Solent Disturbance and Mitigation Project Phase II

Predicting the impact of human disturbance on overwintering birds in the Solent

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A report for the Solent Forum

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Summary

The Solent coastline provides feeding grounds for internationally protected populations of overwintering waders and wildfowl, and is also extensively used for recreation. In response to concerns over the impact of recreational pressure on birds within protected areas in the Solent, the Solent Forum initiated the Solent Disturbance and Mitigation Project to determine visitor access patterns around the coast and how their activities may influence the birds. The project has been divided into two phases. Phase I collated and reviewed information on housing, human activities and birds around the Solent, and reviewed the potential impact of disturbance on birds. Phase II has involved a programme of major new data collection to (i) estimate visitor rates to the coast from current and future housing, (ii) measure the activities and distances moved by people on the shore and intertidal habitats, and (iii) measure the distances and time for which different bird species respond to different activities.

The current report represents the culmination of Phase II, in which the primary data are used to predict whether disturbance may be reducing the survival of birds. Predictions are derived for wader species by developing detailed computer models of birds and disturbance within Southampton Water and Chichester Harbour. These models create a virtual environment within the computer incorporating the intertidal invertebrate food supply of the birds, the exposure and covering of this food through the tidal cycle, disturbance from human activities, and the energy requirements and behaviour of the birds as they avoid humans and search for food. The invertebrate food supply of birds in the models was derived from previous intertidal surveys, and the exposure of intertidal habitat predicted from a tidal model of the Solent. The models incorporate the costs that birds incur when avoiding human activities (e.g. increased density in non-disturbed areas, reduced time for feeding and increased energy demands when flying away), but also their abilities to compensate for these costs (e.g. by feeding for longer or avoiding more disturbed areas). The predictions indicate how disturbance may be effecting the survival of waders throughout the Solent. The following waders were included in the models: Dunlin *Calidris alpina*, Ringed Plover *Charadrius hiaticula*, Redshank *Tringa totanus*, Grey Plover *Pluvialis squatarola*, Black-tailed Godwit *Limosa limosa*, Bar-tailed Godwit *Limosa lapponica* (Chichester Harbour model only), Oystercatcher *Haematopus ostralegus* and Curlew *Numenius arquata*. A simpler approach was used to assess how disturbance may be effecting Brent Geese in the Solent.

As with any models, the predictions of the models used in this project depend on the data with which they are parameterised and the assumptions they make about the real system. The current and future visitor rates used in the models were themselves predicted using statistical analyses of household survey and on-site visitor data. The responses of birds to disturbance were parameterised using on-site observations of the responses of birds to disturbance. Furthermore, models are a simplification of real systems, and it is important to recognise this when interpreting their predictions. The report considers how the model parameters and assumptions may influence predictions. These include: (i) the way in which the disturbance data were measured and assumptions made about how birds and people are distributed in space and time; (ii) the way in which the behaviour of birds to disturbance differs between sites; (iii) the effect of extreme weather on the birds; (iv) how rare or localised activities are incorporated into the models; and (v) how consumption of food by species other than waders is included.

The project predicted changes in visitor numbers to the Solent coast. Local authorities in the Solent region provided projections of future housing developments

in the region. These were combined with data on visitor rates to different parts of the coast and the distance travelled to visit the coast, to predict coastal visitor rates with current and future housing. Using current housing levels, 52 million household visits per year to the Solent coast were predicted (i.e. the shore from Hurst Castle to Chichester Harbour, including the north shore of the Isle of Wight). Using the housing data provided by local authorities, visitor numbers were predicted to rise by around 8 million household visits, to a total of 60 million, an overall increase of 15%.

Within Chichester Harbour, the food supply surveyed was not predicted to be able to support the majority of wading birds modelled. This implied that either the invertebrate survey underestimated the intertidal food supply, or that other food was available either terrestrially, or from neighbouring intertidal sites such as Langstone Harbour. Similar invertebrate surveys have been used to parameterise 17 other similar models, and in all cases birds were predicted to have survival rates close to, or higher than those expected. Due to uncertainties with the Chichester Harbour invertebrate data, it was decided not to use the Chichester Harbour model to predict the effect of disturbance on the birds. However, it is important to note what the effect of low food abundance would be on the effect of disturbance on the birds. The impact of disturbance on survival and body condition will depend on the birds' ability to compensate for lost feeding time and extra energy expenditure. Birds will be better able to compensate when more food is available, and so lower food abundance in a site will make it more likely that disturbance decreases survival and body condition.

Within Southampton Water, in the absence of disturbance, all wader species modelled were predicted to have 100% survival and maintain their body masses at the target value throughout the course of winter. Disturbance from current housing was predicted to reduce the survival of Dunlin, Ringed Plover, Oystercatcher and Curlew. Increased visitor numbers as a result of future housing was predicted to further reduce the survival of Dunlin and Ringed Plover. Disturbance was predicted to have a relatively minor effect on the mean body mass of waders surviving to the end of winter, largely because the individuals with very low mass starved before the end of winter. The Southampton Water model provided evidence that current and future disturbance rates may reduce wader survival in this site.

Hypothetical simulations were run to explore how intertidal habitat area, energy demands of the birds and the frequency of different activities may influence the survival of waders within Southampton Water. The survival rates of Dunlin, Ringed Plover, Oystercatcher and Curlew were predicted to be decreased by any reduction in intertidal habitat area (e.g. due to sea level rise) or increases in energy demands (e.g. due to disturbance at roosts or cold weather). Wader survival was predicted to increase if intertidal activities were moved to the shore. This meant that the disturbance from these activities was restricted to the top of the shore rather than the whole intertidal area, and so the proportion of intertidal habitat disturbed was reduced. Reductions in the number of dogs that were off leads were also predicted to increase the survival of some wader species. Removing bait digging from simulations did not increase wader survival. However, this happened because bait-digging was assumed to be a relatively infrequent activity. This does not mean that bait-digging could not adversely affect the birds if it occurs at a higher frequency, and the simulations did not incorporate the depletion of the invertebrate prey of the birds caused by bait digging, which would be an additional effect on the birds in addition to disturbance.

Brent Geese were considered in the light of the Solent Waders and Brent Goose Strategy. Important issues are the size of individual sites, their spacing and the ease with which birds can move between the sites. A high proportion of each site needs to be further away from visitor access routes than the distances over which birds are disturbed to ensure that disturbance to the birds is minimised. This could be achieved through a network of larger sites or by preventing visitor access through, or close to, smaller sites. Both intertidal and terrestrial food resources are important to the birds, intertidal food typically being of higher food value but dying back and / or becoming depleted during the autumn / early winter. Previous models of Brent Geese have predicted that the loss of terrestrial habitat typically has the highest effect on survival, and so such habitat is predicted to be particularly important for the birds. Maintaining a suitable network of saltmarsh sites will be increasingly important as the total area of saltmarsh declines with sea level rise. The findings of the present project are in general support with the recommendations of the Solent Waders and Brent Goose Strategy.

Predicted current visitor rates varied widely throughout the Solent, but were relatively high within Southampton Water. The highest percentage increases in visitor rates were on the Isle of Wight (50-75%). Wader survival was predicted to be decreased in Southampton Water when daily visitor rates to coastal sections were greater than 30 per ha of intertidal habitat. The potential impact of visitors on wader survival throughout the Solent was calculated by comparing visitor densities throughout the Solent (expressed relative to maximum intertidal habitat area) to the visitor densities predicted to decrease bird survival within Southampton Water. The intertidal food supply within Chichester Harbour was insufficient to support the model birds and so any disturbance (by reducing feeding area or time, or increasing energy demands) would have decreased predicted survival in this site. There is also doubt as to the food supply within the other harbours and so some caution is appropriate when applying the results from Southampton Water to these sites. Coastal sections with daily visitor rates over 30 per ha are identified. The predictions of the Southampton Water model suggest that birds within these sections may have reduced survival due to disturbance from visitors. Whether or not such visitor rates will reduce survival will depend on the food abundance in the coastal sections themselves as well as that in neighbouring sections.

The area of overlap between an activity / development and the distribution of birds is often used as a measure of the impact of the activity on the birds, with 1% overlap often taken as the threshold for impact (note however that this 1% overlap does not necessarily mean that an activity will have an adverse effect on the survival or body condition of birds). Therefore, the percentage of intertidal habitat disturbed within each coastal section was calculated as an index of the potential impact of disturbance on the birds. Assuming the maximum intertidal area and only including intertidal visitors, over 50% of the area of many coastal sections was predicted to be disturbed, with an average of 42%.

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Section 1 Introduction

1.1 Overview of the Solent Disturbance and Mitigation Project

The Solent coastline provides feeding grounds for internationally protected populations of waders and wildfowl, but is also extensively used for recreation by people. The region is highly populated, and future increases in housing are likely to further increase human access to the coast. There is concern that current or future levels of human activity may have a detrimental effect on the Solent's bird populations. In response to concerns over the impact of recreational pressure on features of the Solent Special Protection Areas (SPAs), Special Areas of Conservation (SACs) and Ramsar Sites, the Solent Forum initiated the Solent Disturbance and Mitigation Project to measure how people exploit the coast and how their activities may influence the birds.

Phase I of the project (Stillman et al. 2009) (i) collated existing data on the distribution of housing and human activities around the Solent, (ii) assessed stakeholder opinion of the importance of recreational disturbance on birds through a series of workshops and interviews, (iii) collated data on bird distribution and abundance around the Solent and (iv) outlined the range of mitigation measures that could potentially minimise the impacts of increased recreational disturbance caused by increased housing in the Solent area.

Phase II of the project has involved a programme of major new data collection to measure the distribution and numbers of visitors, predict how these may change with future housing and to predict the behavioural responses of birds to visitors.

Fearnley, Clarke & Liley (2010) (hereafter referred to as Fearnley et al. (2010)) performed on-site interviews of visitors to 20 sections of the Solent coast to determine patterns of access, the frequency of different activities and the distance travelled by visitors along the coastal shoreline and across intertidal habitats.

Liley, Stillman & Fearnley (2010) (hereafter referred to as Liley et al. (2010)) conducted on-site surveys of the response of birds to visitor activities in the same 20 sections surveyed by Fearnley et al. (2010). These data were used to determine the distribution of birds in relation to visitor numbers, and the distances and time for which different bird species responded to different activities throughout these sites.

Fearnley, Clarke & Liley (2011) (hereafter referred to as Fearnley et al. (2011)) conducted a household questionnaire postal survey of residences within the Solent region. The survey data were used to understand coastal visitor rates and activities, how these vary seasonally and daily, and to predict how visitor rates may change in the future with increased housing.

The current project represents the culmination of Phase II of the Solent Disturbance and Mitigation Project, in which all the primary data collected within Phase II is used and modelled with information on tidal exposure and food abundance to understand how disturbance may affect the survival of birds.

1.2 Overview of the current project

The overall aim of the current project is to determine whether visitor rates within the Solent are likely to be reducing the number of birds that are able to survive within the region. The previous studies have measured the number of visitors to the coast and the behavioural response of birds to these visitors (e.g. the distance at which birds take flight or the time for birds to resume feeding). Birds usually have some form of cost when they respond to human activities, for example, less time to feed or higher energy expenditure when they fly away. Whether these costs mean that birds will die or be in poorer condition because of the disturbance depends on their ability to compensate for these costs. They can do this by feeding for longer, or by flying to another location with a similar amount of food to the location from which they were displaced. It does not necessarily follow that birds will starve or be in poorer condition just because they have been disturbed by human activities. However, birds will be less able to compensate for disturbance, and so more likely to starve, when food supplies are low, there are less alternative places to feed and when disturbance rates are higher. Understanding how these factors influence the survival of the birds requires an understanding of the food available to the birds, as well as how they respond to human disturbance. It also requires some form of modelling to keep track of the various costs incurred by the birds, and their ability to compensate for these costs.

This project uses an individual-based model (MORPH) of the bird populations and their responses to human activities to predict the effect on bird survival of current and future amounts of human activity. The project also predicts the impacts on the birds of expected sea level rise and how any impacts of disturbance can be reduced by alternative ways of managing the coast. MORPH is a computer model that follows the behaviour and fate of individual birds within a population as they attempt to meet their daily food requirement while responding to human disturbance and other environmental factors. In effect, the model creates a virtual environment within the computer representing the real system as closely as possible. The model predicts survival rate from the fates of individuals. MORPH and similar models have been used to advise conservation management of birds in several UK sites (Stillman & Goss-Custard 2010). Appendix 1 gives a general overview of MORPH, including the types of conservation issues to which it has been applied and ways in which the accuracy of its predictions have been tested. MORPH requires detailed information on the food supply of the birds and the way in which they respond to disturbance. Data on food supply was only available for overwintering wading birds in Chichester Harbour and Southampton Water, and so the model is restricted to these species. The detailed predictions for Southampton Water are then used to infer how human disturbance throughout the Solent is likely to be influencing waders. Brent Geese are also considered in the project, but are not modelled in the same way as waders.

It was not possible to predict the effect of disturbance on the population sizes of other species within the Solent. This was because suitable data were not available for these species. Further details of the species within the Solent and a review of the potential impact of disturbance on birds can be found in Stillman et al. (2009).

1.3 Aims and objectives of the project

The overall aims of the project were to predict whether current or future amounts of human access to the Solent coast adversely affect overwintering bird populations, and how any adverse effects could be reduced by alternative ways of distributing housing or managing the coast. These aims were addressed through the following objectives.

1) To estimate the effect of human activities on the intertidal feeding habitat area and feeding time for waders.
2) To develop an individual-based model to predict the impact of disturbance on overwintering waders in Southampton Water. To account for current and future housing, sea level rise and alternative ways of managing human access to the coast.
3) To develop an individual-based model to predict the impact of disturbance on overwintering waders in Chichester Harbour. To account for current and future

housing, sea level rise and alternative ways of managing human access to the coast.

4) To use the predictions of the Southampton Water and Chichester Harbour models to infer how human disturbance throughout the Solent is likely to be effecting overwintering waders. To account for current and future housing, sea level rise and alternative ways of managing human access to the coast.
5) To measure the overlap between human activities, Brent Geese and their food supplies to determine whether disturbance could potentially be adversely affecting this species.

1.4 Structure of the report

To simplify the report, much of the technical details are contained within appendices. Section 2 describes how the individual-based model was parameterised for Southampton Water and Chichester Harbour (Objectives 1, 2 and 3). Section 3 describes the predictions for Chichester Harbour and Section 4 describes the predictions for Southampton Water (Objectives 2 and 3). Section 5 uses the detailed predictions for Southampton Water to infer how human disturbance influences waders throughout the Solent (Objective 4). Section 6 quantifies the overlap between human activities, Brent Geese and their food supplies to assess the potential effect of human disturbance on this species (Objective 5). Section 7 summarises the results of the project and describes its conclusions. Appendix 2 lists the datasets used in the project and indicates which were derived from previous Solent Forum projects.

Section 2 Chichester Harbour and Southampton Water models

This section gives an overview of how the MORPH individuals-based model was parameterised for Chichester Harbour and Southampton Water. Full details can be found in Appendix 3, Appendix 4 and Appendix 5. Appendix 3 describes the models in detail and lists all parameter values. Appendix 4 gives full details of how visitor rates to the coast and the responses of birds to these visitors were calculated. Appendix 5 details the disturbance scenarios for which simulations were ran.

2.1 Overview of the models

When parameterised for Southampton Water and Chichester Harbour, MORPH followed the foraging decisions (i.e. patch and prey choice) of each bird, as they attempted to meet their daily energy requirements. The model included the successive exposure and covering of intertidal patches through the tidal cycle, and also included the day / night cycle to account for the variation of bird behaviour and human activities between night and day. The model divided time into a sequence of time steps, during each of which birds either moved to the patch on which their net rate of assimilating energy (energy gained minus energy costs) was greatest or roosted (and did not feed) if no patches were available. The model predicted the distribution of birds between patches, which prey species were consumed by the birds, how much time birds needed to feed for to meet their requirements, the body mass of birds and the percentage of birds that survived to the end of winter. Disturbance from human activities was incorporated by excluding birds from disturbed areas, reducing the time birds had available to feed and increasing their energy demands.

2.2 Time and environmental conditions

Simulations ran from 1st September to 31st March, encompassing the major overwintering period of most waders in the UK, and peaks in the wintering numbers of waders in the Solent. Simulations proceeded in one hour time steps, during each of which environmental conditions were assumed to remain constant. The models incorporated the diurnal cycle, with daylight assumed to occur between the times of sunrise and sunset, and the tidal cycle.

2.3 Space and tidal exposure of patches

The models comprised the intertidal feeding habitat of waders in Southampton Water and Chichester Harbour. The models divided this space into a number of patches based on the coastal sections defined in the Solent Disturbance and Mitigation Project (e.g. Fearnley et al. 2011) (Figure 2.1). Southampton Water comprised coastal sections 13 to 32 (Table A3.1), and Chichester Harbour sections 64 to 84 (Table A3.2), with each section represented by a different patch. In addition, both models incorporated one roost patch. This patch represented a number of potential roost sites throughout the real systems, and was used by the birds for roosting when no intertidal patches were exposed by the tide. Figure 2.2 shows the Southampton Water model and Figure 2.3 shows the Southampton Water model.

The tidal exposure of patches was predicted by a Solent-wide tidal model simulation developed by ABPmer. For each hour time step the model predicted the area of intertidal habitat exposed within each patch derived from an average spring-neap cycle. The maximum intertidal area of each patch was defined as the area between high tide on the lowest neap tide and low tide on the lowest spring tide. This assumed that the invertebrate food supply of the birds would be absent or insignificant above high tide on the lowest neap tide as any area above this point would remain dry throughout some tidal cycles.

Simulations of the Southampton Water model further divided this site into a number of sub-sites to restrict bird movement (see Section 4 for more details). These divisions were based on observations of bird movement within the site (Wood 2007) (three sub-site version), or a finer division of the site (six sub-site version). The restrictions were used because in their absence birds were predicted to move around the site to a greater extent than observed (Wood 2007). Table 2.1 indicates the relationships between sector number and sub-site number for the alternative model versions used. The three sub-site model split the site into southern, mid and northern associations of sectors based on the observation that birds tended to fly more across the site than along its length (Wood 2007). The six sub-site model was designed to test the effect of further restricting bird movement. The southern association of the three sub-site model was further divided into the western and eastern shores. In addition, the mid association was divided into the western shore, eastern shore and River Itchen. Birds were assumed to move without cost within a sub-site and have perfect knowledge of food abundance, availability through the tidal cycle and visitor numbers.

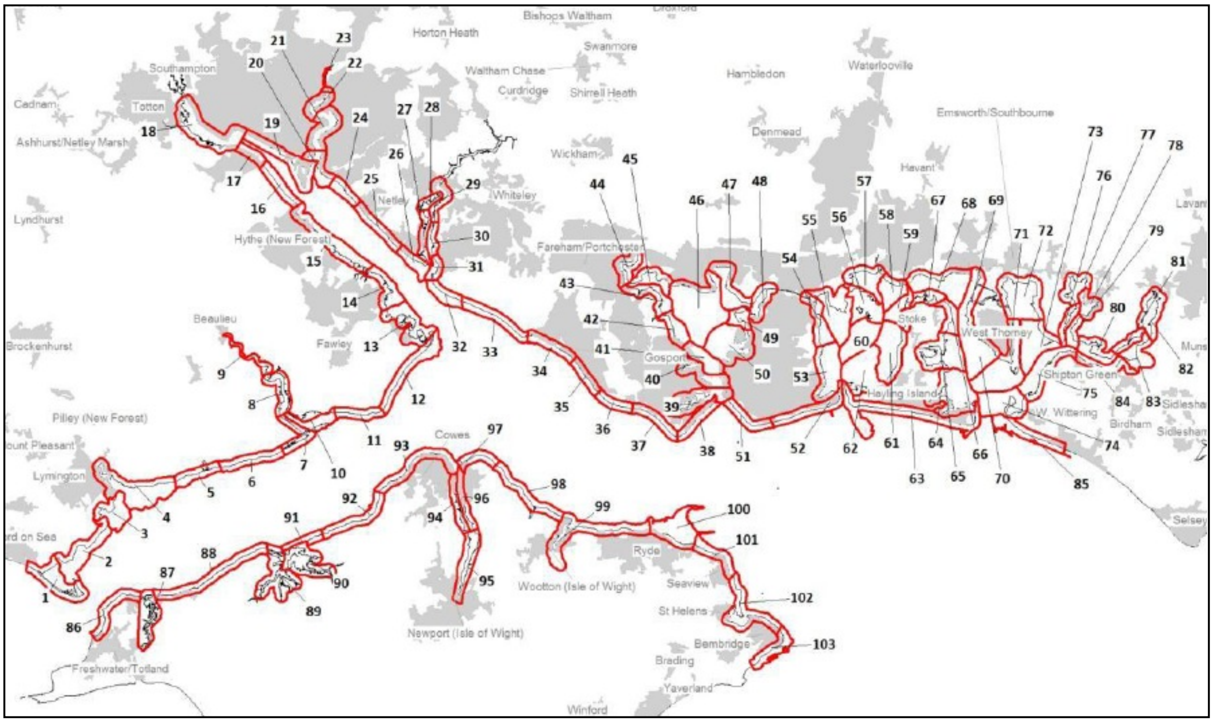


Figure 2.1 Location of the 103 coastal sections defined in the project.

