.2.3. Not surprisingly, the four measures of estuary size (TOTAREA, INTAREA, SHORE and CHANNEL) were all significantly correlated with each other. Also, the five temperature-related variables (TMAX, TMIN, TMEAN, SNOWD and AIRD) were inter-correlated, as expected. These latter five variables were also correlated with latitude. The two rainfall variables, RAINT and RAIND were correlated with each other, as well as being correlated with longitude (increasing in the west).

3. RESULTS

3.1 The Relationship Between High Tide Counts and Low Tide Counts

For each species, all values of HIGHNO and LOWNO were plotted against each other, with the resulting regression coefficients presented in Table 3.1.1. The results for each of the 39 species, all species combined, all waders combined and all wildfowl combined are listed.

There were eight species (Shoveler, Tufted Duck, Scaup, Common Scoter, Snipe, Spotted Redshank, Green Sandpiper and Common Sandpiper) for which there was no relationship between high tide and low tide counts (*i.e.* the gradient of the slope was not significantly different to zero). These are generally uncommon estuarine species that were present either in low numbers or on too few sites for the expected relationship to be detected.

For the other 31 species, however, there was a significant relationship between high and low tide counts. Of these, Bar-tailed Godwit, Dunlin, Grey Plover and Purple Sandpiper had gradients which were not significantly different from one. Of the remaining species, the majority were counted in higher numbers at high tide than at low tide. The only exceptions were Knot and Greenshank for which the gradients were significantly greater than one.

For all species combined, 0.79 birds were counted at low tide for every bird recorded at high tide (see Figure 3.1.1). This gradient is not significantly different to that seen for all wader species combined (0.85), but it is significantly different to that seen for all wildfowl combined (0.48). Wildfowl are much more seriously underestimated by low tide counts than are waders.

3.2 The Relationship Between Estuarine Variables and the Differences Between High Tide and Low Tide Counts

For each species, the residual between high tide and low tide counts, DIFF, was calculated as DIFF = HIGHNO-LOWNO. DIFF was compared with the suite of 13 variables listed in Table 2.2.1, in order to investigate which factors were responsible for the difference between the two types of counts. The results are presented in Table 3.2.1.

The first four of these variables are measures of estuary size and, as mentioned in Section 2.2, are intercorrelated with each other. A total of 24 out of the 39 species under consideration were significantly correlated with at least one of these four variables, most often INTAREA. In virtually all cases, this was a positive correlation, *i.e.* as estuary size increases, the number of birds counted at high tide increases in comparison to the number of birds counted at low tide. This result is entirely to be expected, since counters are less able to see and identify birds at greater distances. The only exception was that DIFF was negatively correlated with both TOTAREA and INTAREA for Bar-tailed Godwit. There would seem to be no intuitive reason why this species would behave any differently to the other species and the result is possibly a statistical anomaly. The grebes and sea-duck (Eider, Long-tailed Duck, Common Scoter and Goldeneye) were correlated with linear measures of estuary size (SHORE and CHANNEL) but not with measures of estuary area (except for Great Crested Grebe). As the length of a channel or the length of shoreline increases, the greater the disparity between numbers counted at high and low tide.

Out of the 39 species, nine of them showed correlations between DIFF and one of the measures of temperature (including latitude). From these temperature-related variables, SNOWD appeared to be the most important. All correlations between DIFF and SNOWD were positive. In other words, as the number of days with snow on the ground increases, the number of birds counted at high tide increases in comparison to the number counted at low tide. The species which show correlations with temperature variables are again mostly diving ducks; none of the common estuarine waders or dabbling ducks appear to be affected by temperature in this respect.

A total of 10 species (Mute Swan, Brent Goose, Red-breasted Merganser, Avocet, Ringed Plover, Grey Plover, Knot, Purple Sandpiper, Greenshank and Green Sandpiper) showed no correlations between DIFF and any external variables.

Finally, comparing 39 species with a suite of 13 variables gives a possible 507 correlations which can be investigated. Checking for correlations at the 5% level of significance means that there is a 5% chance of deciding that a correlation is significant, when in fact it is not. Therefore, out of 507 correlations, one would expect about 25 correlations to appear to be significant simply by chance. The problem of multiple comparisons can be tackled by using the Bonferroni correction, in which the threshold values for P are divided by the number of correlations made. In this case, a threshold value of $P<0.05$ is lowered to $P<0.0001$. Thus, using this method, only those correlations marked **** in Table 3.2.1 (and presented in **bold** type) would be considered significant. The only correlations which remain significant following the Bonferroni correction are some of the correlations with INTAREA and TOTAREA. None of the weather-related correlations remain significant.