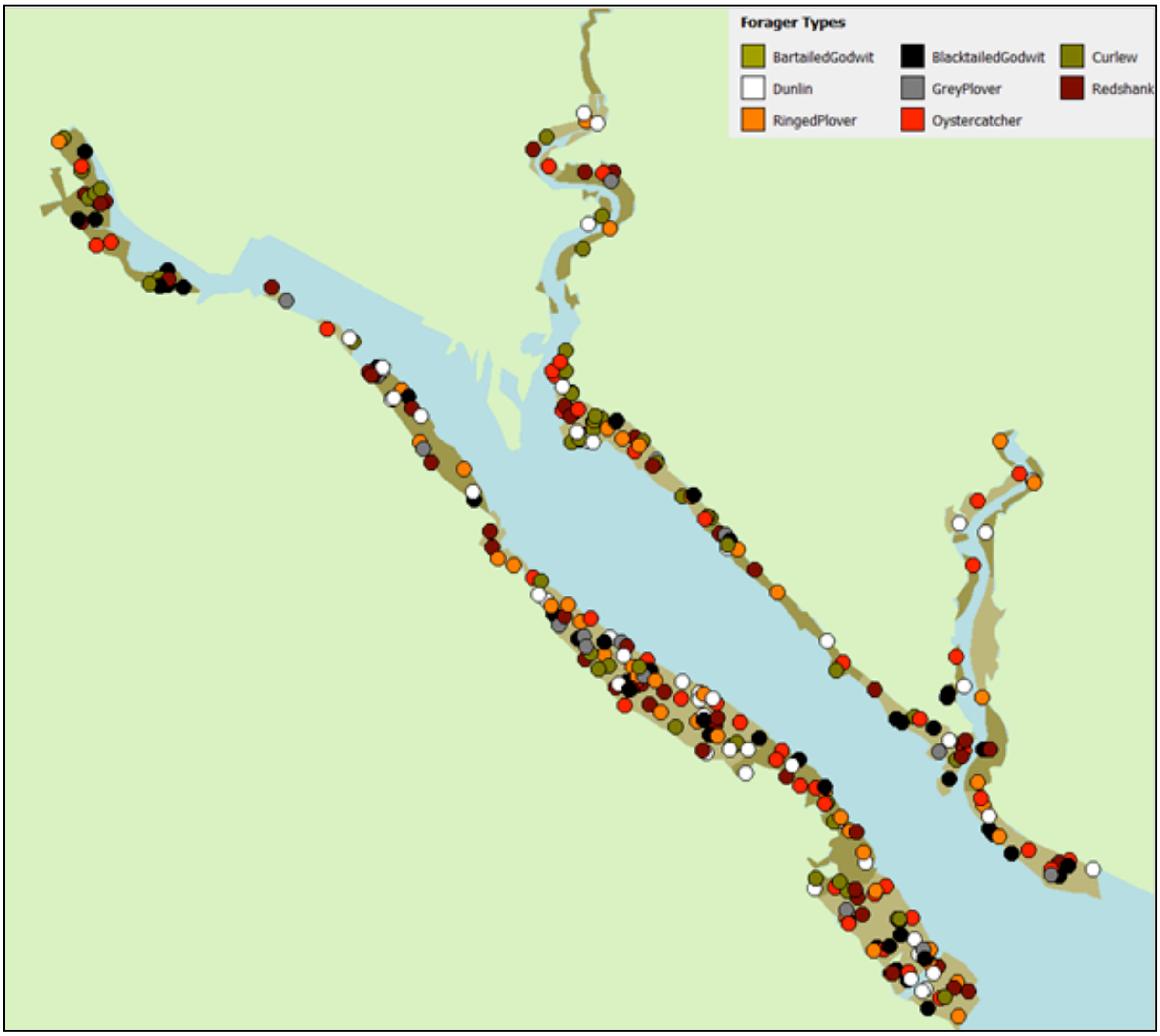


Figure 2.2 Screen shot of the Southampton Water model showing an example low tide distribution of the birds.

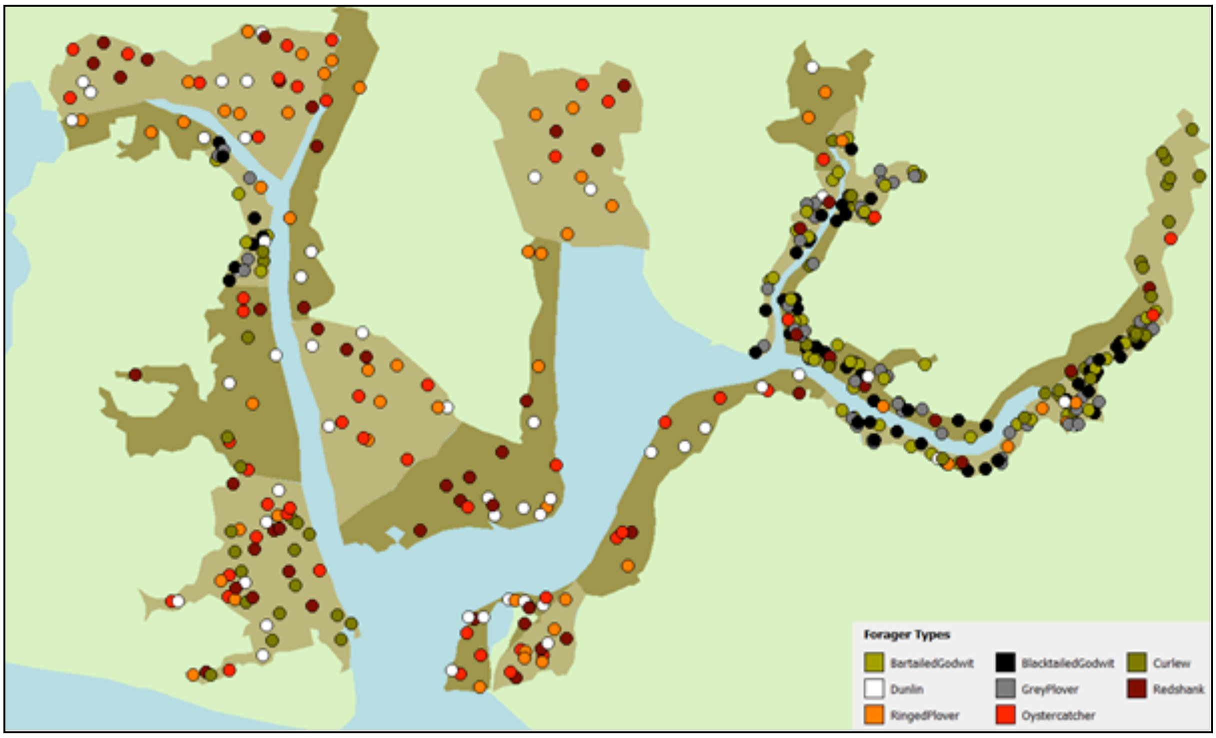


Figure 2.3 Screen shot of the Chichester harbour model showing an example low tide distribution of the birds.

Table 2.1 Relationships between sector number and sub-site number used in the alternative versions of the Southampton Water model.

	Sub-site number	
Sector	3 sub-sites	6 sub-sites
13	1	1
14	1	1
15	2	3
16	2	3
17	3	6
18	3	6
20	2	4
21	2	5
22	2	5
23	2	5
24	2	4
25	2	4
26	2	4
27	1	2
28	1	2
29	1	2
30	1	2
31	1	2
32	1	2

2.4 Food supply for the birds

The intertidal food supply of the birds was derived from intertidal invertebrate surveys of Southampton Water and Chichester Harbour. Southampton Water was surveyed from 108 sampling locations during September 2003 (Wood 2007). Chichester Harbour was surveyed from 45 sampling locations during October 2006 (Emu 2007). Both of these surveys were designed to provided suitable data from an individual-based model, and so measured the size distribution and biomass of invertebrates in addition to their numerical density. The data from these surveys was used to determine the food supply for the birds at the start of winter (Table A3.3; Table A3.4; Table A3.5). The following prey types were included in the models: marine worms, bivalves (split into cockles and other bivalves in Chichester Harbour), Crustacea and *Hydrobia*. Both models assumed that depletion by the birds was the only source of mortality of the prey during the course of winter. The evidence for this was that there was no detectable overwinter decline in prey abundance observed in the Southampton Water invertebrate survey (Wood 2007).

2.5 Bird body mass, energy demands and starvation

The following bird species were included in the models: Dunlin *Calidris alpina*, Ringed Plover *Charadrius hiaticula*, Redshank *Tringa totanus*, Grey Plover *Pluvialis squatarola*, Black-tailed Godwit *Limosa limosa*, Bar-tailed Godwit *Limosa lapponica* (Chichester Harbour model only), Oystercatcher *Haematopus ostralegus* and Curlew *Numenius arquata*. The bird population sizes in the model were derived from Wetland Bird Survey (WeBS) 5-year winter peak mean counts (Table A3.6). All birds were assumed to arrive on the first day of simulations and remained until the final day of the simulation unless they died of starvation during the course of winter.

Model birds had a target body mass that they attempted to maintain throughout the course of winter (Table A3.6). Target body mass was based on the observed body masses of the different bird species. The daily energy requirements of the birds were calculated from the body mass of each species, but also potentially included the cost of avoiding disturbance. If birds were able to consume enough food to meet their energy requirements, they maintained or increased their body mass up to the target mass. Birds that could not meet their energy requirements had to draw on their energy reserves and so lost mass. Each species also had a starvation body mass, derived from the observed mass of starved birds (Table A3.6). If the mass of a model bird decreased to the starvation body mass, the bird died of starvation. Starvation was the only source of bird mortality included in the model.

2.6 Foraging behaviour of the birds

The diets of birds (prey species and size ranges consumed) were based on the observed diets of real birds (Figure A3.1). Typically, the larger bird species consume larger prey. Oystercatcher can consume larger bivalves than the other species as this species opens bivalves and then consumes the flesh, rather than consuming the shell and flesh whole. The rate at which birds consumed food depended on the density of prey and potentially on the density of competitors of the same species. The influence of prey and competitor density on feeding rate was based on prey and bird size, and the mobility of prey. Feeding rate was predicted from prey density, the mass of an individual prey item and bird body mass (see Section A3.4.9). The rate of consuming prey increased with prey density, prey mass and bird mass. The influence of competitors depended on competitor density, prey size and mobility (see Section A3.4.9). Competitor density reduced feeding rate to a greater extent in species (e.g. Oystercatcher) consuming larger prey and / or mobile prey (i.e. worms and Crustacea). Larger prey take longer to consume than smaller prey and so there is typically more fighting over prey items within species consuming such prey, and mobile prey can escape into burrows when disturbed by foraging birds. As oystercatcher consume the largest prey they can be particularly vulnerable to reduced feeding rate when competitor density increases.

2.7 Responses of birds to disturbance

The effect of visitors on the birds depended on the number of visitors in each model patch and the responses of the birds to these visitors. The number of visitors was predicted from the household survey data collected by Fearnley et al. (2011) (see Appendix 4 for further details). The number of visitors to each patch accounted for the distribution of visitors between summer, autumn, spring and summer, and the fact that most visits occur during the hours of daylight. Visitors had three effects on the birds: reduced feeding area, lost feeding time and increased energy demands (see Section A3.5 for further details). These responses were calculated from the results of the bird on-site disturbance study (Liley et al. 2010). The area disturbed was calculated from the distances over which birds responded to visitors and the route lengths of visitors. The time and energy costs of each disturbance event were calculated from the time for which birds were observed to stop feeding after a disturbance and the distance over which they flew when disturbed. Both the number of visitors and the responses of birds to these visitors were therefore based on data collected during the project.

2.8 Disturbance scenarios simulated

The following disturbance scenarios were simulated (see Appendix 5 for further details).

Current and future housing. Based on current and predicted future access to the coast (Fearnley et al. 2010; Fearnley et al. 2011).

Sea level rise and habitat loss. Area of intertidal habitat area changed to simulate the effect of sea level rise and other processes.

Changes in numbers of visitors to the coast. Visitor numbers increased to test how increases beyond those expected with future housing would affect the birds.

Disturbance to birds on roosts. Increases in bird energy requirements to test the effect of disturbance at roosts.

Changes in the frequency of activities. Changes in the frequency of intertidal activities, dog walking and bait digging to test the effect of these activities on the birds.

Section 3 Predictions of the Chichester Harbour model

The Chichester Harbour model was run to predict the survival of birds in the absence of disturbance (Figure 3.1). Redshank and Oystercatcher were predicted to have 100% survival. In contrast, all other species were predicted to have lower survival rates. All Black-tailed Godwit, Bar-tailed Godwit and Curlew were predicted to die, and survival rates were also low in Dunlin, Ringed Plover and Grey Plover. The survival rates of these species were all lower than those typically observed (www.bto.org/birdfacts; assuming that 50% of annual mortality occurs during the over-winter period).

As starvation was the only source of mortality in the model, these results implied that the food supply of all species except Redshank and Oystercatcher was underestimated in the model, as such high mortality rates are unlikely in the real system. The densities of larger worms and bivalves (excluding cockles which were only consumed by oystercatcher and curlew in the model) were much lower in Chichester Harbour than in Southampton Water (Figure 3.2). These provide important food resources for the birds and explained why low survival rates were predicted in Chichester Harbour. Smaller worms and bivalves were more abundant in Chichester Harbour than in Southampton Water, but these do not provide such an important food resource for the birds. A major intertidal invertebrate survey of Chichester Harbour was conducted by Thomas (1987), and the data summarised in Emu (2004). These data could potentially have been used to determine whether the densities of worm and bivalve size classes were significantly different in the 2006 survey used to parameterised the model. However, the earlier study did not measure the size classes of invertebrates and so it was not possible to make such a comparison. Terrestrial food supplies were not included in the invertebrate survey and so were excluded from the model. These are likely to be important food supplies for species such as Curlew and Black-tailed Godwit which frequently feed in terrestrial habitats. However, Bar-tailed Godwit and Grey Plover do not frequently make use of such habitats and also had low predicted survival rates. Another possibility is that birds roosting in Chichester Harbour feed within the intertidal habitat of neighbouring Langstone Harbour.

To explore these possibilities seasonal changes in Wetland Bird Survey low and high tide counts for 2010/11 were compared (Figure 3.3). If birds tended to roost in Chichester Harbour but feed elsewhere (e.g. in Langstone Harbour of terrestrial habitats) low tide counts would be expected to be lower than high tide counts. If birds suffer very high mortality rates within Chichester Harbour, the number of birds would be expected to decline during the course of winter. However, there were no consistent patterns in the relative numbers of birds at low and high tide, and the abundance of most species remained relatively constant during the main overwintering period of November to February during which the low tide counts were recorded. Redshank and Oystercatcher tended to have lower low tide than high tide counts, but the food supply was predicted to be sufficient to support these species. Curlew had lower low tide than high tide counts, which would be consistent with this species roosting in the harbour but feeding elsewhere. In contrast, bar-tailed godwit had lower low tide than high tide counts, and yet low survival rates were predicted for this species.

The Chichester Harbour invertebrate survey was conducted using methods suitable for estimating the bird food supply in such individual-based models, and used a similar approach to that adopted in Southampton Water. The contractors that undertook the survey (Emu Ltd.) have undertaken many similar invertebrate surveys. They were contacted to discuss any problems that may have arisen during the survey, but no potential issues could be identified. Similar invertebrate surveys have been used to parameterise 17 individual-based models (including Southampton Water; Stillman & Goss-Custard 2010), and in all cases birds were predicted to have survival rates close to, or higher than those expected. However, one potential limitation of the Chichester Harbour invertebrate survey was the number of sampling locations relative to the total intertidal area; 45 sampling locations in an intertidal area of 11.6 km^2. In contrast, in Southampton Water there were 108 sampling locations in an intertidal area of 8.8 km^2. Sample density was 3.9 km^{-2} in Chichester Harbour and 12.3 km^{-2} in Southampton Water. It is possible that the lower sample density within Chichester Harbour missed clumped food supplies that occurred in a few places within the harbour (e.g. Lugworm *Arenicola marina*, which can be an important prey of Curlew and Bar-tailed Godwit), and also provided a poorer estimate of the abundance of less clumped food.

A range of approaches were used to attempt to increase the survival of the birds within the Chichester Harbour model. The energy requirements of all species except Redshank and Oystercatcher were reduced to simulate a situation in which these species obtained a proportion of their food requirements from food resources additional to those included in the model. Energy requirements needed to be reduced by approximately half before high survival rates were predicted, implying that these species need to obtain half of their daily energy requirements form other food sources. The abundance of food in the model was also increased to simulate a situation in which the invertebrate survey had underestimated the actual food supply. The amount of food needed to be more than doubled before the model predicted that the birds could survive throughout winter. Given that such large increases in the food supply or large decreases in energy requirements were required to increase survival, it was decided not to use the model to predict the effect of housing on the birds. This would have led to a situation in which the predictions of the model were more dependent on non-measured food supply than on that derived from the invertebrate survey.

In conclusion, it was decided that given uncertainties with the Chichester Harbour invertebrate data, the Chichester Harbour model should not be used to predict the effect of disturbance on the birds. However, given that this was the most up to date data available it is also important to draw some conclusions as to the likely effect of disturbance. The impact of disturbance on the birds' survival and body condition will depend on their ability to compensate for lost feeding time and extra energy expenditure. Birds will be better able compensate when more food is available, and so lower food abundance in a site will tend to increase the likelihood that disturbance decreases survival and body condition.

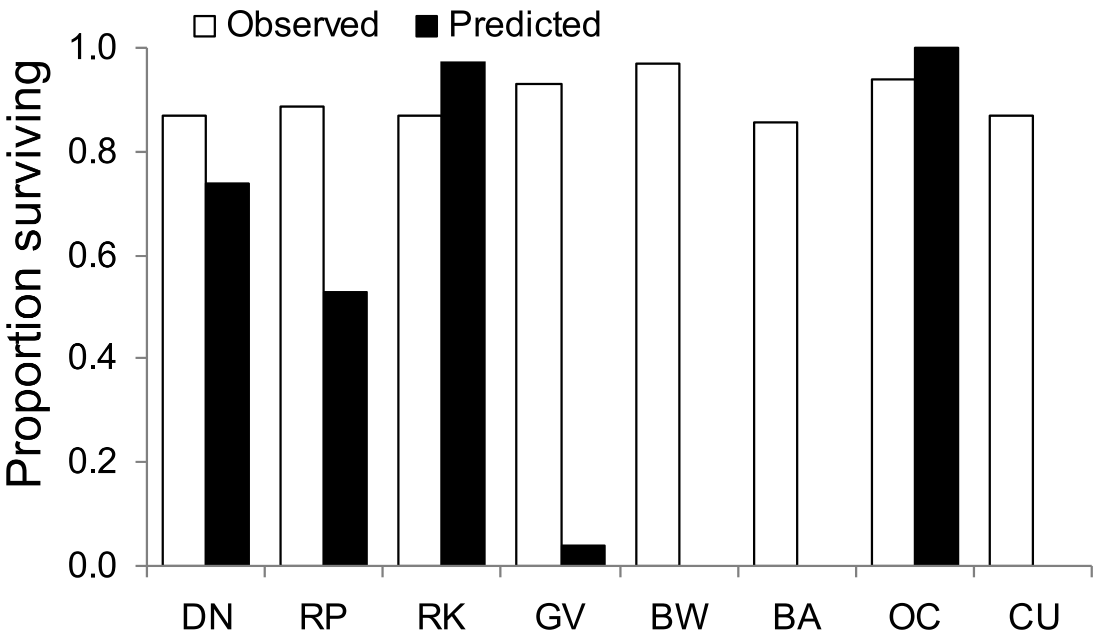
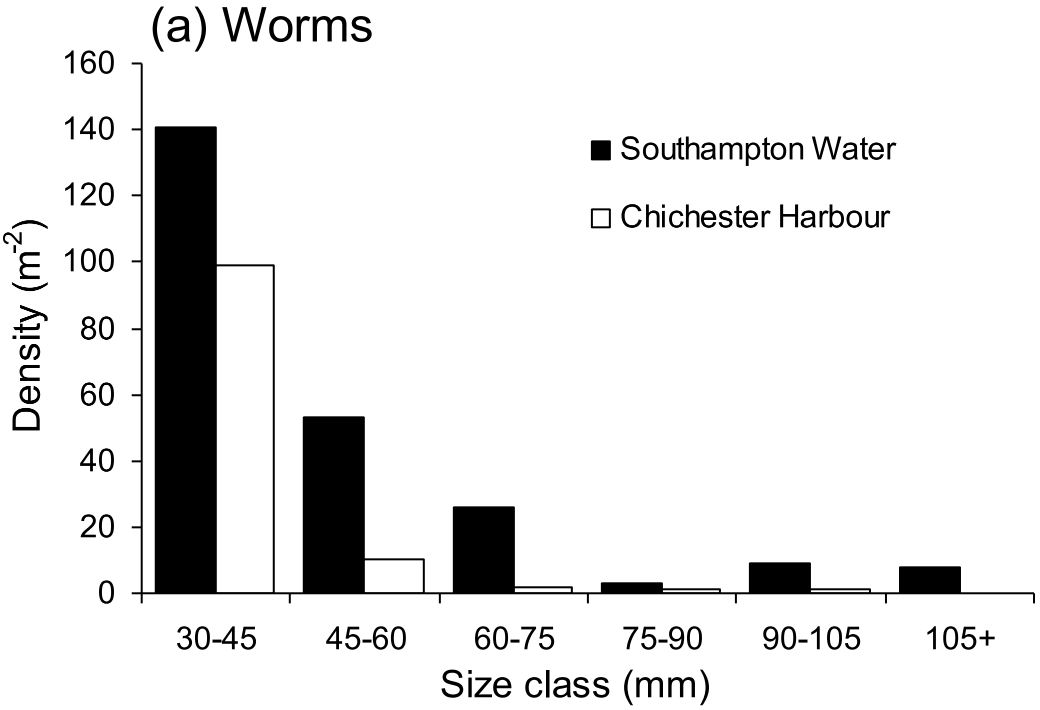


Figure 3.1 Observed and predicted survival of waders. Observed values are derived from adult annual survival rates (www.bto.org/birdfacts), assuming that 50% of annual survival occurs during the winter. These values are not specific to Chichester Harbour. Predicted values are the end-of-winter survival predicted by the Chichester Harbour model. Note that all Black-tailed Godwit, Bar-tailed Godwit and Curlew were predicted to die in Chichester Harbour. The following codes are used for the bird species: DN = Dunlin; RP = Ringed Plover; RK = Redshank; GV = Grey Plover; BW = Black-tailed Godwit; BA = Bar-tailed Godwit; OC = Oystercatcher; CU = Curlew.



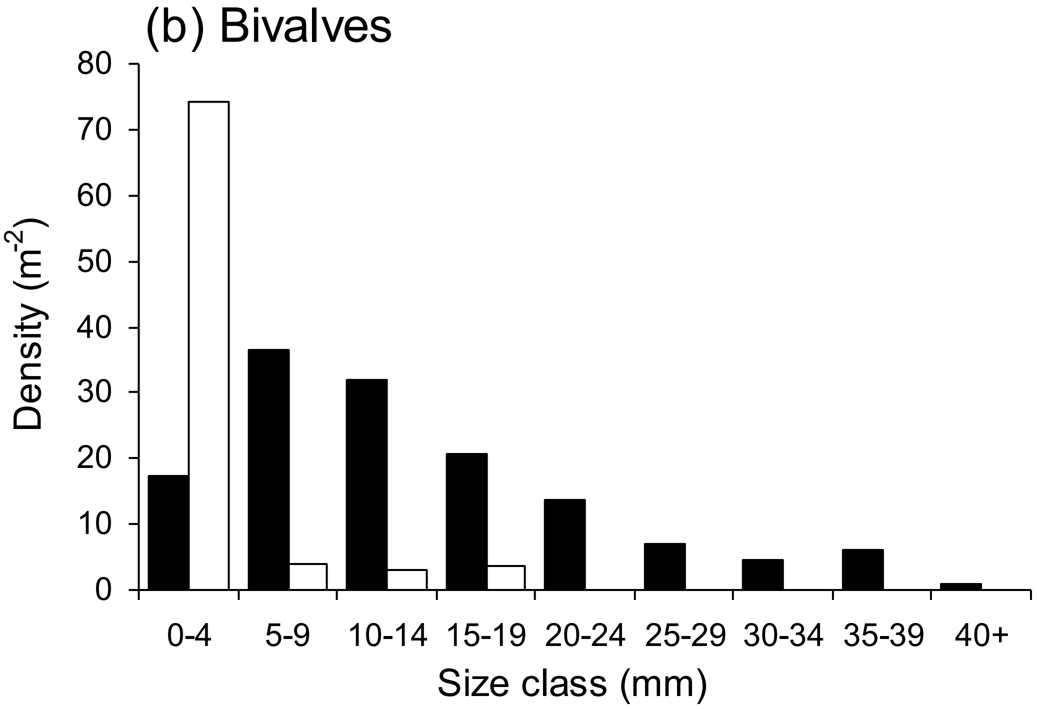


Figure 3.2 Density of worms (a) and bivalve (excluding cockles) (b) size classes in Chichester Harbour and Southampton Water. Data were derived from the intertidal invertebrate surveys of the sites. Cockles are excluded from (b) as these were only consumed by oystercatcher and curlew in the model.

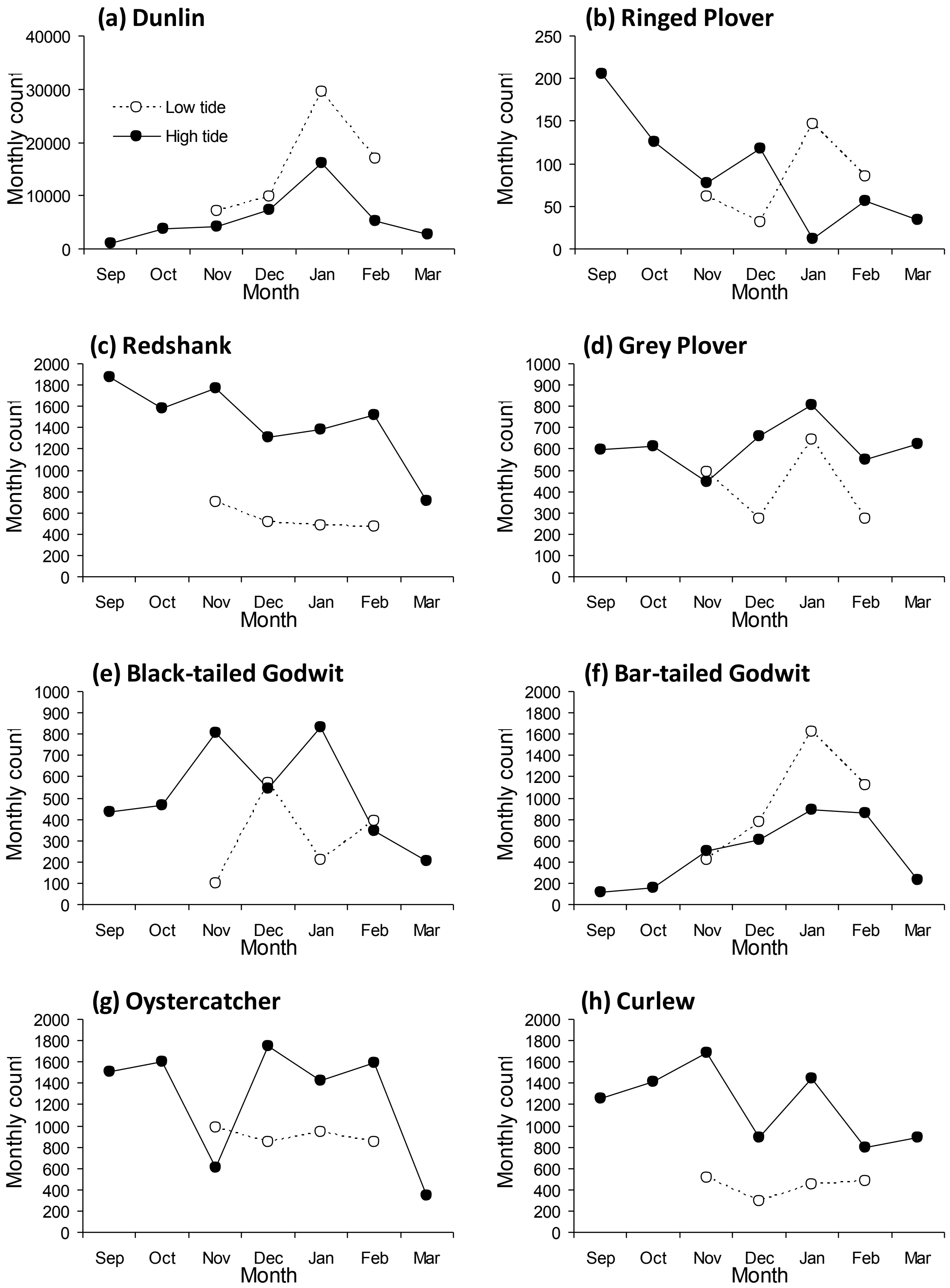

(a) Dunlin
(b) Ringed Plover
(c) Redshank
(d) Grey Plover
(e) Black-tailed Godwit
(f) Bar-tailed Godwit
(g) Oystercatcher
(h) Curlew

Figure 3.3 Monthly counts from the 2010/11 Wetland Bird Survey (WeBS) low tide and high tide counts in Chichester Harbour.

Section 4 Predictions of the Southampton Water model

4.1 Testing predictions

Most parameters within the model were either measured in the Southampton Water itself, predicted from other components of the Solent Disturbance and Mitigation Project or derived from data from other sites. One area of uncertainty, however, was the extent to which birds moved throughout the site, and the amount of knowledge they had of feeding conditions and disturbance rates throughout the site. This uncertainty was addressed by developing three versions of the model which differed in the amount of the site within which individual birds were able to move, and within which they had knowledge of feeding conditions and disturbance. The "no restriction" version assumed that birds were able to move freely throughout the whole of Southampton Water and so locate patches with low disturbance rates and / or high food abundance. The "three sub-site" version divided the site into southern, mid and northern sub-sites based on the observations of bird movements made by Wood (2007). The initial numbers of birds in each sub-site was derived from Wetland Bird Survey (WeBS) counts. Model birds could move freely within their "home" sub-site but could not move between sub-sites, dying of starvation if they could not consume food at a high enough rate. The "six sub-site" model further divided the site. The three sub-site model was the most directly related to observations but the other versions were considered due to the uncertainty associated with the extent of bird movements throughout the site. The three versions of the model were tested by comparing predicted wader overwinter survival, distribution and diets with observed or expected values. These simulations were based on the current housing scenario and so represented present day conditions in the site.

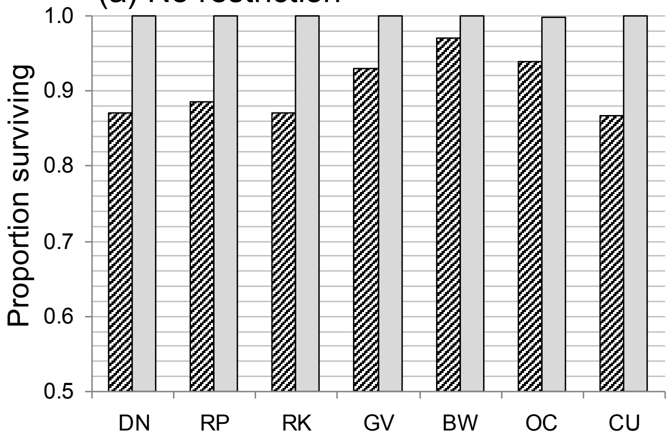
The three sub-site model most accurately predicted expected overwinter mortality (Figure 4.1). In the absence of restrictions to movement, predicted survival rate was 100% in all species. This happened because model individuals of each species were able to move throughout the site to find the patches that provided the best combination of low disturbance rates and high food availability. The six sub-site model predicted that the survival rate of Dunlin, Ringed Plover, Oystercatcher and Curlew were around 10% lower than expected. Higher mortality rates were predicted in these simulations because birds were more restricted in their movement and so could not always locate the areas of lowest disturbance. The three sub-site model predicted intermediate survival rates which were on average closer to the expected values.

The six sub-site model most accurately predicted the observed distribution of birds throughout the site, and the no restriction model least accurately predicted distribution (Figure 4.2). This happened because the six sub-site model constrained the movement of birds to a greater extent and the initial number of birds within each sub-site was based on the observed distribution of birds. The other models could have potentially predicted distribution with similar accuracy if the model distribution of the food supply and disturbance, and the behaviour of the model birds very closely matched that in the real system. This was not the case and so the models with less constraints on the distribution of the birds predicted distribution less accurately.

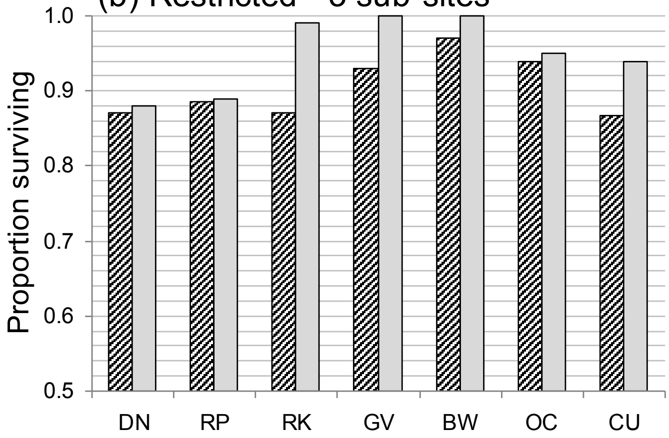
The diets consumed by the model birds were similar in the three model versions (Figure 4.3). Worms dominated the diets of most species. Crustacea comprised up to 20% of the diets of the smaller species (Dunlin, Ringed Plover and Redshank), with bivalves comprising a larger proportion of the diets of the larger species, particularly Black-tailed Godwit and Oystercatcher. As diets were very similar in the different model versions, they were not could not be used to determine which model best described the real system.

In summary, it was decided that the three sub-site model provided the best representation of the real system. Although this model did not predict the distribution of birds as accurately as the six sub-site model, it more accurately predicted expected survival and was based on observed movements of birds throughout the site. In contrast, the six sub-site model constrained the movements of model birds to a greater extent than real birds, and the no restriction model allowed birds to move too freely. The three sub-site model was therefore used as the basis for all the following predictions.

(a) No restriction



(b) Restricted - 3 sub-sites



(c) Restricted - 6 sub-sites

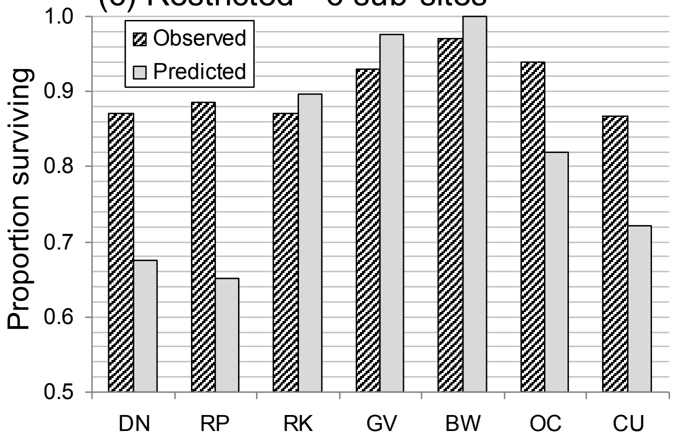


Figure 4.1 Observed and predicted survival of waders. Observed values are derived from adult annual survival rates (www.bto.org/birdfacts), assuming that 50% of annual survival occurs during the winter. These values are not specific to Southampton Water. Predicted values are the end-of-winter survival predicted by the Southampton Water model: (a) No restrictions on bird movement within the site; (b) site divided into 3 sub-sites; (c) site divided into 6 sub-sites (see text for details). The horizontal bars show the 95% confidence intervals of predicted survival – values must differ by more than this value to be significantly different. The following codes are used for the bird species: DN = Dunlin; RP = Ringed Plover; RK = Redshank; GV = Grey Plover; BW = Black-tailed Godwit; BA = Bar-tailed Godwit; OC = Oystercatcher; CU = Curlew.

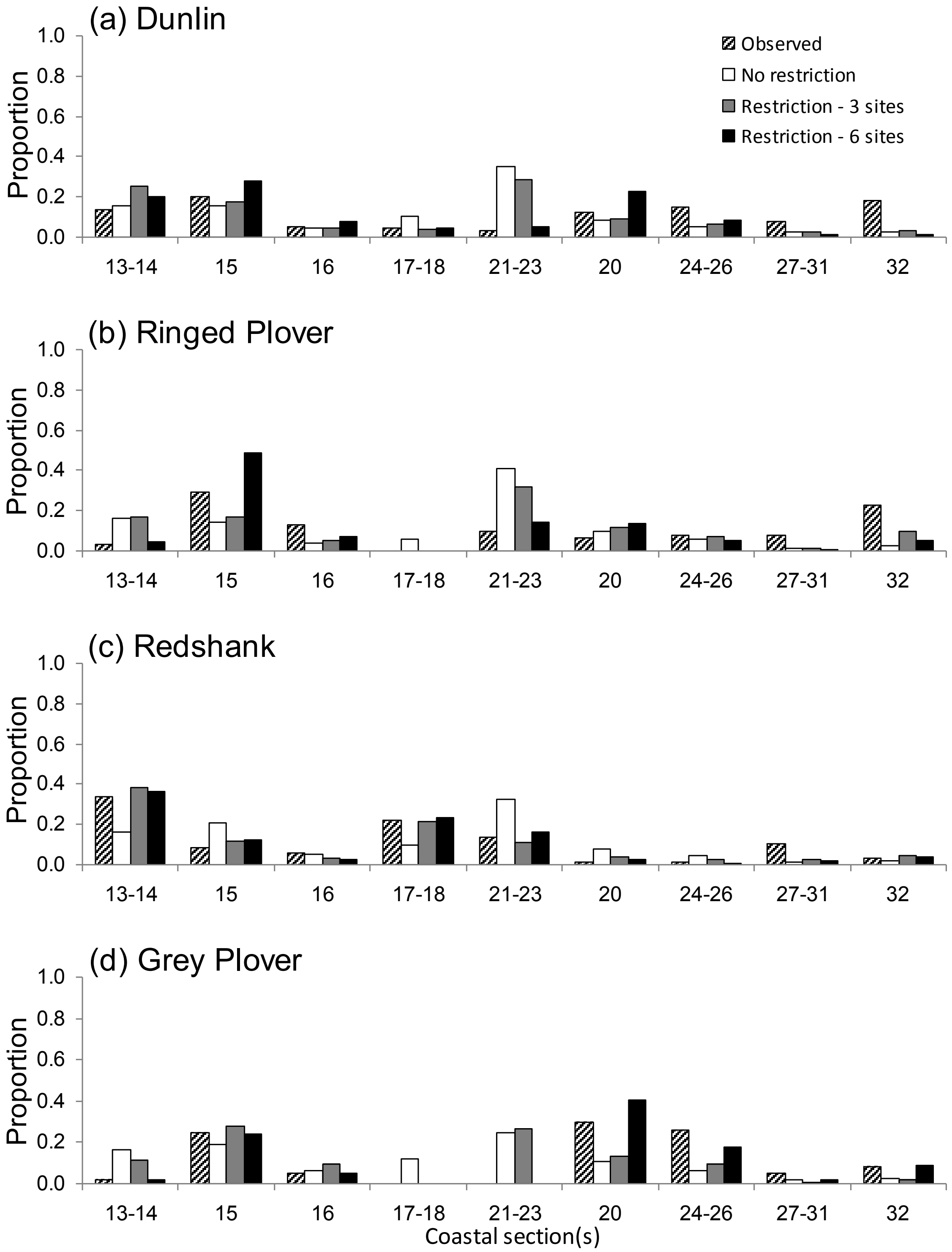
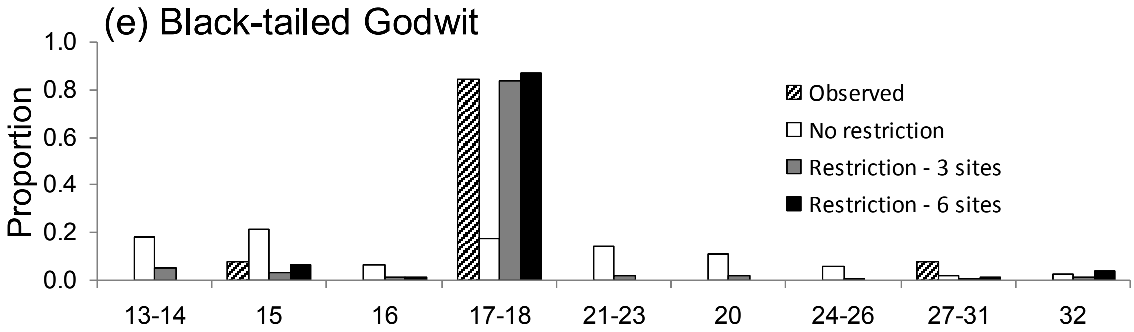
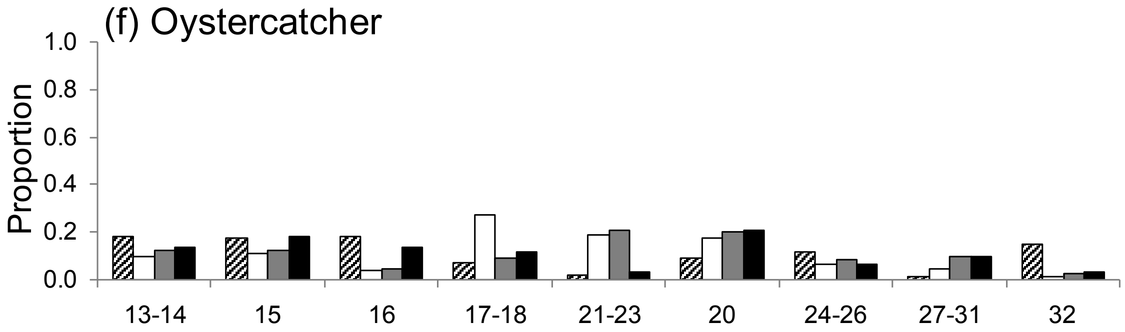


Figure 4.2 Observed and predicted distribution of waders within Southampton Water. The bars show the proportion of each species within coastal sections (some smaller sections have been grouped). Observed values are derived from Wetland Bird Survey low tide counts during 2000/01. Predicted values are over-winter averages: (white bars) No restrictions on bird movement within the site; (grey bars) site divided into 3 sub-sites; (black bars) site divided into 6 sub-sites (see text for details).