3.3 The Relationship Between Estuarine Variables with the Residuals of the Regression Line Between High Tide and Low Tide Counts

In Section 3.2, the residual from the line of a 1:1 relationship between low tide and high tide counts was used, to try to examine why high tide and low tide counts might differ from each other. For the current section, residuals were taken from the regression line (as discussed in Section 3.1), to examine what factors might cause scatter around the calculated relationship between the variables HIGHNO and LOWNO. Only regression models significant at the $P<0.05$ level were analysed further. For each of the remaining species, the residual from the regression line was compared with the suite of 13 variables described in Table 2.2.1. The results are presented in Table 3.3.1. Only variables found to be significant at $P<0.05$ are included in the table.

The table reveals a scatter of significant correlations, with no striking pattern except for a bias towards the estuary size variables TOTAREA and INTAREA. As mentioned in Section 3.2, one would expect about 5% of possible correlations to be significant at the 5% level, by definition. From comparing 31 species with 13 variables, giving 403 possible correlations, one would expect about 20 correlations to appear significant simply by chance. After Bonferroni corrections have been applied, almost all of the correlations displayed in Table 3.3.1 cease to be significant. The only correlations which meet this threshold are those presented in **bold** type and are all correlations with the variable INTAREA.

3.4. Forward Stepwise Regression

Forward stepwise regression analysis was run for the dependent variable, DIFF, for all species with all available independent variables (SAS Institute 1989). The significance level for entry into and elimination from the model was set to $P<0.05$. The resulting regression coefficients and the coefficients of determination are listed in Table 3.4.1. The 10 species (Mute Swan, Brent Goose, Red-breasted Merganser, Avocet, Ringed Plover, Grey Plover, Knot, Purple Sandpiper, Greenshank and Green Sandpiper) which showed no correlations between DIFF and any of the independent variables used in the analyses are omitted from the table.

The robustness of all models which included more than one variable was assessed using the following procedure. Each model was run omitting one of the variables and the residuals were calculated between the observed and expected values. Additionally, the model was run with only the omitted variable, and again the residuals were calculated. These two sets of residuals were then plotted against one another. Any outliers present were identified and the models were run again without the relevant estuaries. If there was still a significant relationship between the two sets of residuals, then the original model suggested by the stepwise regression was considered robust. No variables selected by the forward stepwise procedure were lost from any of the models.

The most important explanatory variables are evidently INTAREA, SHORE and SNOWD. This agrees well with the inital correlations reported upon in Section 3.2. However, this analysis has demonstrated that TOTAREA and CHANNEL, which were previously found to be correlated with DIFF, explain little of the variation in DIFF that is not alternatively explained by INTAREA and SHORE.

The coefficients of determination calculated for the models for individual species varied greatly, with highly significant models explaining over 70% of the variation for Pintail, Oystercatcher and Sanderling, and over 50% of the variation for Teal, Scaup, Bar-tailed Godwit and Curlew. The model for all species combined (containing only the variable INTAREA) was also highly significant, but only explained 4% of the variation in DIFF.

Forward stepwise regression was not applied to the residuals from the regression line between HIGHNO and LOWNO because there was so little correlation with the independent variables discovered in Section 3.3.

4. DISCUSSION

A simple comparison of high tide *vs* low tide counts, over all species, reveals that low tide counts produce about 79% of the birds counted at high tide. This figure is encouragingly high. Although the WeBS Low Tide Counts are principally designed to investigate the low tide feeding distribution within an estuary, if only a small proportion of the birds had been noted at low tide this would have left the results open to criticism (although it could be that the missing birds had left the estuary).

When comparing high tide to low tide counts for all waders combined, the proportion of birds located is similar to the proportion for all birds, at about 85%. However, the combined results for wildfowl suggest that this group is recorded in lower numbers by low tide counts, with 48% of the birds counted at high tide recorded at low tide. This may in part be due to differences in the counting schemes. The WeBS Core Counts aim to find all of the birds on an estuary, and if birds are present on adjacent inland pools, these may be included within the count area. However, the majority of the WeBS Low Tide Counts cover only the intertidal zone, and thus birds may be missed. However, it could also be that wildfowl are making use of the estuary at high tide but are moving elsewhere (either inland, out to sea or to an adjacent site) at low tide (Unsworth 1993). Species such as Teal may roost in wrecks at low tide where they are difficult to record.

Out of the sample of 39 species, 31 show significant linear relationships between their high and low tide counts; the other eight species for which no significant relationships were found are all relatively uncommon and localised on a few estuaries. The gradients vary from as low as 0.08 for Sanderling to 1.23 for Greenshank. Four species (Bar-tailed Godwit, Dunlin, Grey Plover and Purple Sandpiper) have gradients which are not significantly different to one and thus could be monitored equally well at high or low tide. Of these species, the result for Purple Sandpiper is interesting. Being a small inconspicuous species, it might be expected that low tide counts would be much lower than high tide counts. However, the rocky areas favoured by this species for feeding are often also the same areas that are used for roosting, and so the distance over which the observer has to locate the species does not increase greatly. Additionally, da Prato & da Prato (1979) suggest two other reasons why Purple Sandpipers are better counted at low tide than high tide. Firstly, the species regularly roosts at high tide on offshore islets and so may not be visible from the shore. Secondly, the species can be exceptionally difficult to see on dark rocks and so a stationary roosting bird would be much more difficult to see than a mobile feeding one.