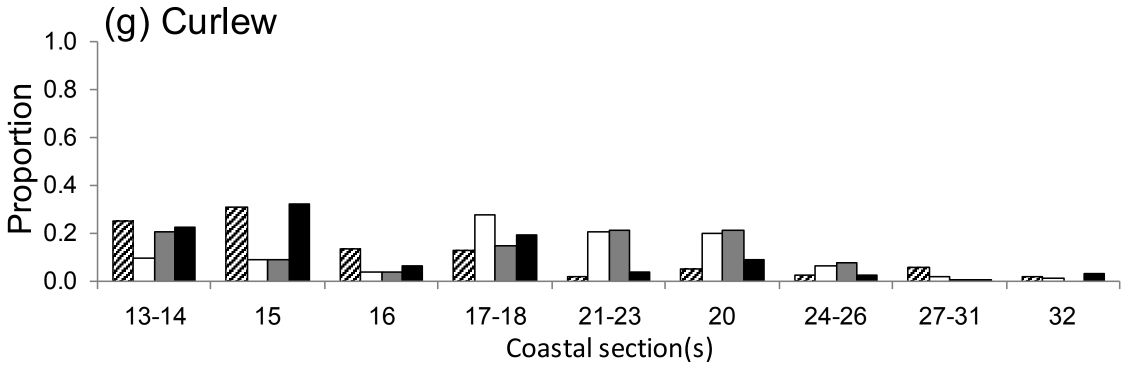


Figure 4.2 (continued) Observed and predicted distribution of waders within Southampton Water. The bars show the proportion of each species within coastal sections (some smaller sections have been grouped). Observed values are derived from Wetland Bird Survey low tide counts during 2000/01. Predicted values are over-winter averages: (white bars) No restrictions on bird movement within the site; (grey bars) site divided into 3 sub-sites; (black bars) site divided into 6 sub-sites (see text for details).

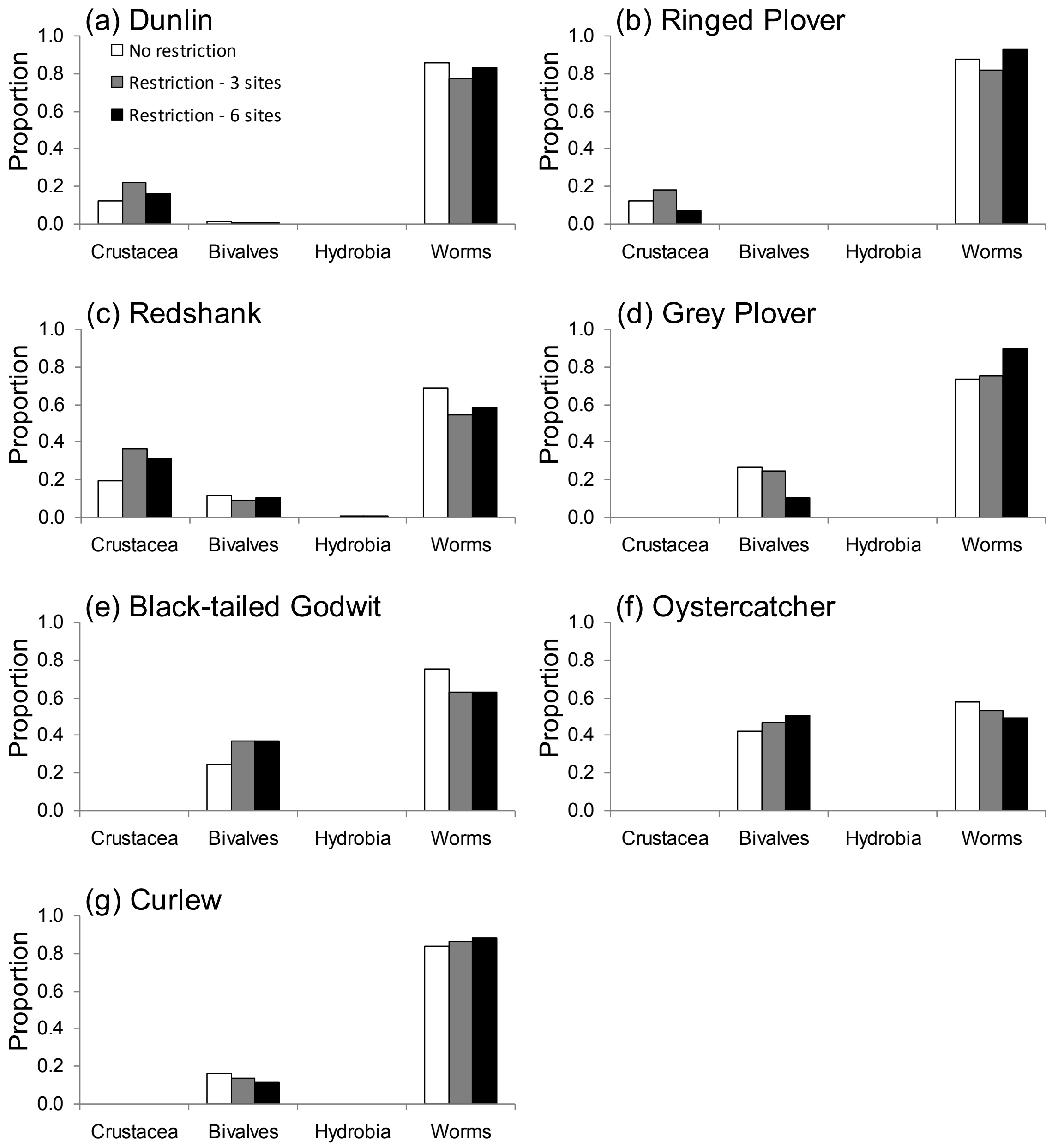


Figure 4.3 Predicted diets of waders within Southampton Water. The bars show the proportion of time spent consuming each diet. Values are over-winter averages: (white bars) No restrictions on bird movement within the site; (grey bars) site divided into 3 sub-sites; (black bars) site divided into 6 sub-sites (see text for details).

4.2 Comparing current and future housing

Simulations were run to predict the effect of current and future housing on wader survival, end-of-winter body mass and feeding effort (Figure 4.4). The effect of housing was determined by comparing the predictions of simulations including disturbance with simulations excluding disturbance.

4.2.1 Impact of disturbance on survival

Disturbance was predicted to reduce the survival of Dunlin, Ringed Plover, Oystercatcher and Curlew (lower survival in current / future housing simulations than in simulations excluding disturbance) (Figure 4.4a). Future housing was predicted to further reduce the survival of Dunlin and Ringed Plover (lower survival in future housing simulations than in current housing simulations). Dunlin, Ringed Plover, Oystercatcher and Curlew were predicted to be the species most vulnerable to disturbance due to their combination of disturbance distances, night-time feeding efficiency and vulnerability to food competition at high competitor densities. Redshank, Grey Plover and Black-tailed Godwit typically had the shortest disturbance distances and were able to feeding relatively efficiently at night. This meant that they were less effected by visitors than species with longer disturbance distances, and were better able to compensate at night for lost feeding time and increased energy expenditure during the day. In addition, Black-tailed Godwit were able to feed terrestrially to supplement intertidal feeding. The remaining species had longer disturbance distances and so were more effected by disturbance from visitors. Ringed Plover had the lowest night-time efficiency and so was the species least able to compensate for disturbance by feeding at night. Although Oystercatcher and Curlew could feed terrestrially, these species had the longest disturbance distances. Furthermore, Oystercatcher consume larger prey items than the other wading bird species, which take longer to consume, which means there is more fighting over prey (interference competition) in this species than in others. Disturbance has the effect of compressing birds into a smaller area and hence increases density and the strength of interference competition. It is therefore not surprising that Oystercatcher are adversely effected by disturbance as they will suffer more interference competition than other species as disturbance increases their density.

4.2.2 Impact of disturbance on body mass

Disturbance was predicted to have a relatively minor effect on the mean body mass of waders surviving to the end of winter (Figure 4.4b). Body mass was reduced in the current and future housing simulations in Oystercatcher and Curlew, being lower in the future scenarios. Body mass was reduced in the future scenarios alone in Ringer Plover, Redshank and Black-tailed Godwit. Predicted changes in mean body of surviving individuals are typically relatively small in such individual-based models because the individuals of very low body mass die of starvation and so are removed from calculations.

4.2.3 Impact of disturbance of time spent feeding

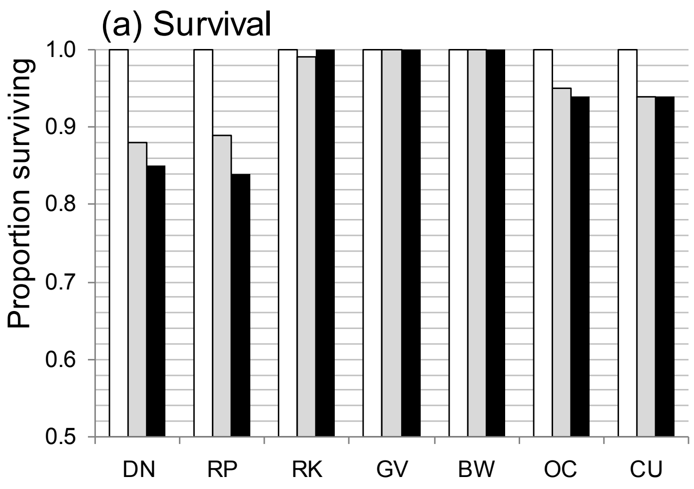
Disturbance was predicted to increase the amount of time spent feeding intertidally by Dunlin, Ringed Plover, Redshank and Grey Plover, have no effect on Black-tailed Godwit, and reduce the time spent feeding intertidally by Oystercatcher and Curlew (Figure 4.4c). These differences were related to the ability of model birds to feed in terrestrial habitats. Dunlin, Ringed Plover, Redshank and Grey Plover were not assumed to be able to feed terrestrially and so compensated for the costs of disturbance by feeding for longer in intertidal habitats. Black-tailed Godwit, Oystercatcher and Curlew were assumed to be able to feed terrestrially and so could either compensate by feeding intertidally or terrestrially. Black-tailed Godwit had a relatively short disturbance distance and was able to feed equally efficiently by night as by day and compensated through a combination of increase feeding intertidally and terrestrially. Oystercatcher and Curlew had larger disturbance distances and fed terrestrially rather than intertidally when visitor densities were high, so reducing the proportion of time spent feeding intertidally. In all species, the predicted amount of time spent feeding intertidally was similar in the current and future housing scenarios.

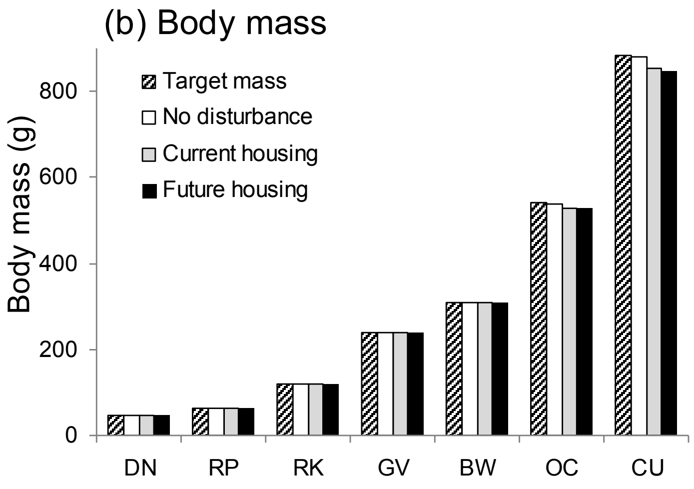
4.2.4 Spatial variation in survival

Wader survival was only predicted to be reduced in sub-site 1 of the model (i.e. the southern sub-site incorporating sectors 13, 14, 27, 28, 29, 30, 31 and 32). Wader survival remained at 100% in the mid and northern sub-sites for both the current and future housing scenarios. To understand these differences, visitor rates, habitat area and food abundance were compared between the sectors and sub-sites (Table 4.1). Mean daily visitor rates per ha (including all patches) were lower in sub-site 3 (24.5) than in sub-sites 1 and 2 (49.6 and 56.0). When the smallest sites (<10ha) were excluded from calculations, mean daily visitor rates were higher in sub-site 1 (50.6) than in sub-sites 2 and 3 (24.5 and 29.3). The biomass of wader food was lower in sub-site 1 than in sub-sites 2 and 3. Sub-site 3 had both relatively low visitor rates and high food abundance; birds in this sub-site had a relative abundant food supply and were subject to less disturbance than in the other sub-sites. Sub-sites 1 and 2 had relatively similar visitor rates, but food was more abundant in sub-site 2, allowing the birds in this sub-site to better compensate for the costs of disturbance. Average visitor rates were over 50 per ha in sub-site 1, irrespective of whether smaller sections were excluded from calculations. All birds survived in the sub-sites with average visitor rates of 29.3 or less, when the smallest sections were excluded from calculations. For the purposes of scaling up (see Section 5) it was concluded that wader survival could potentially be reduced if visitor rates exceed 30 per ha.

4.2.5 Overlap of waders and visitors

No data were available on the relative location of birds and intertidal visitors, and so the previous simulations assumed that they were distributed independently (although note that the simulations did assume that shore-based visitors were restricted to the top of the shore). The amount of disturbance from intertidal visitors could have been less than simulated if birds and intertidal visitors were found in different parts of the intertidal (e.g. visitors upshore and birds downshore). Alternatively, it could have been more than simulated if birds and intertidal visitors were found in the same parts of the intertidal (e.g. both downshore). To test the sensitivity of predictions to these alternatives, simulations were run in which the relative overlap between visitors and birds was varied (Figure 4.6); 0 = no overlap; 1 = birds and people distributed independently; <1 = birds and people found in different parts of intertidal (e.g. 0.5 means that 50% of visitors occur in the same parts of the intertidal as the birds); >1 = birds and people found in similar parts of intertidal (e.g. 2 means that birds are disturbed twice as much as when birds and visitors are distributed independently). Increasing the overlap between visitors and birds tended to decrease survival, whereas decreasing the overlap tended to increase survival. Oystercatcher and Curlew survival was still decreased even with a relative overlap of 0.5; this indicates that only 50% of visitors occur in the same part of the intertidal as the birds. Although the simulations showed the sensitivity of predictions to the overlap between birds and visitors, in the absence of data measuring this overlap, all subsequent simulations, as previous simulations, assumed that birds and visitors were distributed independently.


(a) Survival


(b) Body mass

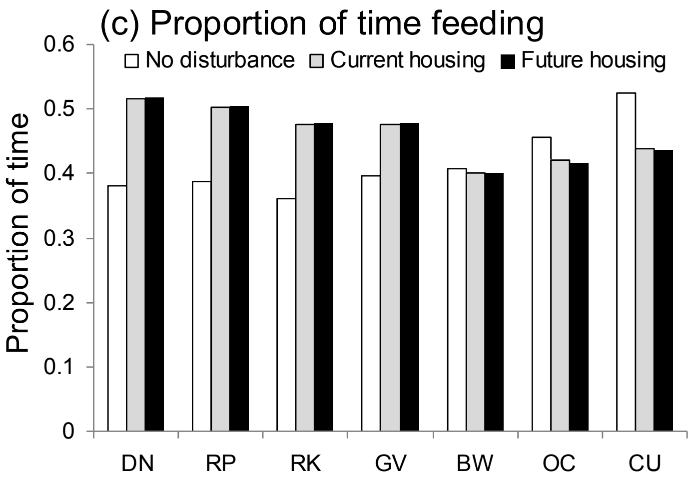

(c) Proportion of time feeding

Figure 4.4 Predicted effect of disturbance on waders in Southampton Water: (a) survival; (b) end of winter body mass; and (c) mean proportion of time feeding on intertidal habitat. Open bars show predictions in the absence of disturbance, grey bars predictions with disturbance from current housing and black bars predictions with disturbance from future housing. Simulations assumed that the site was divided into 3 sub-sites. The horizontal bars in (a) show the 95% confidence intervals of predicted survival – values must differ by more than this value to be significantly different. The following codes are used for the bird species: DN = Dunlin; RP = Ringed Plover; RK = Redshank; GP = Grey Plover; BW = Black-tailed Godwit; BA = Bar-tailed Godwit; OC = Oystercatcher; CU = Curlew.

Table 4.1 Maximum intertidal area, visitor rates during autumn / winter and food supply in coastal sectors and sub-sites in Southampton Water. Dunlin and Ringed Plover food comprises Crustacea and 15-60 mm worms. Oystercatcher and Curlew food comprises bivalves over 5mm and worms over 30mm.

Sub-site	Sector	Maximum area (ha)	Daily visits during winter	Daily visits per ha	Dunlin / Ringed Plover food biomass (gm^{-2})	Oystercatcher / Curlew food biomass (gm^{-2})
1	13	104.0	952	9.2	9.6	11.3
	14	67.8	945	13.9	11.1	14.0
	27	14.1	1199	85.2	2.2	6.5
	28	9.9	421	42.4	2.2	6.5
	29	17.5	1380	78.8	2.2	6.5
	30	13.9	1176	84.9	2.2	6.5
	31	15.9	1164	73.3	4.1	6.1
	32	66.4	593	8.9	6.7	8.7
	Mean	38.7	979	49.6 50.6*	5.0	8.2
2	15	155.0	1957	12.6	11.0	19.5
	16	65.8	1084	16.5	4.9	18.2
	20	49.2	244	5.0	8.1	37.8
	21	37.4	171	4.6	16.9	22.9
	22	19.1	638	33.4	16.9	22.9
	23	5.1	1388	269.9	16.9	22.9
	24	54.2	3008	55.5	8.5	23.5
	25	49.4	3639	73.6	8.7	17.6
	26	64.2	2126	33.1	8.7	17.6
	Mean	55.5	1584	56.0 29.3*	11.2	22.5
3	17	14.7	582	39.6	4.9	18.2
	18	54.5	517	9.5	3.1	40.9
	Mean	34.6	549	24.5 24.5*	4.0	29.6

* Ignoring patches less than 10ha in area.

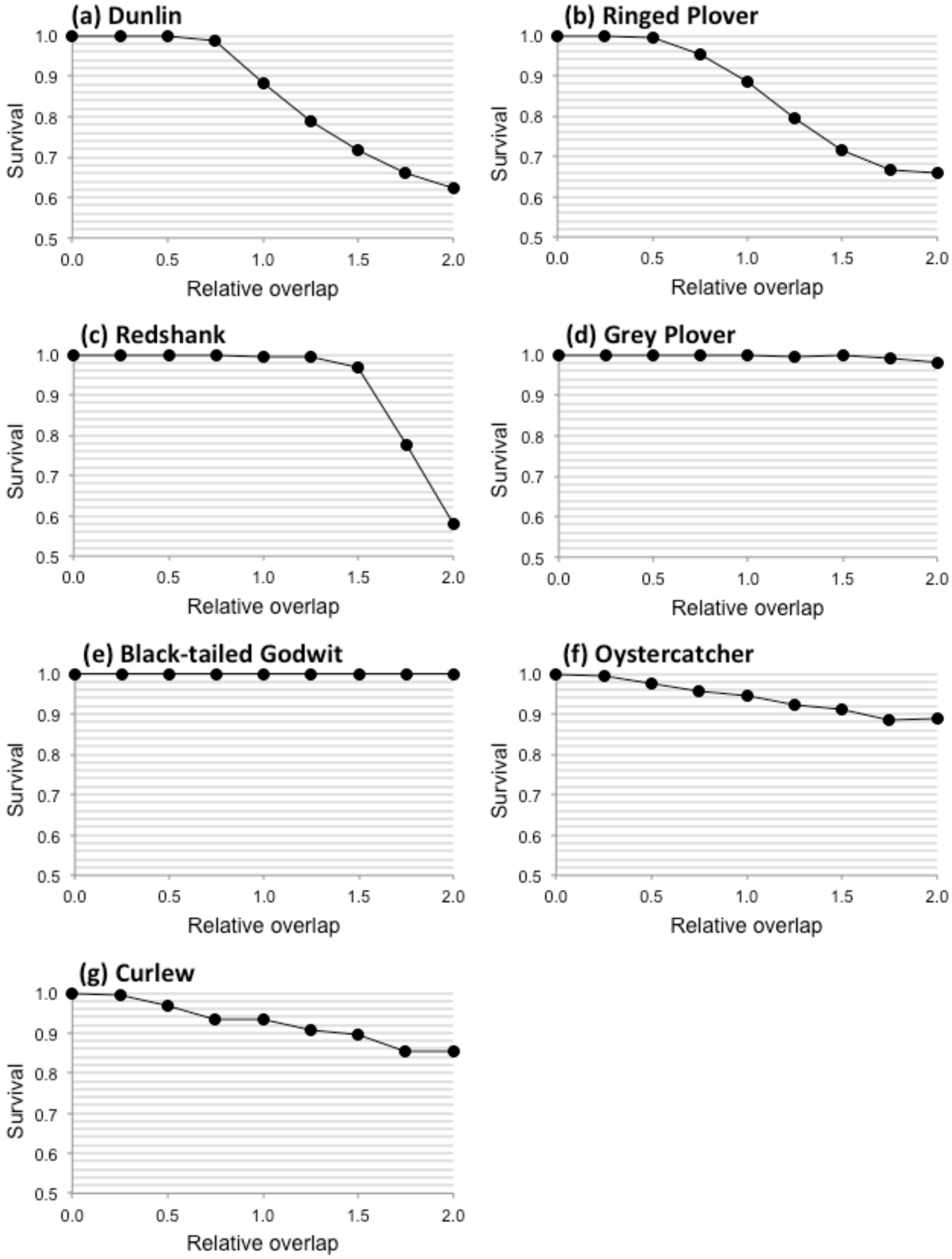


Figure 4.5 Predicted effect of the overlap between the distributions of birds and visitors on the survival of waders in Southampton Water. Simulations assumed that the site was divided into 3 sub-sites, and were based on the current housing scenario. A relative overlap of 1 indicates that birds and visitors are distributed independently. A value greater than 1 indicates that birds and visitors are aggregated, and less than 1 that birds and visitors are separated. The horizontal bars show the 95% confidence intervals of predicted survival – values must differ by more than this value to be significantly different.

4.3 Hypothetical simulations

A set of hypothetical simulations were run to better understand the factors influencing the predicted survival of waders. These are simulations of extreme situations designed to identify “tipping points” at which disturbance from visitors reduces the survival of the birds.

4.3.1 Changes in visitor numbers

The future housing scenario simulations included higher visitor numbers than the current scenario simulations. However, to further test the effect of visitor numbers, simulations were run in which visitor numbers were increased by up to 2 times those in the current housing scenarios (Figure 4.6). In contrast to the future housing scenarios, these simulations assumed that that distribution of visitors throughout Southampton Water remained the same as in the current housing scenario (i.e. visitor numbers were increased by the same proportion in all patches).

Survival rates of Dunlin, Ringed Plover, Oystercatcher and Curlew were predicted to be decreased by any increases in visitor rates. Redshank survival rate was predicted to decrease when visitor rates were over 1.25 times the current rate, approximately double the increase expected through future housing. Grey Plover survival rate was decreased slightly when visitor rates were over 1.5 times the current rate, and Black-tailed Godwit survival was not reduced even when visitor rates were doubled.

4.3.2 Sea level rise and changes in habitat area

In order to test the potential impact of changes in habitat area through sea level rise and other processes, simulations were run in which the area of intertidal habitat was varied from 70% to 110% of the current area (Figure 4.7). Simulations were based on the current housing scenario.

The expected sea level rise-related changes of intertidal area over the next 100 years were taken from the Solent Dynamic Coast Project main report (Cope, Bradbury & Gorczynska 2008). Expected changes in intertidal mudflat area are relatively small compared to changes in saltmarsh, with a small net increase in area is expected across the Solent as a whole (60 ha). In Chichester Harbour, a larger increase is predicted with the current area of 1800 ha predicted to increase to 2000 ha (10% increase). No predictions for changes in mudflat area in Southampton Water were given in the report. Given that the area of mudflat area was expected to increase, simulations were run assuming a 10% increase in habitat area.

Survival rates of Dunlin, Ringed Plover, Oystercatcher and Curlew were predicted to be decreased by any decreases in habitat area, suggesting that these species will be particularly vulnerable to any future changes in habitat area. Redshank survival rate was predicted to be decreased by a greater than 10% decrease in habitat area, whereas a 30% decrease in habitat area did not decrease the survival of Grey Plover or Black-tailed Godwit. A 10% increase in habitat area were predicted to increase the survival or Dunlin and Ringed Plover, suggesting that these species, in particular, could benefit from any long-term increases in habitat area.

4.3.3 Disturbance to roost sites

Disturbance to birds on roosting sites was not measured during the disturbance study and so it was not possible to directly predict the effect of roost disturbance on the survival of the birds. One of the major effects of disturbance to roosts is an increase in the energy demands of the birds as they need to spend more time flying rather than roosting. Energy demands may also be increased if disturbance means that birds abandon a roosting site and subsequently need to fly further distances between their roosting site and feeding grounds. Simulations were therefore run to predict the effect of increasing energy demands on the survival of the birds (Figure 4.8).

Survival rates of Dunlin, Ringed Plover, Oystercatcher and Curlew were predicted to be decreased by any increases in energy requirements, suggesting that these species will be most vulnerable to increased energy expenditure due to disturbance at roosts. Redshank survival rate was predicted to be decreased by over 10% increases in energy demands, and Grey Plover and Black-tailed Godwit survival by over 15% increases in energy demands.

4.3.4 Changes to the frequency of activities

The effects of dog walking, bait digging and intertidal activities on the birds were determined by making changes to the frequencies of these activities. The relative effect of water-based activities was not simulated as the statistical analysis of disturbance distances (see Section A4.3) combined these activities with general intertidal activities, and route lengths of water-based activities were based on only 4 observations (see Section A4.5). Simulations were based on the current housing scenario.

The largest increase in predicted survival was achieved by moving all intertidal activities to the shore (Figure 4.9a). This meant that the disturbance from these activities was restricted to the top of the shore rather than the whole intertidal, and so the proportion of intertidal disturbed was reduced. The survival of all species except Oystercatcher and Curlew was predicted to be 100% in these simulations, showing that intertidal disturbance was a major factor reducing predicted wader survival.

Converting dogs off-lead to dogs on-lead did not result in any changes in predicted survival (Figure 4.9b). This happened because off-lead dogs represented a relatively small proportion of all disturbances, and the area disturbed by general intertidal activities (to which off-lead dogs were converted) was larger than that disturbed by off-lead dogs (shorter effective disturbance distance (Table A4.3) but longer average route length (Table A4.4)). However, Dunlin and Ringed Plover survival was predicted to increase if off-lead dogs were removed from the simulations (Figure 4.9b). This happened because the number of disturbing visitors was reduced in these simulations, and reducing the area, time and energy costs of disturbance for the birds.

Removing bait digging from simulations did not increase wader survival (Figure 4.9c). This happened because bait-digging was assumed to be a relatively infrequent activity. This does not mean that bait-digging could not adversely affect the birds if it occurred at a higher frequency, and the simulations did not incorporate the depletion of the invertebrate prey of the birds caused by bait digging, which would be an additional effect on the birds in addition to disturbance.

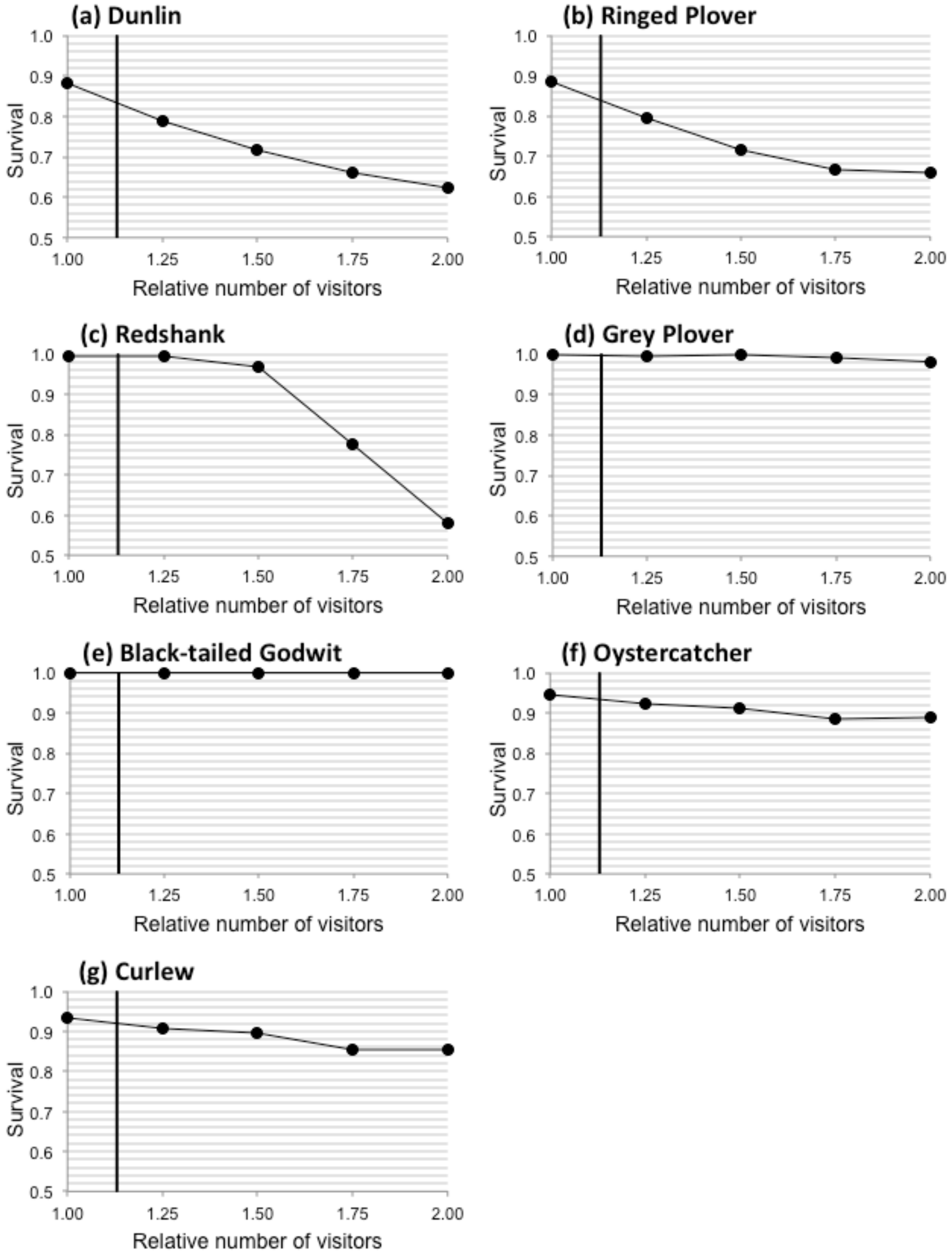
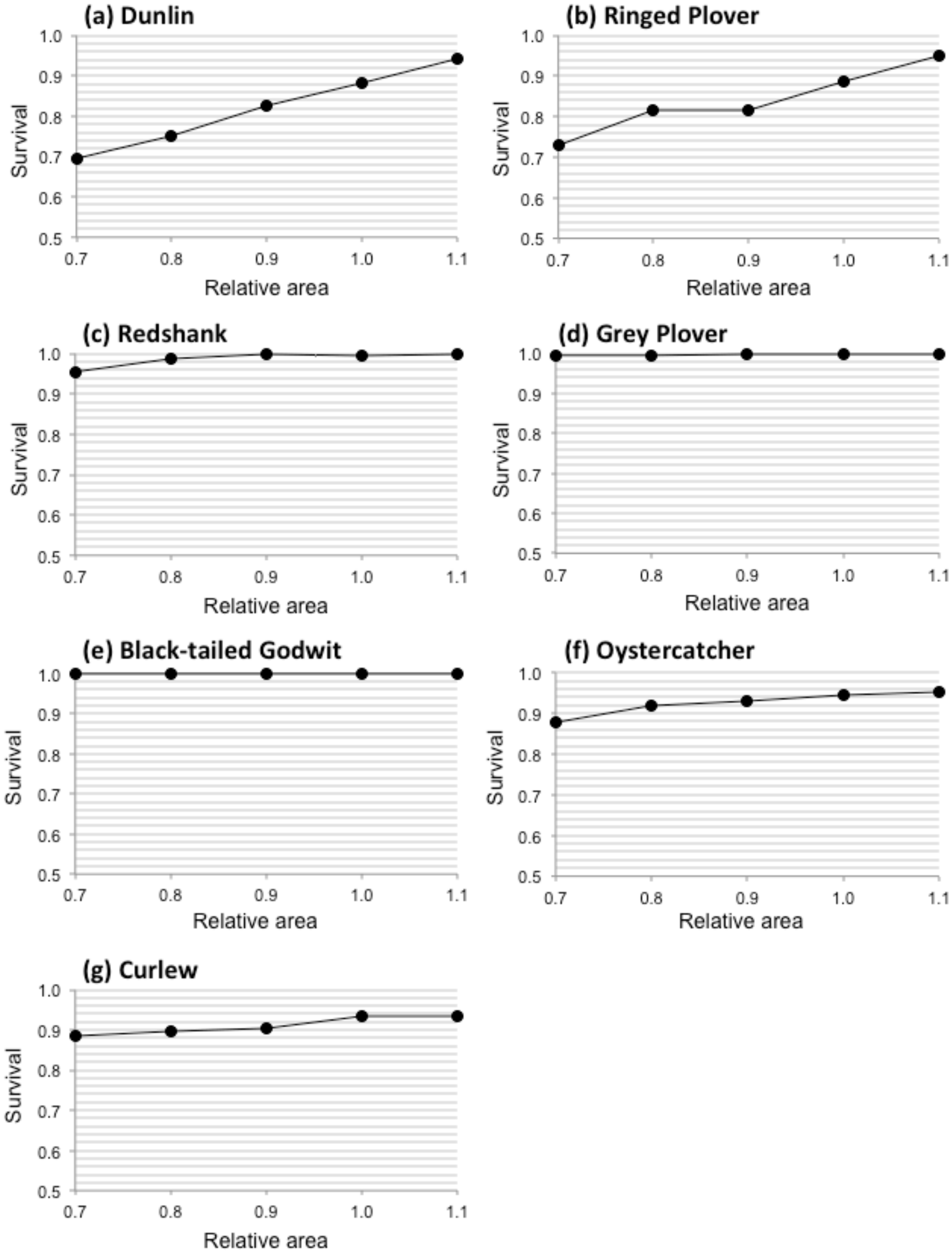


Figure 4.6 Predicted effect of hypothetical extreme increases in visitor numbers on the survival of waders in Southampton Water. Simulations assumed that the site was divided into 3 sub-sites. Baseline simulations (Relative number = 1) were based on the current housing scenario. The solid vertical line shows visitor rates within Southampton Water based on the future housing scenario. The horizontal bars show the 95% confidence intervals of predicted survival – values must differ by more than this value to be significantly different.


(a) Dunlin

(b) Ringed Plover

(c) Redshank

(d) Grey Plover

(e) Black-tailed Godwit

(f) Oystercatcher

(g) Curlew

Figure 4.7 Predicted effect of hypothetical extreme changes in intertidal habitat area on the survival of waders in Southampton Water. Simulations assumed that the site was divided into 3 sub-sites. Baseline simulations (Relative area = 1) were based on the current housing scenario. The horizontal bars show the 95% confidence intervals of predicted survival – values must differ by more than this value to be significantly different.

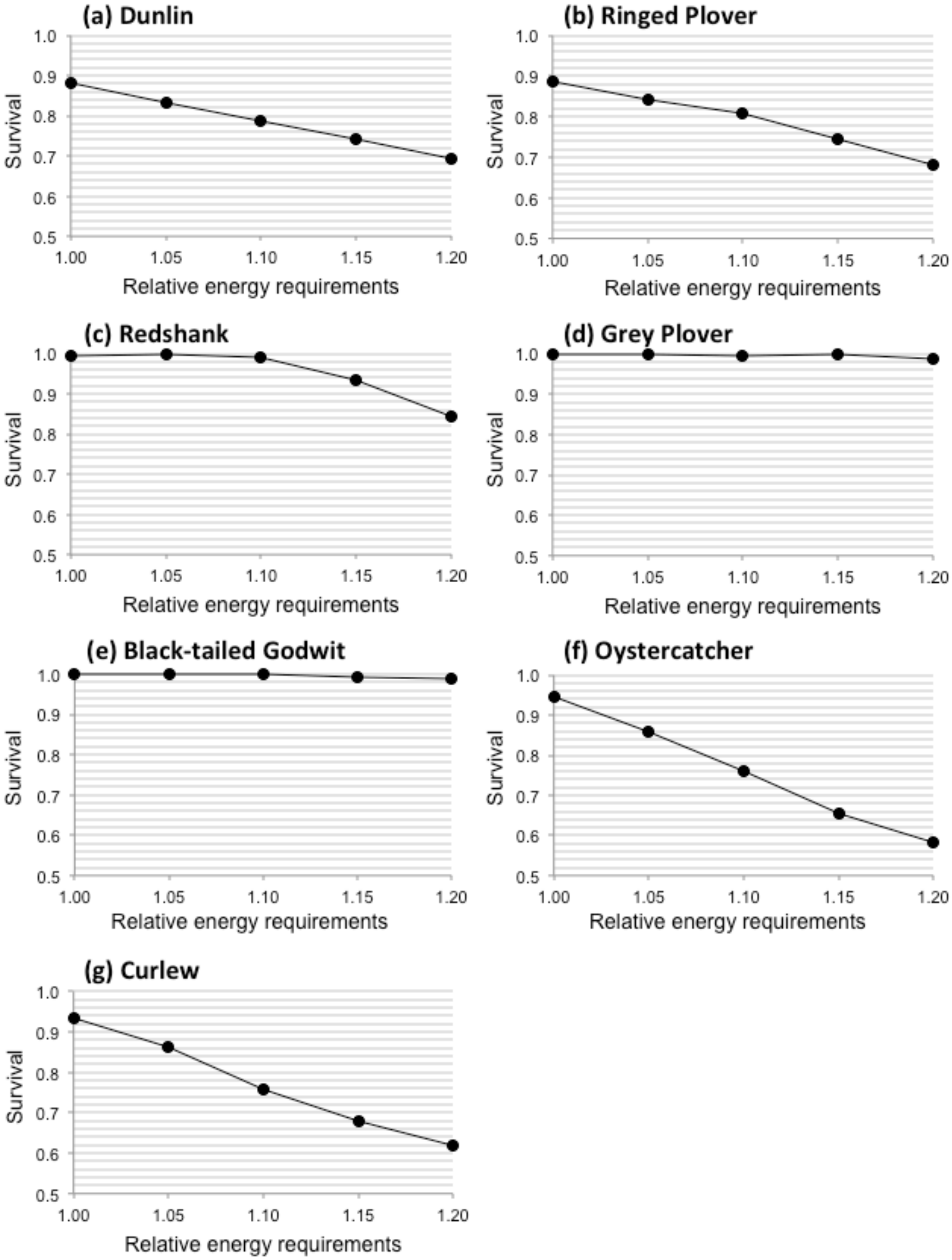
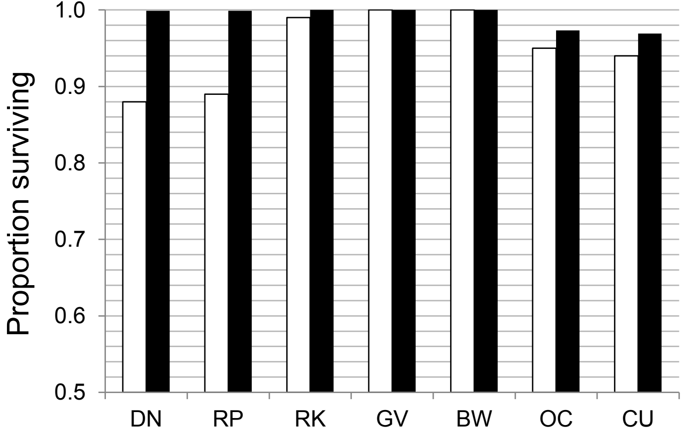
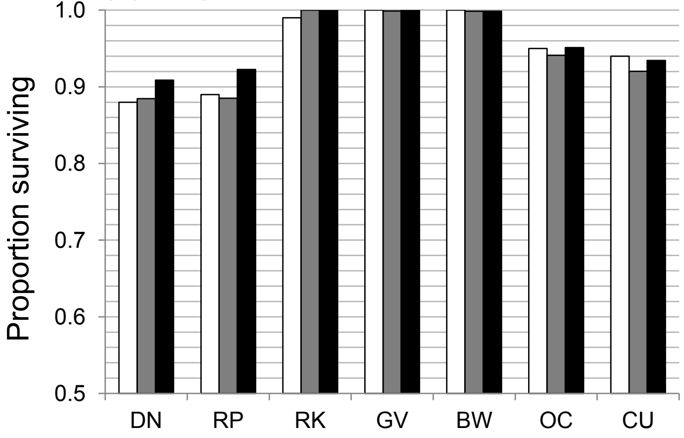


Figure 4.8 Predicted effect of hypothetical changes in energy requirements on the survival of waders in Southampton Water. Simulations assumed that the site was divided into 3 sub-sites. Baseline simulations (Relative energy = 1) were based on the current housing scenario. The horizontal bars show the 95% confidence intervals of predicted survival – values must differ by more than this value to be significantly different.