Two species (Greenshank and Knot) have gradients which are significantly greater than one and it would appear that these species are better counted at low tide. Greenshank often roost in saltmarshes and may be more difficult to see at high tide than when feeding at low tide. However, the result for Knot is more surprising. It is possible that this is a result of underestimating the numbers of birds in dense flocks of roosting Knots. However, in the case of Knot this relationship might be less applicable if one were looking at many of the other large estuaries which are important for Knot but which have not yet been counted at low tide, such as the Wash. All other species are counted in larger numbers at high tide than at low tide.

The differences between high and low tide counts can be related to external variables. It appears that measures of estuary size are of the greatest significance. A stepwise regression revealed that the intertidal area of an estuary had the greatest effect on the difference between counts. The larger the estuary, the smaller the proportion of the high tide total recorded at low tide. This is presumably because as the size of an estuary increases, the birds can be further away from the observer at low tide, becoming less easy to count. Consequently, it is likely that it is the width of the mudflat that is more important (*i.e*. the distance between the observer and the low tide mark), but wider mudflats occur most frequently on the larger estuaries. This relationship was found for most of the common estuarine waders and wildfowl although, interestingly, such a relationship was not apparent for Knot, Grey Plover and Ringed Plover. It is possible that these three species were recorded relatively well at low tide because they fed at shorter distances from the observer than, for example, Dunlin. However, this does seem unlikely. Another potential hypothesis could be that many individuals of these species were roosting outside the estuaries (on adjacent rocky shores for example) and then flying in to feed at low tide, and these additional numbers were masking the birds being lost due to greater viewing distances.

Two other variables which appeared to explain the difference between high tide and low tide counts were the length of the shoreline and the number of days with snow cover. Neither relationship was significant following a Bonferroni correction, but since the species for which these trends were identified formed a well-defined group (*i.e.* sea-duck and grebes), it is possible that a weak relationship exists.

The longer the shoreline, the smaller the proportion of the high tide total counted at low tide. This trend was apparent for the grebes and sea-duck species, but not for estuarine waders. This linear measurement of estuary size presumably correlates better with these species since they inhabit what is essentially a more linear habitat within the estuary, along creeks and channels (including the central "channel").

The trend relating the difference between high tide and low tide counts with snowfall was almost exclusively confined to sea-ducks (Eider, Long-tailed Duck, Common Scoter, Goldeneye and Tufted Duck). As the number of days with snow on the ground increased, the smaller was the number of birds at low tide in comparison to high tide. If this correlation is indeed a real one, this could be for one (or both) of two reasons. Firstly, it could be that snowy weather causes birds which are present in an estuary to move out of it at low tide, as their relatively shallow intertidal feeding areas get colder and their prey become less accessible. Secondly, it could be that the birds' feeding patterns are unchanged, but that a larger number of birds move in to the site at high tide during snowy weather. This hypothesis could be tested by looking more closely at the relationships between sea-duck count data and climatic conditions. However, the relationship does not seem likely (particularly as other measures of temperature did not appear to be important) and the relationship between sea-duck and snow is probably due to the majority of sites supporting large sea-duck numbers being those at higher latitudes.

5. SUMMARY

Overall, low tide estuarine counts record about 79% of the birds counted at high tide, although this proportion varies considerably with species. There is a greater discrepancy between high tide and low tide counts for wildfowl than there is for waders. The principal factor influencing the difference between high tide and low tide counts is the size of the estuary, best described by its intertidal area. This is presumably because as the intertidal area of the estuary increases, birds can occur at further distances from the observers making counting and identification more difficult.

It has to be considered whether, with a potentially decreasing number of counters and thus increasing time pressure on those remaining, WeBS Low Tide Counts could take the place of WeBS Core Counts for the purpose of population monitoring. (The converse is not an option since the latter scheme could not be used to identify the importance of feeding areas on a site.) This report suggests that this would not be appropriate in the immediate future since for the majority of species the number of birds recorded at low tide was significantly less than that at high tide. As this discrepancy was correlated most strongly with the size of the estuary this implies that this difference in counts was influenced more by observers' abilities to detect birds at greater distances than by movements of birds in and out of the estuaries.

It must be remembered that WeBS Low Tide Counts have not yet been carried out on the largest UK estuaries. As the greatest discrepancies between high tide and low tide counts occurred on estuaries with the largest intertidal areas implies that were a full set of low tide count data for all British estuaries available, the overall proportion of 79% mentioned above would almost certainly be substantially lowered. It is important to remember that approximately half of the UK's wintering waterfowl occur on just the eight largest sites (Musgrove & Holloway 1997). The findings of this report add to the concerns about the feasibility of carrying out reliable low tide counts of larger estuaries by standard methods.

Although not recommended for monitoring the size of estuarine waterfowl populations, there would seem to be no reason why WeBS Low Tide Counts should not be used for monitoring trends in numbers of estuarine waterfowl. However, to achieve this, longer runs of low tide data than are currently available would be needed. WeBS Low Tide Counts have been carried out in more than two consecutive years on only five sites at time of writing (Belfast Lough, Orwell Estuary, Pagham Harbour, Southampton Water and Strangford Lough). An investigation of the trends in numbers recorded by WeBS Low Tide Counts at these sites compared to the trends recorded by WeBS Core Counts would be useful in further quantifying the relationship between the two schemes.

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Site	Winter	Nov	Dec	Jan	Feb
Artro Estuary	1994-95		✓	✓	✓
Auchencairn Bay	1994-95	✓	✓	✓	✓
Belfast Lough	1995-96	✓			
Blackwater Estuary	1994-95	✓	✓	✓	
Blyth Estuary	1994-95	✓		✓	✓
Breydon Estuary	1994-95			✓	✓
Chichester Harbour	1992-92	✓			✓
Clwyd Estuary	1992-93	✓	✓	✓	✓
Colne Estuary	1994-95	✓	✓	✓	✓
Cromarty Firth	1994-95		✓	✓	
Crouch/Roach Estuary	1995-96	✓	✓	✓	✓
Deben Estuary	1994-95	✓	✓	✓	✓
Dee Estuary	1994-95	✓	✓	✓	✓
Dengie Flats	1992-93	✓	✓		
Duddon Estuary	1993-94	✓	✓	✓	✓
Dyfi Estuary	1994-95	✓	✓	✓	✓
Eden Estuary	1992-93	✓	✓	✓	✓
Forth Estuary	1992-93		✓	✓	✓
Foryd Bay	1994-95	✓	✓	✓	✓
Hamford Water	1992-93	✓	✓	✓	✓
Inland Sea	1995-96	✓	✓	✓	
Langstone Harbour	1993-94		✓		✓
Lavan Sands	1995-96	✓	✓		
Mawddach Estuary	1994-95			✓	✓
Medina Estuary	1995-96	✓	✓	✓	✓
Montrose Basin	1992-93	✓	✓		✓
North-west Solent	1992-93	✓	✓	✓	✓
Orwell Estuary	1995-96	✓		✓	✓
Pagham Harbour	1995-96		✓		✓
Pegwell Bay	1994-95		✓	✓	✓
Portsmouth Harbour	1992-93	✓	✓	✓	✓
Southampton Water	1994-95	✓	✓		
Strangford Lough	1995-96	✓		✓	
Swale Estuary	1992-93	✓	✓	✓	✓
Swansea Bay	1994-95	✓	✓	✓	✓
Taw/Torridge Estuary	1994-95	✓	✓	✓	✓
Tay Estuary	1993-94			✓	
Tyninghame Estuary	1994-95	✓	✓	✓	✓
Wigtown Bay	1992-93	✓	✓	✓	✓

Table 2.1.1 Sites and months used in the comparison of high and low tide counts.

Species	Species code
Little Grebe *Tachybaptus ruficollis*	LG
Great Crested Grebe *Podiceps cristatus*	GG
Cormorant *Phalacrocorax carbo*	CA
Mute Swan *Cygnus olor*	MS
Brent Goose *Branta bernicla*	BG
Shelduck *Tadorna tadorna*	SU
Wigeon *Anas penelope*	WN
Teal *Anas crecca*	T.
Mallard *Anas platyrhynchos*	MA
Pintail *Anas acuta*	PT
Shoveler *Anas clypeata*	SV
Pochard *Aythya ferina*	PO
Tufted Duck *Aythya fuligula*	TU
Scaup *Aythya marila*	SP
Eider *Somateria mollissima*	E.
Long-tailed Duck *Clangula hyemalis*	LN
Common Scoter *Melanitta nigra*	CX
Goldeneye *Bucephala clangula*	GN
Red-breasted Merganser *Mergus serrator*	RM
Oystercatcher *Haematopus ostralegus*	OC
Avocet *Recurvirostra avosetta*	AV
Ringed Plover *Charadrius hiaticula*	RP
Golden Plover *Pluvialis apricaria*	GP
Grey Plover *P. squatarola*	GV
Lapwing *Vanellus vanellus*	L.
Knot *Calidris canutus*	KN
Sanderling *C. alba*	SS
Purple Sandpiper *C. maritima*	PS
Dunlin *C. alpina*	DN
Snipe *Gallinago gallinago*	SN
Black-tailed Godwit *Limosa limosa*	BW
Bar-tailed Godwit *L. lapponica*	BA
Curlew *Numenius arquata*	CU
Spotted Redshank *Tringa erythropus*	DR
Redshank *T. totanus*	RK
Greenshank *T. nebularia*	GK
Green Sandpiper *T. ochropus*	GE
Common Sandpiper *Actitis hypoleucos*	CS
Turnstone *Arenaria interpres*	TT