(a) Intertidal activities



(b) Dogs off leads



(c) Bait-digging

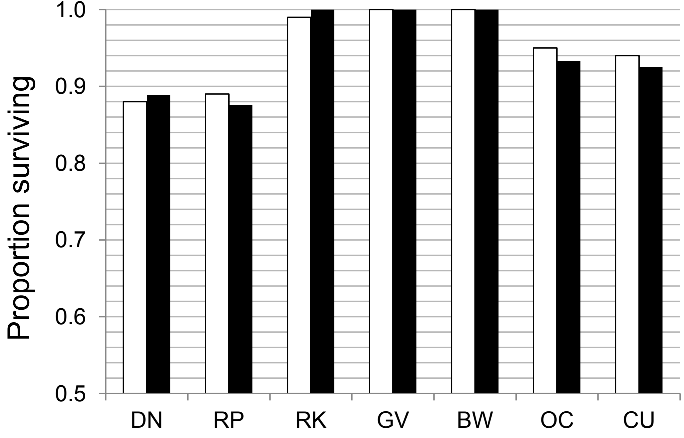


Figure 4.9 Predicted effect of hypothetical changes in the frequency of different activities. The open bars show predictions of the default simulation (current housing scenario, site divided into 3 sub-sites) and the black / grey bars show predictions with the following changes: (a) all intertidal activities moved to the shore; (b) all dogs put onto leads (grey bars) and all off-lead dogs removed from simulation (black bars); (c) all bait digging removed from simulation. The horizontal bars show the 95% confidence intervals of predicted survival – values must differ by more than this value to be significantly different. The following codes are used for the bird species: DN = Dunlin; RP = Ringed Plover; RK = Redshank; GP = Grey Plover; BW = Black-tailed Godwit; BA = Bar-tailed Godwit; OC = Oystercatcher; CU = Curlew. Six simulations were run for each combination of parameter values.

Section 5 Scaling up predictions to the Solent

The overall purpose of the project was to determine the consequences of disturbance for birds throughout the Solent rather than just within Southampton Water and Chichester Harbour. The ideal way to have done this would have been to have built a large-scale individual-based model of the entire Solent. This would have required data on the abundance of food resources throughout the Solent. As this approach was not feasible, this section uses alternative approaches to scale up from the predictions of the Southampton Water and Chichester Harbour models. The section presents visitor rates throughout the Solent and, based on the predictions of the Southampton Water and Chichester Harbour models, assesses whether these are likely to be reducing wader survival. The section also discusses general predictions from the Southampton Water model in terms of the Solent as a whole. In order to determine how much confidence can be placed in the scaling up, it is important to determine how representative Southampton Water and Chichester Harbour are of the Solent as a whole. Therefore, the section also compares the characteristics of Southampton Water and Chichester Harbour to those of the wider Solent.

Figure 5.1 shows the location of the 103 coastal sections defined in the project. Southampton Water comprises sections 13 to 32, and Chichester Harbour sections 64 to 84. The two sites comprised 41 of the 103 sections. Table 5.1 lists the description of the coastal sections (Fearnley et al. 2011).

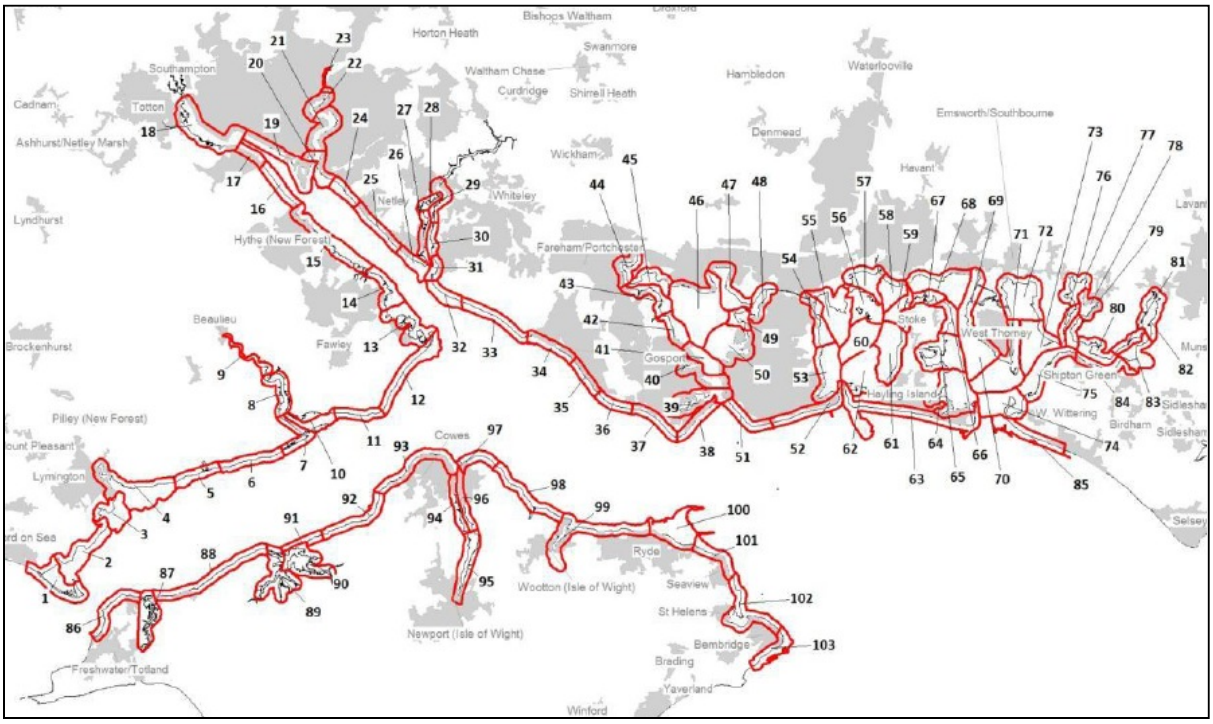


Figure 5.1 Location of the 103 coastal sections defined in the project.

Table 5.1 Description of the 103 coastal sections defined in the project.

Section	Description	Section	Description
1	Milford on sea to Hurst Castle	53	Fort Cumberland west of .Langstone Harbour
2	Hurst Castle to Pennington	54	Portsea Island to Highbury Coll
3	Pennington to Salterns Marina	55	Hibury Coll to North Binness Island
4	Waterford to Pylewell Point	56	Langstone Harbour Islands
5	Pylewell Point to Whitehouse Copse	57	North Binness Island to Brockhampton
6	Whitehouse Copse to Gravelly Marsh	58	Brockhampton to Langstone Bridge
7	Gravelly Marsh to Royal Soton Yacht Club	59	Langstone Bridge to Stoke
8	Royal Soton Yacht Club - Bucklers Hard	60	Langstone Harbour
9	Bucklers Hard to Bealieu	61	Stoke to Newton
10	Lower Exbury to Inchmery	62	Newton to Fort Cumberland
11	Inchmery to Stansore Point	63	South Hayling
12	Stansore Point to Calshot Castle	64	Black Point to Mill Rythe Holiday village
13	Calshot Castle to Fawley	65	Mill Rythe Holiday Village to Tye
14	Fawley to Cadland Creek	66	Tye to Northney
15	Cadland Creek to Hythe	67	Northney to Langstone Bridge
16	Hythe Pier to Marchwood	68	Langstone Bridge to East of Quay Mill
17	Marchwood to Marchwood Industrial Park	69	East of Quay Mill to Marker Point
18	Marchwood Industrial Park to Freemantle	70	Marker Point to Longmere Point
19	Freemantle to Ocean Village	71	Longmere Point to Stanbury Point
20	Ocean Village Marina to Itchen Bridge	72	Stanbury Point to Chidham
21	Itchen Bridge to Northam Bridge	73	Chidham to Cobnor Point
22	Northam Bridge to St. Denys	74	Roockwood to Black Point
23	St. Denys - Cobden Bridge to Swaything	75	West Itchenor to Rookwood
24	Weston to Netley	76	Cobnor Point to Easton Farm
25	Netley to Hamble-le -Rice	77	Easton Farm to Bosham Shipyard
26	Hamble-le-Rice to Hamble Rice	78	Bosham Shipyard to Southwood Farm
27	Hamble Rice to Hound - Mercury Yacht Marina	79	Southwood Farm to Itchenor Ferry
28	Mercury Yacht Marina to Bursledon	80	Itchenor Ferry to Longmore Point
29	Burlesdon to Hollyhill Woodland Park	81	Longmore Point to Hook Farm
30	Hollyhill Woodland Park to Warsash	82	North Fishbourne Harbour to Dell
31	Warsash to Newton Farm	83	New Barn to Birdham Pool
32	Newton Farm to Solent Breezer	84	Birdham Pool to West Itchenor
33	Solent Breezes Caravan Site to Hill Head	85	East Stoke Point to East Wittering
34	Hill Head to Lee-on-the-Solent	86	Warden Point to Norton
35	Lee-on-the-Solent to Car Park by Angling Club	87	Norton to Yarmouth
36	Car Park by Angling Club to Browndown	88	Yarmouth to Hamstead
37	Browndown Point to Glickicker Point	89	Hamstead to Newton
38	Gilkicker Point to South coastal side of Gosport	90	Newton to Clamerkin Lake
39	Alverstoke - Newtown to Old Portsmouth area	91	Fish House point to Saltmead Ledge
40	Forton Lake-Priddys Hard-Gunwharf Quays	92	Saltmead Ledge to Gunard Ledge
41	North of Priddys Hard –Hardway-Naval Base	93	Gunard Ledge to Cowes Medina Road
42	Hardway to Fort Elson	94	Cowes - Medina Road to Werrar Farm
43	Fort Elson to Fleetlands	95	Werrar Farm to Whippingham
44	Fleetlands to south side of Golf Course	96	Whippingham to East Cowes Ferry Terminal
45	Golf Course to Boat Yard	97	East Cowes Ferry Terminal to Norris Wood
46	Boat Yard to Porchester East	98	Norris Wood to Woodside
47	Porchester East to M275	99	Woodside to Ryde Pier
48	M275 to Hilsea to Tipner	100	Ryde pier to Puckpool Park
49	Tipner to Stamshaw	101	Puckpool Park to Horestone Point
50	Stamshaw to HM Naval Base	102	Horestone Point to Bembridge
51	Old Portsmouth Marina to South Parade Pier	103	Bembridge to Whitecliff Bay
52	South Parade Pier to Fort Cumblerland		

5.1 Potential impact of disturbance throughout the Solent

This section presents visitor rates and intertidal habitat size throughout the Solent, and assesses whether disturbance from visitors is potentially reducing wader survival.

5.1.1 Current and future visitor rates

Predicted current visitor rates varied widely throughout the Solent (Figure 5.2). Predicted visitor rates within Chichester Harbour were typically lower than those in Southampton Water. The highest visitor rates were predicted to occur along sections of open shore, particularly to the east of Southampton Water in association with high densities of housing. Visitor rates to the west of Southampton Water were predicted to be lower with the exception of Section 1. Langstone Harbour was predicted to have similar visitor rates to Chichester Harbour, whereas Portsmouth Harbour was predicted to have generally higher visitor rates. Predicted future visitor rates (Figure 5.3) showed a broadly similar pattern to current visitor rates, with similar differences between sites and the same coastal sections having the highest visitor rates.

Despite the similar pattern of current and future visitor numbers, changes in visitor numbers varied widely throughout the Solent, whether measured as a percentage (Figure 5.4) or absolute change (Figure 5.5). The lowest percentage increases (less than 10%) in visitor numbers were predicted to be to the west of Southampton Water, an area in which current visitor rates were also predicted to be relatively low. Percentage increases in visitor rates within Southampton Water and to the east (including Portsmouth, Langstone and Chichester Harbours) were higher, and generally in the range 10 to 20%. Predicted percentage increases in visitor numbers were highest on the Isle of Wight, ranging from 25 to 80%. Predicted changes in the absolute number of visitors did not show such a clear pattern between different locations. The highest absolute increases were on the Isle of Wight (where large percentage increases were predicted), and on open sections of the northern shore of the Solent where predicted current visitor rates were high.

5.1.2 Potential impact of visitors on wader survival

The effect of visitors on waders depends not only on the number of visitors but also on the area of habitat across which these visitors are distributed. A fixed number of visitors is likely to have a lower effect on birds within a large area of habitat than within a smaller area of habitat. This is because the visitor density will be lower and hence birds will be expected to encounter (and be disturbed by) visitors less frequently.

The potential impact of visitors on wader survival throughout the Solent can be inferred by comparing visitor densities throughout the Solent (expressed relative to intertidal habitat area) to visitor densities predicted to decrease survival within Southampton Water. Comparison of the survival rates within the three sub-site model showed that daily disturbance rates over 30 per ha were predicted to decrease survival (see Section 4.2.4 for more details). The intertidal food supplies within Chichester Harbour were insufficient to support the birds and so any disturbance (by reducing feeding area or time, or increasing energy demands) would have decreased predicted survival. The ability of birds to compensate for the time, area and energy costs of disturbance will depend on the food supply available both within the disturbed location, and any other locations in which the birds may feed. As food supply was not known throughout the Solent, it was assumed that parts of the Solent similar to Southampton Water would have similar amounts of intertidal prey available.

A few coastal sections had very high predicted numbers of future visits per ha of intertidal habitat (Figure 5.6). These were typically sections with a relatively low area of intertidal habitat, and so predicted numbers per ha was also calculated for coastal sections greater than 10 ha in area (Figure 5.7). The vertical grey bar in Figure 5.7 indicates a daily visitor density of 30 per ha. Table 5.2 lists the coastal sections with predicted future daily visitor densities over 30. The predictions of the Southampton Water model suggest that birds within any coastal sections with higher visitor densities may have reduced survival due to disturbance from the visitors. Whether or not such visitor rates will reduce survival will depend on the food abundance in the coastal sections themselves as well as that in neighbouring sections. In the absence of data on the food supply throughout the Solent, it was considered that the most appropriate and precautionary approach was to identify any coastal sections with visitor densities over 30 per ha. In addition, due to the low recorded abundance of invertebrates within Chichester Harbour it should also be noted that birds in this site may have reduced survival at lower visitor densities.

Southampton Water had a relatively high predicted future number of visits per ha, especially along its east shore. Overall predicted visitor rates per ha were lower in Portsmouth, Langstone and Chichester Harbours, although some sections within these sites had visitor rates per ha close to the maximum observed in Southampton Water. Section 1 had a relatively high predicted visitor rate per ha, but other sections to the west of Southampton Water had relatively low visitor rates per ha. Similarly predicted visitor rates per ha were low to the west of the Isle of Wight. The highest visitor rates per ha were on sections of open shore between Southampton Water and Chichester Harbour, and to the east of the Isle of Wight.

Overall, Southampton Water had a relatively high predicted density of future visitors. No other comparably sized parts of the Solent have such high average visitor rates, although smaller sections of coast do have comparable visitor rates over 30 visits per ha. These include Section 1, parts of Portsmouth Harbour, open sections of coast to the east of Southampton Water, and coastal sections to the east of the Isle of Wight. These are the coastal sections in which, based on the predictions of the Southampton Water model, disturbance is most likely to be decreasing Dunlin, Ringed Plover, Oystercatcher and Curlew survival. Although disturbance rates were relatively low within Chichester Harbour, the low measured abundance of food, implies that birds would also be vulnerable to disturbance in this site. Uncertainty also exists over the quantity of the food supply in Langstone Harbour and Portsmouth Harbour, and hence whether birds would also be vulnerable to disturbance in these sites, even though disturbance rates are lower than in Southampton Water.

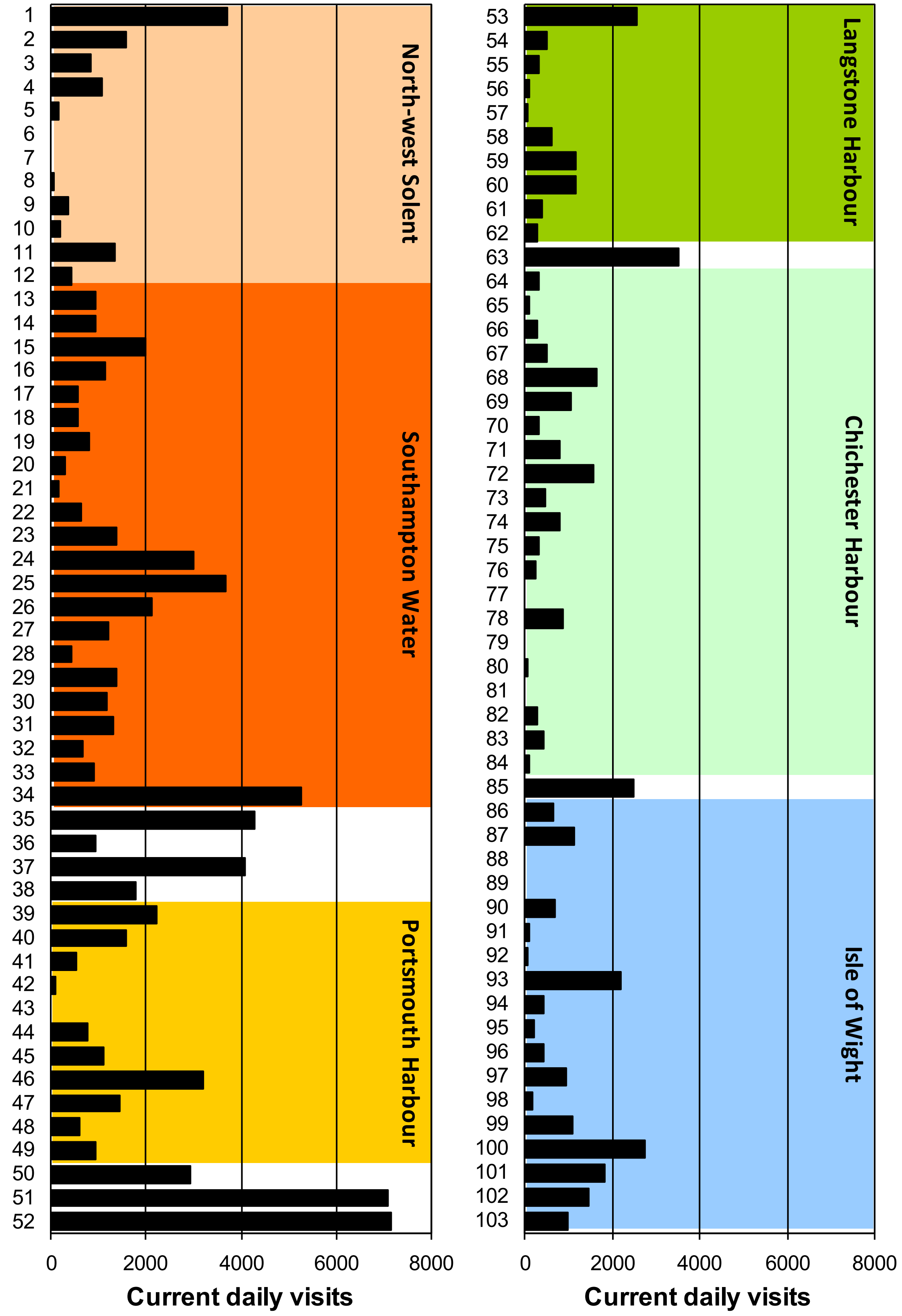


Figure 5.2 Predicted current daily visitor rates during autumn and winter throughout the Solent. The numbers refer to the coastal sections shown in Figure 5.1, and the colours indicate sections within different sites. Sections without colour do not contain an habitat within a Special Protection Area.

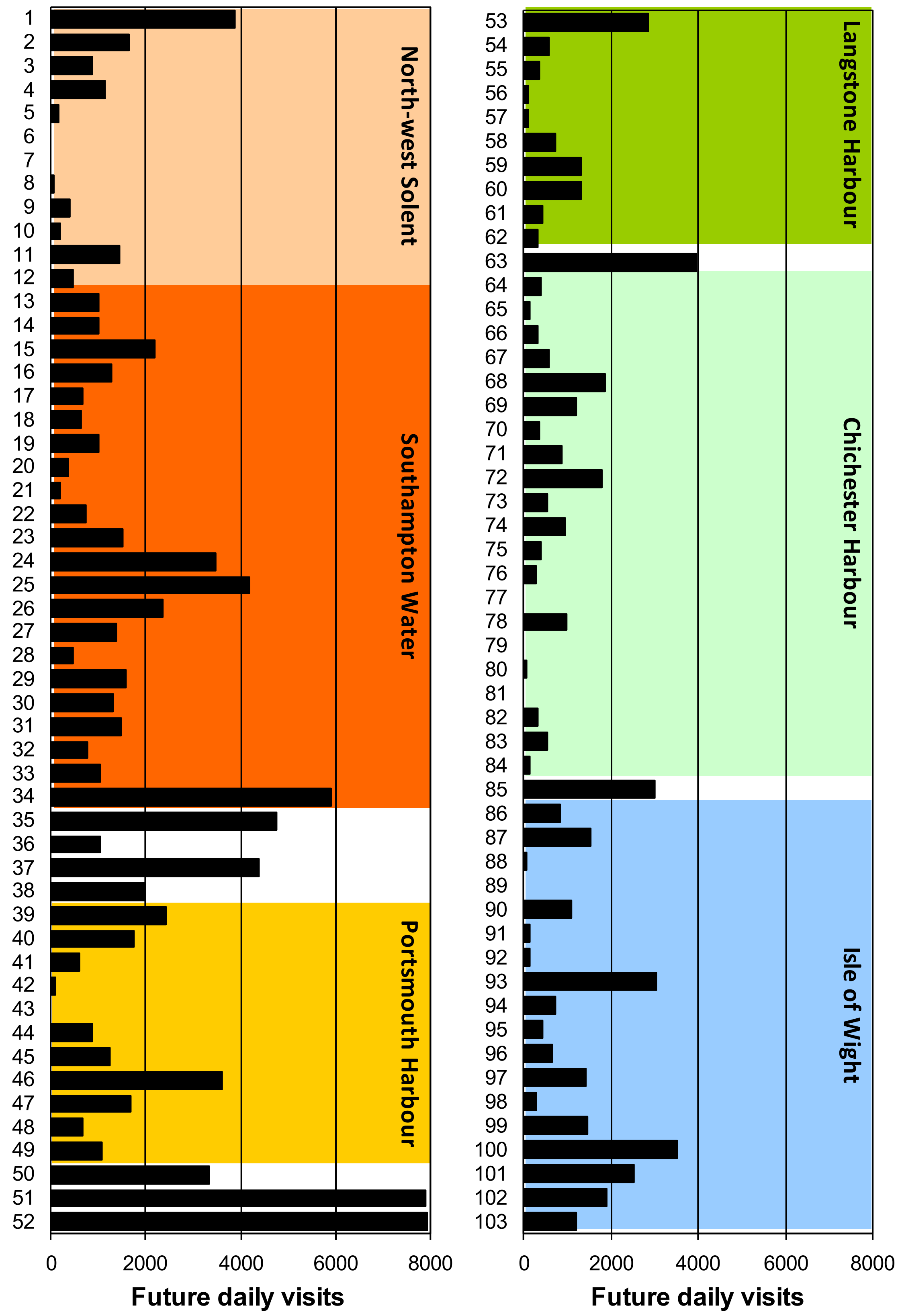


Figure 5.3 Predicted future daily visitor rates during autumn and winter throughout the Solent. The numbers refer to the coastal sections shown in Figure 5.1, and the colours indicate sections within different sites. Sections without colour do not contain an habitat within a Special Protection Area.

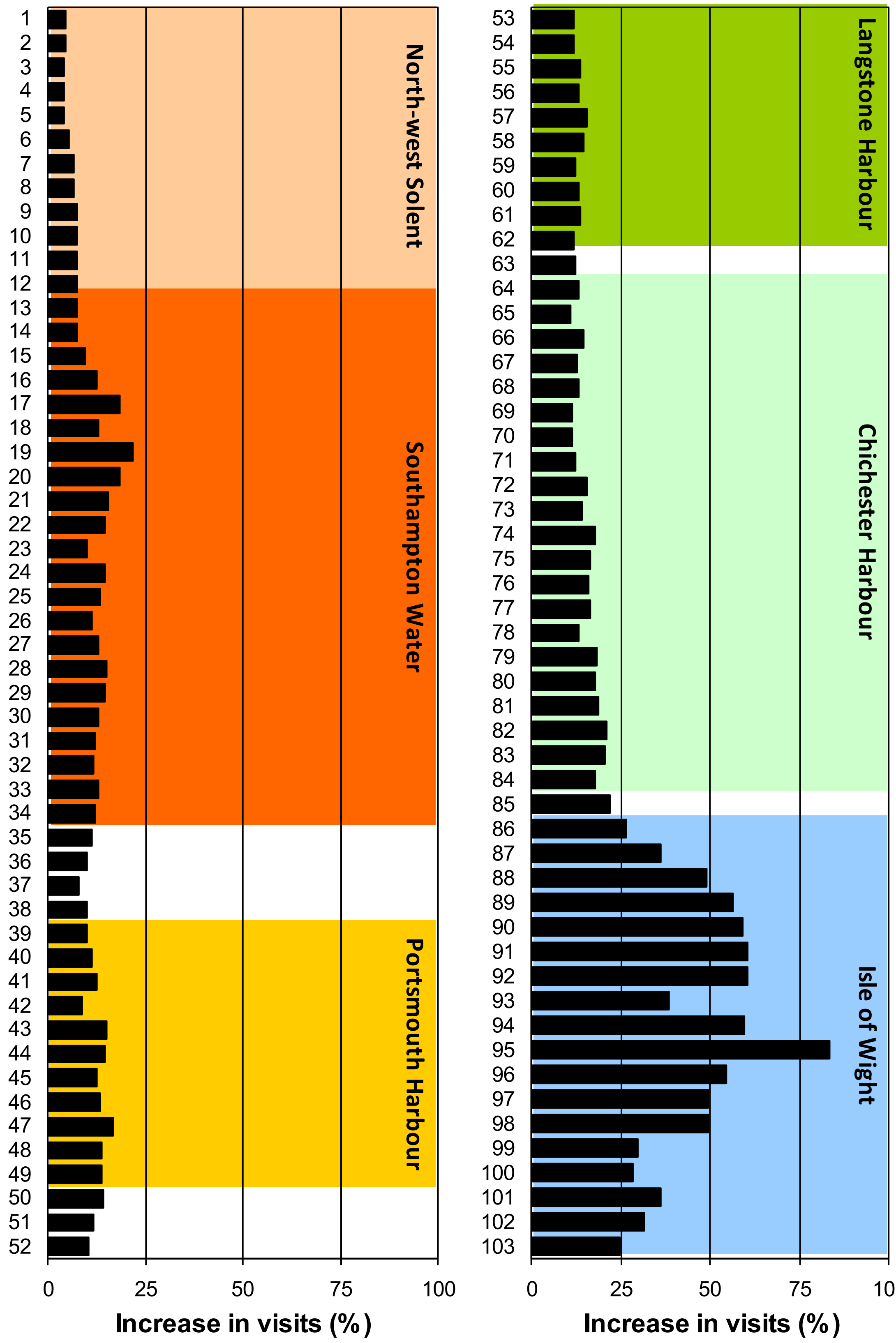


Figure 5.4 Predicted percentage increase in visitor numbers throughout the Solent (= 100 x (Future visits – Current visits) / Current visits). The numbers refer to the coastal sections shown in Figure 5.1, and the colours indicate sections within different sites. Sections without colour do not contain an habitat within a Special Protection Area.

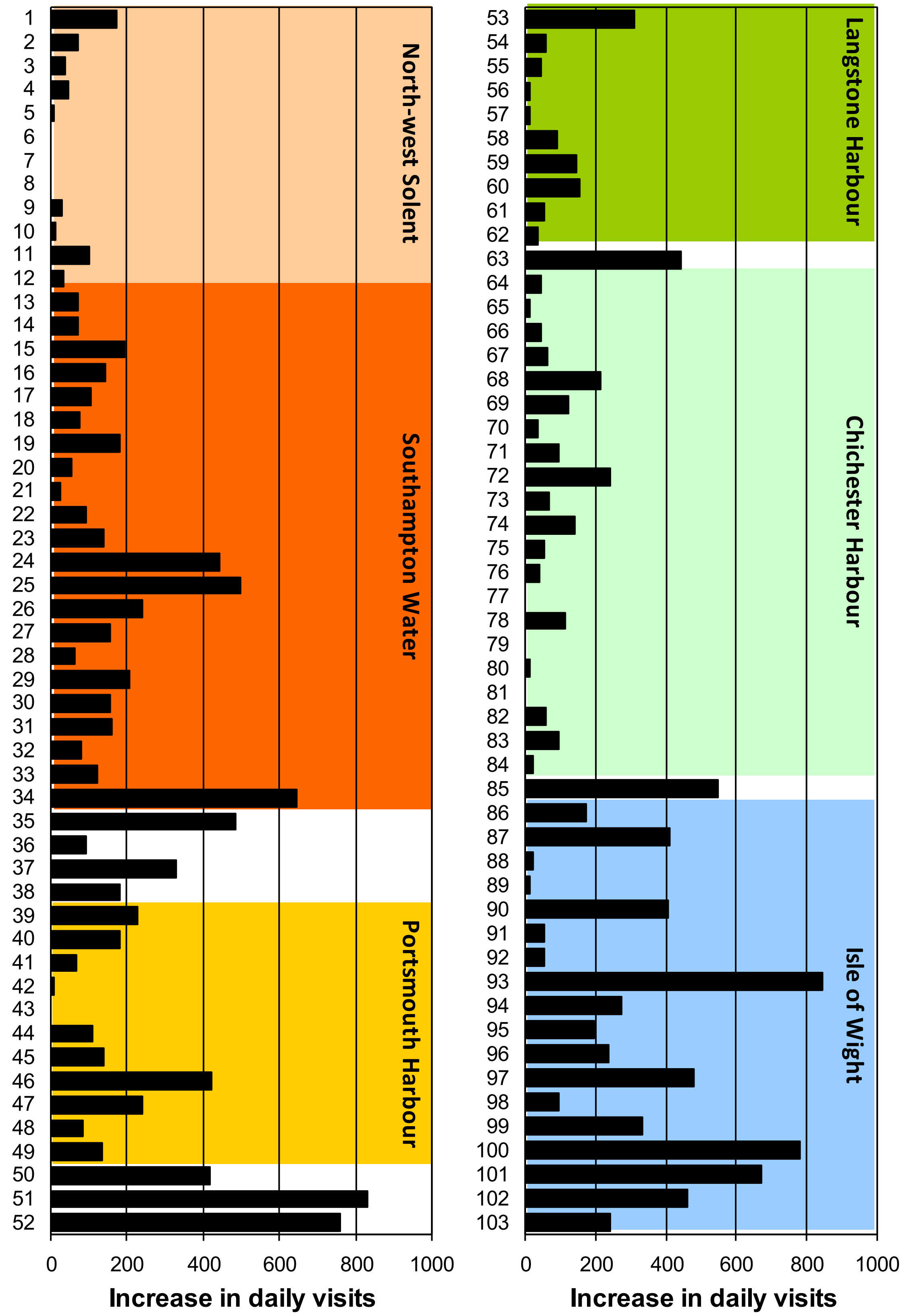


Figure 5.5 Predicted absolute increase in visitor numbers throughout the Solent (= Future visits – Current visits). The numbers refer to the coastal sections shown in Figure 5.1, and the colours indicate sections within different sites. Sections without colour do not contain an habitat within a Special Protection Area.

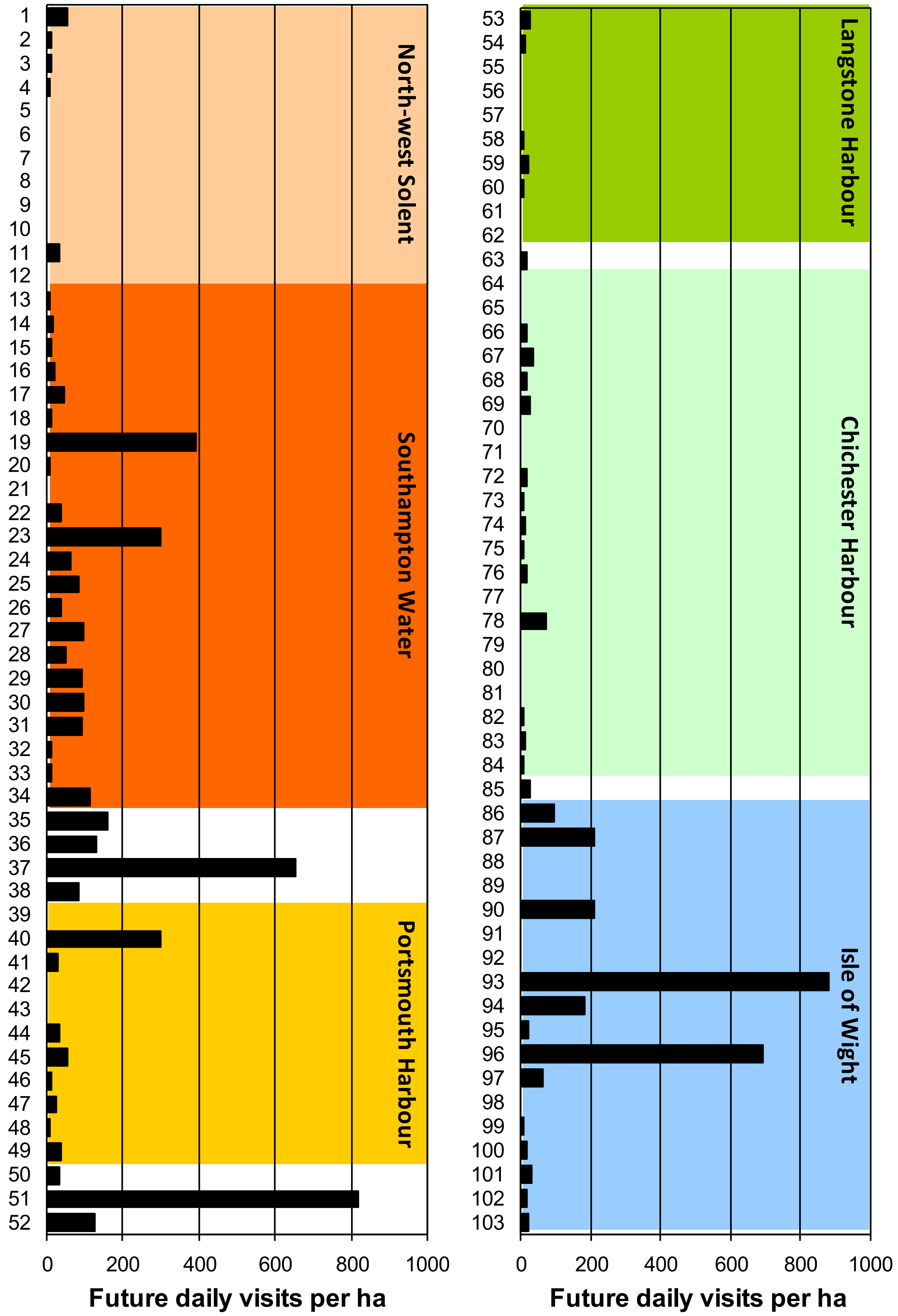


Figure 5.6 Predicted future daily visitor rates during autumn and winter per ha of intertidal habitat (on a spring low tide) within each coastal section throughout the Solent. The numbers refer to the coastal sections shown in Figure 5.1, and the colours indicate sections within different sites. Sections without colour do not contain an habitat within a Special Protection Area.

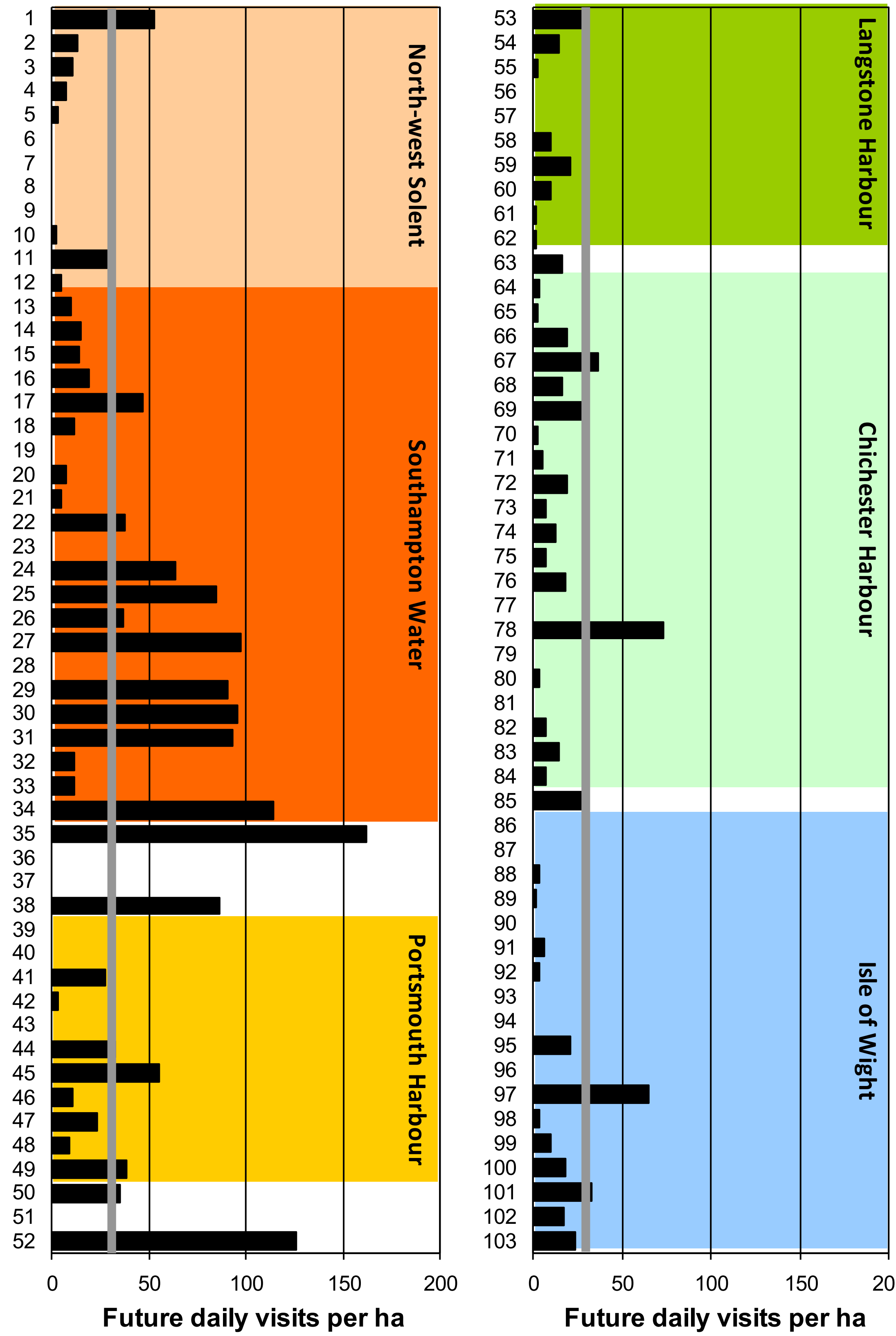


Figure 5.7 Predicted future daily visitor rates during autumn and winter per ha of intertidal habitat (on a spring low tide) within each coastal section throughout the Solent. Values are only shown for sections with an intertidal area over 10 ha. The numbers refer to the coastal sections shown in Figure 5.1, and the colours indicate sections within different sites. Sections without colour do not contain an habitat within a Special Protection Area. The vertical grey bars indicate a daily visitor rate of 30 per ha.