Table 2.1.2 Species included in the comparisons**.**

Estuary	Weather station
Taw/Torridge Estuary	Swansea
North-west Solent	Hastings
Medina Estuary	Hastings
Southampton Water	Hastings
Portsmouth Harbour	Hastings
Langstone Harbour	Hastings
Chichester Harbour	Hastings
Pagham Harbour	Hastings
Pegwell Bay	Manston
Swale Estuary	Manston
Crouch/Roach Estuary	Mean of Lowestoft and Manston
Dengie Flats	Mean of Lowestoft and Manston
Blackwater Estuary	Mean of Lowestoft and Manston
Colne Estuary	Mean of Lowestoft and Manston
Hamford Water	Mean of Lowestoft and Manston
Orwell Estuary	Mean of Lowestoft and Manston
Deben Estuary	Mean of Lowestoft and Manston
Blyth Estuary	Lowestoft
Breydon Water	Lowestoft
Tyninghame Estuary	Edinburgh
Forth Estuary	Edinburgh
Eden Estuary	Mean of Dyce and Edinburgh
Tay Estuary	Mean of Dyce and Edinburgh
Montrose Basin	Mean of Dyce and Edinburgh
Cromarty Firth	Fortrose
Wigtown Bay	Dumfries
Auchencairn Bay	Dumfries
Duddon Estuary	Squires Gate
Dee Estuary	Squires Gate
Clwyd Estuary	Squires Gate
Lavan Sands	Squires Gate
Inland Sea	Mean of Squires Gate and Swansea
Foryd Bay	Mean of Squires Gate and Swansea
Artro Estuary	Mean of Squires Gate and Swansea
Mawddach Estuary	Mean of Squires Gate and Swansea
Dyfi Estuary	Mean of Squires Gate and Swansea
Swansea Bay	Swansea
Strangford Lough	Stormont
Belfast Lough	Stormont

Table 2.2.1 Weather stations allocated to each estuary.

Variable	Units	Definition
TOTAREA	*ha*	The total area of the estuary
INTAREA	*ha*	The intertidal area of the estuary
SHORE	*km*	The length of the shoreline
CHANNEL	*km*	The length of the tidal channel
LAT	^{o}	Latitude
LONG	^{o}	Longitude (negative values are east of Greenwich)
TMAX	^oC	Mean maximum temperature
TMIN	^oC	Mean minimum temperature
TMEAN	^oC	Mean of max and min temperatures
RAINT	*mm*	Total rainfall
RAIND	*days*	Rainy days (>= 0.2 mm)
SNOWD	*days*	Days with snow lying at 0900
AIRD	*days*	Days with air minimum below 0^oC

Table 2.2.2 Independent variables used in the analyses.

	TOTAREA *ha*	INTAREA *ha*	SHORE *km*	CHANNEL *km*	LAT ^{o}	LONG ^{o}	TMAX ^{o}C	TMIN ^{o}C	TMEAN ^{o}C	RAINT *mm*	RAIND *days*	SNOWD *days*
AIRD *days*	0.13	0.27	-0.04	0.31	0.77****	0.34*	-0.75****	-0.92****	-0.88****	0.10	0.38*	0.53***
SNOWD *days*	0.10	0.07	0.21	0.22	0.63****	-0.02	-0.59****	-0.63****	-0.63****	-0.42**	-0.17	
RAIND *days*	0.28	0.15	-0.04	0.09	0.45**	0.90****	0.08	-0.16	-0.07	0.80****		
RAINT *mm*	-0.06	-0.03	-0.29	-0.08	0.04	0.76****	0.40*	0.20	0.29			
TMEAN ^{o}C	-0.24	-0.27	-0.14	-0.41*	-0.80****	-0.06	0.96****	0.98****				
TMIN ^{o}C (^{o}C)	-0.25	-0.26	-0.13	-0.41**	-0.82****	-0.15	0.89****					
TMAX ^{o}C	-0.19	-0.25	-0.15	-0.36*	-0.70****	0.08						
LONG ^{o}	0.33*	0.14	-0.07	0.10	0.52***							
LAT ^{o}	0.40*	0.24	0.19	0.38*								
CHANNEL *km*	0.62****	0.52***	0.72****									
SHORE *km*	0.56***	0.38*										
INTAREA *ha*	0.76****											

Table 2.2.3 Pearson correlation coefficients between estuarine variables, along with the significance level of the correlations. n=39 for all comparisons. $^{*}P<0.05$; $^{**}P<0.01$; $^{***}P<0.001$; $^{****}P\leq0.0001$

SPCODE	Intercept ±SE	Regression coefficient ± SE (HIGHNO)	*n* and overall model significance	Model coefficients of determination adjusted for degrees of freedom r^2_{adj}
LG	0.213±1.296	0.402±0.054****	39****	0.602
GG	-10.936±6.449	0.646±0.040****	39****	0.875
CA	3.836±6.528	0.615±0.064****	39****	0.713
MS	3.207±4.723	0.522±0.095****	39****	0.449
BG	112.206±131.951	0.651±0.050****	39****	0.821
SU	143.100±109.228	0.671±0.105****	39****	0.523
WN	473.416±115.558***	0.112±0.052*	39*	0.112
T.	79.902±55.025	0.295±0.061****	39****	0.390
MA	15.971±43.864	0.493±0.071****	39****	0.568
PT	39.930±22.090	0.131±0.046**	39**	0.178
SV	4.089±2.344	0.070±0.037	39	0.089
PO	-3.838±9.375	0.396±0.141**	39**	0.175
TU	2.457±6.627	0.109±0.088	39	0.040
SP	0.562±0.412	0.002±0.007	39	0.000
E.	10.526±9.928	0.400±0.011****	39****	0.972
LN	-0.012±0.116	0.200±0.002****	39****	0.997
CX	0.214±0.132	-0.000±0.001	39	0.003
GN	18.962±11.372	0.159±0.040***	39***	0.297
RM	-1.332±4.655	0.574±0.053****	39****	0.759
OC	416.211±160.678*	0.685±0.041****	39****	0.882
AV	3.748±4.122	0.552±0.083****	39****	0.543
RP	50.676±15.651**	0.234±0.102*	39*	0.124
GP	88.222±94.981	0.419±0.056****	39****	0.605
GV	8.990±68.774	0.856±0.098****	39****	0.676
L.	243.906±280.139	0.582±0.067****	39****	0.673
KN	-66.919±125.977	1.202±0.067****	39****	0.898

Table 3.1.1 The intercepts, regression coefficients and coefficients of determination for regression equations relating high tide to low tide counts.
$^{*}P<0.05$; $^{**}P<0.01$; $^{***}P<0.001$; $^{****}P\leq0.0001$

SPCODE	Intercept ±SE	Regression coefficient ± SE (HIGHNO)	*n* and overall model significance	Model coefficients of determination adjusted for degrees of freedom r^2_{adj}
SS	9.285±4.380*	0.076±0.034*	39*	0.120
PS	-0.585±0.361	1.088±0.057****	39****	0.907
DN	618.714±742.397	0.958±0.119****	39****	0.637
SN	7.196±3.447*	0.053±0.079	39	0.012
BW	47.571±26.947	0.381±0.108**	39**	0.251
BA	73.358±84.319	0.840±0.188****	39****	0.349
CU	192.929±65.906**	0.379±0.069****	39****	0.453
DR	0.299±0.290	0.412±0.348	39	0.036
RK	181.565±102.364	0.710±0.077****	39****	0.694
GK	-0.391±0.482	1.228±0.107****	39****	0.780
GE	0.087±0.066	0.045±0.065	39	0.013
CS	0.038±0.036	0.177±0.100	39	0.079
TT	-0.091±14.685	0.720±0.075****	39****	0.716
All species	9.530±20.964	0.794±0.013****	1521****	0.702
All waders	35.591±37.764	0.848±0.019****	780***	0.727
All wildfowl	32.324±15.287*	0.480±0.020****	624****	0.603

Table 3.1.1 (continued) The intercepts, regression coefficients and coefficients of determination for regression equations relating high tide to low tide counts.
$^{*}P<0.05$; $^{**}P<0.01$; $^{***}P<0.001$; $^{****}P\leq0.0001$

SPCODE	TOTAREA *ha*	INTAREA *ha*	SHORE *km*	CHANNEL *km*	LAT °	LONG °	TMAX *°C*	TMIN *°C*	TMEAN *°C*	RAINT *mm*	RAIND *days*	SNOWD *days*	AIRD *days*
LG			0.329*										
GG	0.371*		0.384*	0.358*									
CA		0.394*											
SU		**0.603******											
WN		0.334*											
T.	0.427**	**0.694******											
MA	**0.587******	**0.683******	0.392*										
PT	0.513***	**0.809******											
SV						-0.331*					-0.328*		
PO	0.487**	0.534***	0.408**	0.336*									
TU	**0.619******	0.488**	0.485**	0.457**								0.317*	
SP					0.482**		-0.317*						
E.			0.431**	0.349*								0.448**	
LN			0.453**	0.374*									
CX			0.416**	0.311*								0.483**	
GN			0.445**	0.349*								0.404*	
OC	0.383*	**0.768******											

Table 3.2.1 Pearson correlation coefficients and *P*-values for correlations of the difference between numbers of birds counted at high tide and low tide with a suite of variables. n=39 in all comparisons. The correlation coefficients that remain significant after Bonferroni corrections have been applied are in bold. Only those variables found to be significant at P<0.05 are included.
$^{*}P<0.05$; $^{**}P<0.01$; $^{***}P<0.001$, $^{****}P\leq0.0001$

SPCODE	TOTAREA *ha*	INTAREA *ha*	SHORE *km*	CHANNEL *km*	LAT °	LONG °	TMAX °*C*	TMIN °*C*	TMEAN °*C*	RAINT *mm*	RAIND *days*	SNOWD *days*	AIRD *days*
GP			0.464**										
L.	0.479**	0.519***	0.499**										
SS	0.501**	**0.807******											
DN		0.324*											
SN					-0.318*								
BW		0.508**											
BA	-0.458**	**-0.706******											
CU	0.492**	**0.775******		0.332*									
DR							-0.377*			-0.366*			
RK		0.522***											
CS							0.354*			0.382*			
TT	0.482**	0.388*											
All species	**0.132******	**0.199******	0.093***	0.081**	0.060*		-0.073**		-0.060*				0.052*
All wildfowl	**0.180******	**0.243******	0.138***	0.115**			-0.081*			-0.087*			
All waders	0.123***	**0.198******	0.081*	0.072*			-0.078*						

Table 3.2.1 (continued) Pearson correlation coefficients and *P*-values for correlations of the difference between numbers of birds counted at high tide and low tide with a suite of variables. n=39 in all comparisons. The correlation coefficients that remain significant after Bonferroni corrections have been applied are in bold. Only those variables found to be significant at P<0.05 are included.

$^{*}P<0.05$; $^{**}P<0.01$; $^{***}P<0.001$, $^{****}P\leq0.0001$

SPCODE	TOTAREA *ha*	INTAREA *ha*	SHORE *km*	CHANNEL *km*	LAT ^{o}	LONG ^{o}	TMAX ^{o}C	TMIN ^{o}C	TMEAN ^{o}C	RAINT *mm*	RAIND *days*	SNOWD *days*	AIRD *days*
MS												0.350*	
BG								0.349*					
WN			0.357*										
PO		-0.320*											
E.												0.348*	
LN					-0.346*								
GN	0.457**												
RP			0.476**	0.324*									
L.	-0.398*	-0.403*				-0.328*					-0.346*		
KN		-0.399*											
PS	-0.409**	-0.415**											
SN				0.370*									
BW											-0.328*		
BA	0.523***	**0.764******											
DR							0.376*			0.338*			
All species	-0.070**	**-0.127******			-0.065*		0.061*		0.051*		-0.053*		-0.060*
All wildfowl	-0.092*	**-0.152******			-0.101*			-0.092*	0.089*				-0.104**
All waders		-0.131***									-0.079*		

Table 3.3.1 Pearson correlation coefficients and *P*-values for correlations of the residual from the regression line with a suite of variables. n=39 in all comparisons. The correlation coefficients that remain significant after Bonferroni corrections have been applied are in bold. Only those variables found to be significant at $P<0.05$ are included.

$^{*}P<0.05$; $^{**}P<0.01$; $^{***}P<0.001$; $^{****}P\leq0.0001$

SPcode	Intercept ± SE	Partial regression coefficients ± SE										n and overall model significance	Model coefficients of determination adjusted for degrees of freedom r^2_{adj}
		TOTAREA *ha*	INTAREA *ha*	SHORE *km*	CHANNEL *km*	LAT *o*	LONG *o*	TMAX *^oC*	RAINT *days*	SNOWD *days*	AIRD *days*		
LG	2.216 ±3.142		0.065 ± 0.031^{*}									39^{*}	0.108
GG	5.350 ±14.041			0.347 ±0.137*								39^{*}	0.147
CA	-6.134 ±9.096	-0.011 ± 0.003^{****}	0.021 ±0.004^{****}	0.284 ±0.102^{**}								39^{****}	0.459
SU	-78.869 ±108.821		0.194 ±0.034^{****}	-3.135 ±1.095^{**}								39^{****}	0.481
WN	201.403 ±342.313		0.248 ±0.115^{*}									39^{*}	0.112
T.	90.893 ±95.800		0.186 ±0.028^{****}				-74.902 ±28.322^{*}					39^{****}	0.566
MA	22.322 ±47.671		0.091 ±0.016^{****}									39^{****}	0.466
PT	-51.561 ±56.777		0.167 ±0.018^{****}		-7.572 ±2.680^{**}							39^{****}	0.717
SV	38.211 ±11.019^{**}						-7.820 ±3.664^{*}					39^{*}	0.110
PO	-2.756 ±10.880		0.014 ±0.004^{***}									39^{***}	0.285
TU	-30.225 ±15.353	0.010 ±0.002^{****}								33.147 ±15.990^{*}		39^{****}	0.449

Table 3.4.1 The intercepts, partial regression coefficients and coefficients of determination of multiple regression equations selected by forward stepwise regression relating the difference between numbers of birds counted at high tide and low tide to a suite of estuarine variables.
$^{*}P<0.05$; $^{**}P<0.01$; $^{***}P<0.001$; $^{****}P\leq0.0001$

SPcode	Intercept ± SE	Partial regression coefficients ± SE										*n* and overall model significance	Model coefficients of determination adjusted for degrees of freedom r^2_{adj}
		TOTAREA *ha*	INTAREA *ha*	SHORE *km*	CHANNEL *km*	LAT °	LONG °	TMAX ^oC	RAINT *days*	SNOWD *days*	AIRD *days*		
SP	-954.064 ±352.267*					27.768 ±5.077****		-43.408 ±19.888*			-27.264 ±5.244****	39****	0.567
E.	-340.868 ±128.691*			2.555 ±1.026*						355.641 ±134.262*		39**	0.318
LN	-30.916 ±12.027*			0.258 ±0.096*						29.363 ±12.548*		39**	0.310
CX	-87.571 ±32.443*			0.609 ±0.259*						100.360 ±33.848**		39***	0.335
GN	-141.233 ±59.478*			1.245 ±0.474*						140.648 ±62.053*		39**	0.298
OC	-569.596 ±166.550**	-0.178 ±0.048***	0.710 ±0.086****									39****	0.704
GP	-75.401 ±207.654			6.464 ±2.027**								39**	0.216

Table 3.4.1 (continued) The intercepts, partial regression coefficients and coefficients of determination of multiple regression equations selected by forward stepwise regression relating the difference between numbers of birds counted at high tide and low tide to a suite of estuarine variables. $^{*}P<0.05$; $^{**}P<0.01$; $^{***}P<0.001$; $^{****}P\leq0.0001$

L.	-308.221 ±408.580		0.449 ±0.129**	17.496 ±5.097**	-56.994 ±25.389*							39****	0.454
SS	-18.072 ±16.402		0.049 ±0.005****		-2.276 ±0.774**							39****	0.719
DN	-1377.201		0.490									39*	0.105

SPcode	Intercept ± SE	Partial regression coefficients ± SE										*n* and overall model significance	Model coefficients of determination adjusted for degrees of freedom r^2_{adj}
		TOTAREA *ha*	INTAREA *ha*	SHORE *km*	CHANNEL *km*	LAT °	LONG °	TMAX ^oC	RAINT *days*	SNOWD *days*	AIRD *days*		
	±701.355		±0.235*										
SN	357.096 ±167.907*					-6.464 ±3.169*						39*	0.101
BW	-56.088 ±36.151		0.043 ±0.012**									39**	0.258
BA	65.549 ±88.437		-0.144 ±0.022****							238.663 ±91.107*		39****	0.579
CU	-131.655 ±71.700		0.179 ±0.024****									39****	0.601
DR	10.853 ±4.436*							-1.310 ±0.530*				39*	0.142
RK	-176.570 ±101.942		0.127 ±0.034***									39***	0.272

Table 3.4.1 (continued) The intercepts, partial regression coefficients and coefficients of determination of multiple regression equations selected by forward stepwise regression relating the difference between numbers of birds counted at high tide and low tide to a suite of estuarine variables.
$^*P<0.05$; $^{**}P<0.01$; $^{***}P<0.001$; $^{****}P\leq0.0001$

CS	-0.368 ±0.166*								0.005 ±0.002*			39*	0.146
TT	-0.556 ±15.717	0.010 ±0.003**										39**	0.232
All species	-55.675 ±27.382*		0.072 ±0.009****									1521****	0.039

SPcode	Intercept ± SE	Partial regression coefficients ± SE										n and overall model significance	Model coefficients of determination adjusted for degrees of freedom r^2_{adj}
		TOTAREA *ha*	INTAREA *ha*	SHORE *km*	CHANNEL *km*	LAT º	LONG º	TMAX ^oC	RAINT *days*	SNOWD *days*	AIRD *days*		
All wildfowl	143.646 ±74.962		0.063 ±0.010****						-1.904 ±0.920*			624****	0.065
All waders	-111.222 ±47.358*		0.090 ±0.016****									780****	0.039

Table 3.4.1 (continued) The intercepts, partial regression coefficients and coefficients of determination of multiple regression equations selected by forward stepwise regression relating the difference between numbers of birds counted at high tide and low tide to a suite of estuarine variables.
$^{*}P$<0.05; $^{**}P$<0.01; $^{***}P$<0.001; $^{****}P$≤0.0001