Table 5.2 Coastal sections with predicted future daily visitor rates during autumn and winter per ha of intertidal habitat (on a spring low tide) over 30. Sections without colour do not contain an habitat within a Special Protection Area.

Site	Section	Intertidal area (ha)	Future daily visitor rate per ha
North-west Solent	1	73.4	52.9
	11	45.1	31.8
Southampton Water	17	14.7	46.7
	19	2.6	391.9
	22	19.1	38.1
	23	5.1	298.3
	24	54.2	63.9
	25	49.4	84.7
	26	64.2	37.1
	27	14.1	97.3
	28	9.9	49.1
	29	17.5	91.0
	30	13.9	96.2
	31	15.9	93.2
	34	51.7	114.5
	35	29.5	161.9
	36	7.8	132.4
	37	6.7	654.6
	38	23.0	86.3
Portsmouth Harbour	40	5.9	298.9
	44	26.7	32.8
	45	22.8	55.2
	49	28.4	38.4
	50	94.8	35.3
	51	9.7	817.5
	52	62.8	126.1
Chichester Harbour	67	15.5	37.1
	78	13.5	73.4
Isle of Wight	86	8.7	95.7
	87	7.4	209.7
	90	5.2	211.5
	93	3.5	878.7
	94	4.0	183.0
	96	1.0	694.6
	97	22.2	65.0
	101	76.9	32.8

5.2 General predictions of the Southampton Water model

This section describes how general predictions of the Southampton Water model can be scaled up to the Solent as a whole.

5.2.1 Threshold disturbance above which wader survival is decreased

The disturbance rates at which bird survival was reduced varied between species. Dunlin, Ringed Plover, Oystercatcher and Curlew were the species most adversely affected by disturbance. These species had the highest effective disturbance distances and so for a given number of visitors would be excluded from a larger area, and have greater time and energy costs than the other species. In addition, Oystercatcher consume larger prey items than the other wading bird species, which take longer to consume, which means there is more fighting over prey (interference competition) in this species than in others. Disturbance has the effect of compressing birds into a smaller area and hence increases density and the strength of interference competition. It is therefore not surprising that Oystercatcher are one of the species most adversely effected by disturbance as they will suffer more interference competition than other species as disturbance increases their density. As these predictions are based on the responses to disturbance of Ringed Plover, Dunlin, Oystercatcher and Curlew, and biology of Oystercatcher rather than anything specific to Southampton Water, it is likely that these species would still have been predicted to be those most vulnerable to disturbance in a model of the whole Solent.

5.2.2 Sea level rise and changes in habitat area

The area of intertidal mudflat in the Solent as a whole is predicted to change very little over the next 100 years (60ha, Cope, Bradbury & Gorczynska 2008). Therefore, changes to habitat area are not expected to be a factor that will influence the birds, although changes in habitat quality may be an issue. Dunlin, Ringed Plover, Oystercatcher and Curlew were the species most sensitive to changes in intertidal habitat area with any reduction in habitat area reduced the survival of these species. As discussed above, the biology of Oystercatcher may make this species particularly vulnerable to reductions in habitat area caused by disturbance or other factors. A prediction for the Solent is that any reduction in area, in association with disturbance for current or future housing, may reduce the survival of these species.

5.2.3 Influence of dog walking, bait digging and water-based activities

The effects of dog walking, bait digging and intertidal activities on the birds were tested using the current housing scenario. The aim was then to see if changes in the frequencies of different activities could increase bird survival. Moving intertidal activities to the shore had the greatest effect on wader survival, as shore-based activities can only disturbance the upshore area. It would be expected that a similar prediction would have been produced if a model had been built for the whole Solent. Eliminating off-lead dog walking had the next largest effect on survival of the birds. Converting off-lead dogs to on-lead dogs and removing bait digging had less effect. The extent to which these predictions can be applied to the Solent as a whole depends on the relative frequency of these activities. Dog walking was a common activity throughout the Solent and so any changes to the management of dog walking are likely to have a relatively large effect on the amount of disturbance to the birds. All or nothing changes (e.g. separate dog walking from the birds) will have a greater effect than more subtle changes (e.g. keep dogs on leads). Removing bait digging had a relatively small effect on survival as it was a relatively rare activity in Southampton Water. However, bait digging can sometimes occur at a high intensity and the combined effect of disturbance and depletion of prey would be expected to have a larger impact on the birds in some situations.

5.3 Percentage of habitat disturbed by visitors

The area of overlap between an activity / development and the distribution of birds is often used as a measure of the impact of the activity on the birds, with 1% overlap often taken as the threshold for impact. Therefore, the percentage of intertidal habitat disturbed within each coastal section was calculated as an index of the potential impact of disturbance on the birds. Calculations were for the maximum area of intertidal habitat within each section exposed at low tide on a spring tide. Only intertidal activities (i.e. general, dog-off lead and bait digging) were used in calculations, as disturbance from shore-based activities was shown to have a relatively minor effect on wader survival (Figure 4.9a), being restricted to the top of the shore. A higher overlap between disturbance and habitat would have been calculated if shore- and water-based activities were included, or if calculations had been made when the sections were less than fully exposed. Calculations were based on the number of visitors predicted with current housing.

The number of annual visitors within each section for current housing and the proportion of visits by each activity type are given in Table A4.5. Annual visitor rates were converted to hourly rates in winter during daylight by assuming that 41.9% (see Section A4.7) of visits are during the winter, winter lasts for 181 days (September to February) and that all visits occur during 12 hours per day. Each visitor was assumed to disturb 41ha of intertidal habitat (mean of general and dog off-lead disturbance areas; Table A4.4b). Each disturbance was assumed to last for 1.57 minutes (see Section A4.4). The area of intertidal disturbed was derived from the area and time of disturbances, and assumed that birds and visitors were distributed independently (see equation in Section A3.5.1).

Figure 5.8 shows that, even assuming the maximum intertidal area and only including intertidal visitors, over 50% of the area of many coastal sections was predicted to be disturbed. The average percentage of habitat disturbed was 42%, much higher than the 1% overlap often used to determine whether an activity is deemed to be having a significant effect on the birds. It should be noted however that the 1% overlap does not necessarily transform into a population consequence of an activity.

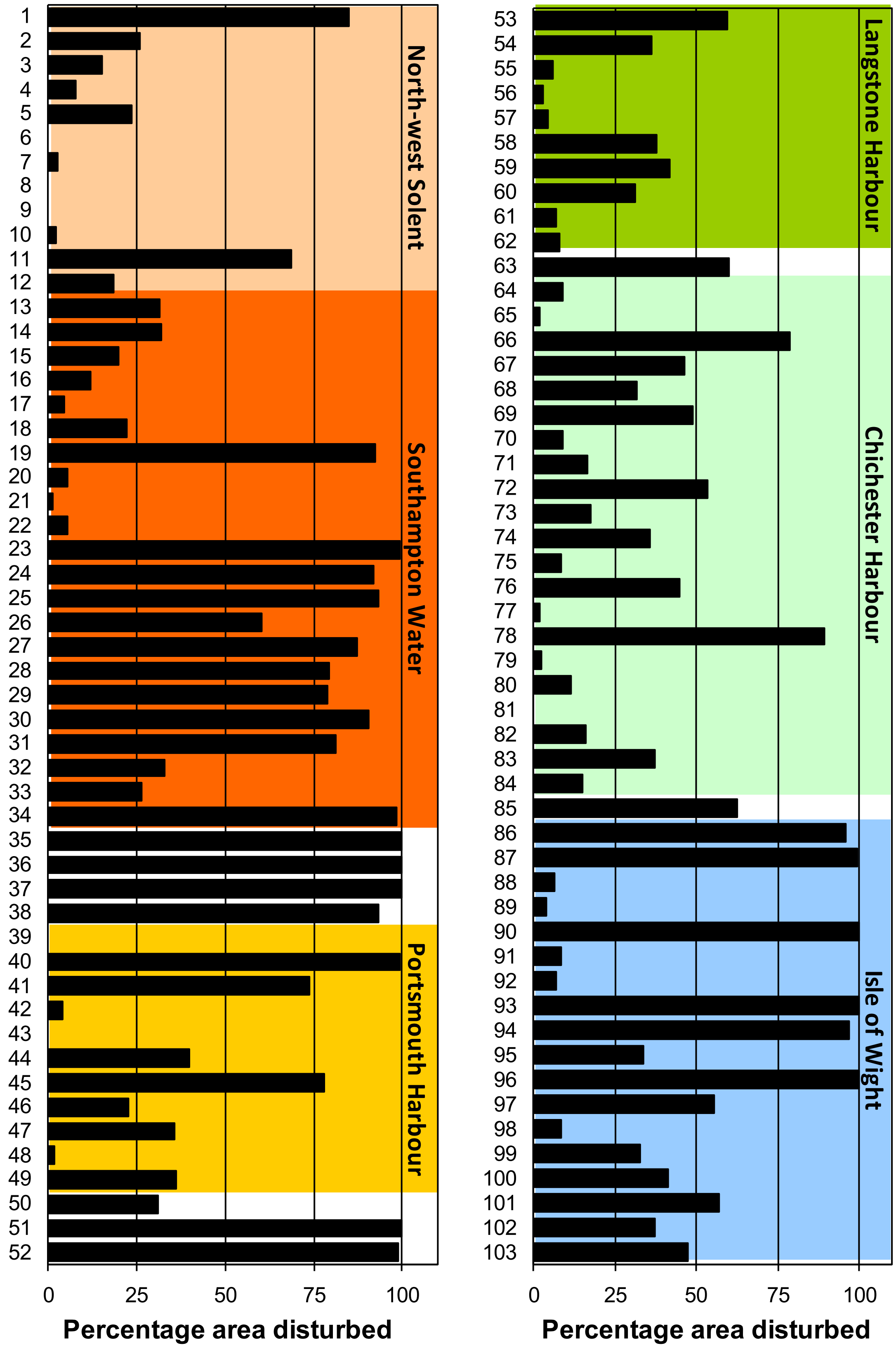


Figure 5.8 Predicted percentage of intertidal habitat disturbed (on a spring low tide) by intertidal visitors within each coastal section throughout the Solent. See text for method used to calculate values. The numbers refer to the coastal sections shown in Figure 5.1, and the colours indicate sections within different sites. Sections without colour do not contain an habitat within a Special Protection Area.

Section 6 Predictions for Brent Geese

It was not possible to build an individual-based model of Brent Geese as the biomass of the intertidal and terrestrial food supplies of this species had not previously been measured. Furthermore, the responses of birds to disturbance were measured on intertidal habitats, whereas terrestrial habitats are used extensively by Brent Geese, especially in late winter when intertidal food resources have become depleted. Instead the following approaches were used to determine how disturbance may be influencing Brent Geese.

- Compare the responses to visitors of Brent Geese with the responses of waders.
- Discuss how the predictions of previous models of Brent Geese can be applied to the Solent.
- Consider the potential overlap between visitors and Brent Goose food supplies.
- Discuss links with the Solent Waders and Brent Goose Strategy (King 2010; Liley & Sharp 2010).

These issues are discussed in the following sections.

6.1 Response of Brent Geese to visitors

The on-site bird disturbance study (Liley et al. 2010) measured the behavioural responses of both waders and Brent Geese to disturbance from visitors. These responses were measured in intertidal habitats, and so do not measure the response of Brent Geese in the full range of habitats they exploit. However, they can be used to compare the relative responses of waders and Brent Geese. The consequences of disturbance for survival depends on the area, time and energy costs of disturbance, and the ability of the birds to compensate for these costs. Their ability to compensate depends on the amount of food available and the time over which the birds can exploit this food. Although these details were not available for Brent Geese, some information on the relative costs for Brent Geese can be obtained by comparing their behavioural response to disturbance with the responses of waders. For example, if Brent Geese responded to visitors at much closer distances than waders, they would be expected to have lower area, time and energy costs for a fixed number of visitors.

The distances at which Brent Geese and waders responded to visitors are shown in Table 6.1. Although, as discussed by Liley et al. (2010) (Sections 3.25 to 3.31), there are between-species differences in the response to disturbance, the response distance of Brent Geese is within the range of the distances observed in wader species. In intertidal habitats it would therefore be expected that a fixed number of visitors would exclude Brent Geese from a comparable amount of habitat to that from which waders are excluded. There is therefore no reason to expect that Brent Geese would have lower disturbance costs than waders when feeding intertidally. However, Brent Geese may be more habituated to disturbance in terrestrial habitats and so have shorter disturbance distances than in intertidal habitats.

6.2 Predictions of other Brent Goose models

Two previous individual-based models, comparable to those developed for waders during this study, have been developed for Brent Geese.

Stillman et al. (2005a) developed a large scale model of Brent Geese along their western European flyway (Denmark, Germany, Netherlands, England and France).

The model incorporated the saltmarsh, intertidal and terrestrial food supplies of geese throughout this range. These needed to be incorporated in a simplistic way given the large scale of the model. Disturbance to birds was incorporated by reducing the proportion of time for which the birds could feed. In some simulations disturbance on intertidal habitats was predicted to cause birds to move to terrestrial habitats, but disturbance was not predicted to decrease the survival of Brent Geese which was 100% in all simulations.

Stillman et al. (2005b) developed a model of Brent Geese feeding on intertidal *Zostera* beds and terrestrial pasture grasses on the Exe Estuary. Disturbance to birds feeding intertidally was incorporated by reducing the proportion of time for which the birds could feed. It was assumed that disturbance just occurred during the hours of daylight. The main model output was the date during autumn at which the geese switched from feeding on intertidal *Zostera* to terrestrial food. The model predicted that increasing amounts of disturbance did not cause birds to switch to terrestrial food supplies at an earlier date than they would have done in the absence of disturbance. Instead birds were predicted to feed for longer during the night in order to compensate for the lost feeding time during the day. It was assumed that the geese could feed equally efficiency at night than by day. The birds did not switch to terrestrial food supplies until the quality of the intertidal *Zostera* had declined due to depletion by the geese themselves and due to die-back of the plant.

In summary, the previous models show that both intertidal and terrestrial sites are important for Brent Geese, terrestrial sites becoming increasing important as the winter progresses and intertidal food becomes less abundant. The terrestrial food supplies incorporated in these models included both saltmarsh and grassland, as both habitats can be important for the birds. The previous models did not predict that disturbance would decrease the survival rate of Brent Geese, which was 100% in all simulations. Realistic amounts of disturbance were incorporated for the sites modelled, but higher disturbance rates may occur throughout the Solent. The models did not incorporate the energetic costs to the birds, which would have increased the chance that disturbance would have been predicted to decrease survival. The previous studies did not measure disturbance distances and so these data cannot be compared with the present study. Birds were able to compensate for intertidal disturbance during the day by feeding at night, and the area of terrestrial habitats were relatively large given the size of the goose populations modelled, meaning that the birds did not significantly deplete their terrestrial food during simulations. Disturbance would be more likely to reduce survival in a situation in which the area of habitat was lower relative to the size of the bird population (e.g. the amount of habitat per bird), as birds would be more likely to deplete the food supply. As the food supply is depleted birds would have a lower rate of feeding, and so need to feed for longer to meet their energy requirements. This would mean that they would have less spare time to compensate for disturbance. A smaller area of habitat would also mean that birds have less spare habitat to move to if some habitat becomes disturbed.

6.3 Overlap between visitors and Brent Goose intertidal food supplies

Figure 6.1 shows the distribution of visitors, Brent Geese and *Zostera* (derived from the Hampshire and Isle of Wight Wildlife Trust *Zostera* database) within the Solent. Both Brent Geese and *Zostera* tend to be found in sections of coast with lower visitor numbers. One explanation for this is that *Zostera* often grows on muddy substrate that would not be suitable for many recreational activities. However, extensive Zostera beds are also found on Ryde Sands, Section 100, an area that also has high visitor numbers. Furthermore, even *Zostera* beds on muddy substrate may be disturbed if they occur close to the shoreline. The geese also feed on saltmarsh vegetation, grassland and crops (particularly in later winter) and so will also potentially be subject to disturbance when feeding in terrestrial habitats. While the area of intertidal mudflat in the Solent as a whole is predicted to change very little over the next 100 years, larger reductions in saltmarsh are expected (Cope, Bradbury & Gorczynska 2008). Therefore, changes in the abundance of saltmarsh food supplies of Brent Geese may be an important factor that reduces the ability of these birds to compensate for costs associated with disturbance. The reduction in area of this habitat may also bring visitors and Brent Geese into closer contact increasing the amount of disturbance. It is therefore difficult to use the overlap between visitors, Brent Geese and there intertidal food supplies to infer the likely consequences of disturbance for the birds.

6.4 Links to the Solent Waders and Brent Goose Strategy

This section considers how the discussion in Sections 6.1, 6.2 and 6.3 links with the Solent Waders and Brent Goose Strategy (King 2010). This strategy sets out recommendations for policy makers, site owners and land managers within the Solent area. The aim of the strategy is to inform strategic planning and development proposals, whilst ensuring that sufficient feeding and roosting resources are available for the birds and that the integrity of the network of sites is maintained. The underlying principle of the strategy is to wherever possible, conserve existing sites and to create new sites. The policies and proposals set out in the strategy are shown in Table 6.2. The majority of the policies and recommendations centre around the strategy’s main aim of maintaining a network of feeding and roosting sites.

The strategy has been informed by data on brent geese and waders collected from around the Solent by volunteer counters over three consecutive winters (2006 to 2009). Liley & Sharp (2010) performed an analysis of these data to identify important sites for Brent Geese and waders throughout the Solent, and to highlight the characteristics of these sites and the threats they may face in the future. Sites that were categorised as important, for either brent geese or waders, tended to be coastal or grassland habitats, large, flat and low-lying and close to the coast (Liley & Sharp 2010). The number of buildings surrounding the site was identified as an important factor for waders but less so for Brent Geese (Liley & Sharp 2010). Important sites for waders tended to be further away from roads and also to be more isolated from other wader sites, but, by contrast, important sites for brent geese were less isolated from each other (Liley & Sharp 2010).

Section 6.1 indicates that, at least in the intertidal, Brent Geese respond to visitors over the same range of distances as waders. There is evidence from Liley & Sharp (2010) that Brent Geese tend to occur closer to buildings than do waders; the number of buildings around a site was an important factor determining whether a site was important for waders, but less so for Brent Geese (Liley & Sharp 2010). This finding could be interpreted in alternative ways; Brent Geese may be more habituated to buildings, or alternatively suitable Brent Goose habitat may tend to be closer to buildings than that of waders.

The strategy is concerned with maintaining a network of sites that is able to support overwinter populations of the birds. Important issues are the size of individual sites, their spacing and the ease with which birds can move between the sites. A high proportion of each site needs to be more than the disturbance distances away from visitor access routes to ensure that disturbance to the birds is minimised. This could be achieved through a network of larger sites or by preventing visitor access through, or close to, smaller sites. The size of sites will also be important in terms of the amount of food provided to the birds. In the absence of disturbance distances from terrestrial habitats and estimates of food abundance, it is not possible to estimate the minimum size of sites that would minimise disturbance and provide a sufficient food resource.

Section 6.2 highlights that previous models predict that both intertidal and terrestrial food resources are important to the birds. Intertidal food is typically of higher food value but becomes more scarce later in winter as it is depleted by the birds and seasonally dies back. These models typically predict that disturbance does not decrease the survival of the birds provided that suitable areas of habitat are available. Loss of terrestrial habitat typically has the highest predicted effect on survival, and so such habitat is predicted to be particularly important for the birds. This finding supported the strategies aim of supporting a network of sites for the birds.

Section 6.3 highlights the predicted reduction in the area of saltmarsh within the Solent, which provides an important feeding resource for Brent Geese. Maintaining a suitable network of saltmarsh sites will be increasingly important as the total area of saltmarsh declines. Similarly, Liley & Sharp (2010) make the point that the network should include sites that although not used extensively at present, may become important in the future due to, for example, sea level rise. Reductions in saltmarsh area and coastal squeeze may mean that in the future Brent Geese exploit more sites than they do at the present.

In summary, Sections 6.1, 6.2 and 6.3 broadly support the Solent Waders and Brent Goose Strategy and the analysis performed by Liley & Sharp (2010).

Table 6.1 Comparison of the distances (m) at which Brent Geese and waders either did or did not respond to visitors. Data are from Table 5 of Liley et al. (2010).

	No response			Disturbance occurred		
	Median	Range	Count	Median	Range	Count
Brent Goose	97	17-215	681	51.5	5-178	132
Dunlin	115	29-200	90	75	25-300	21
Redshank	90	20-200	402	44.5	75-150	98
Turnstone	80	16-200	183	50	5-100	61
Grey Plover	80.5	22.5-200	126	75	30-125	12
Oystercatcher	100	38-200	455	46	10-200	151
Curlew	100	40-200	240	75	25-200	58

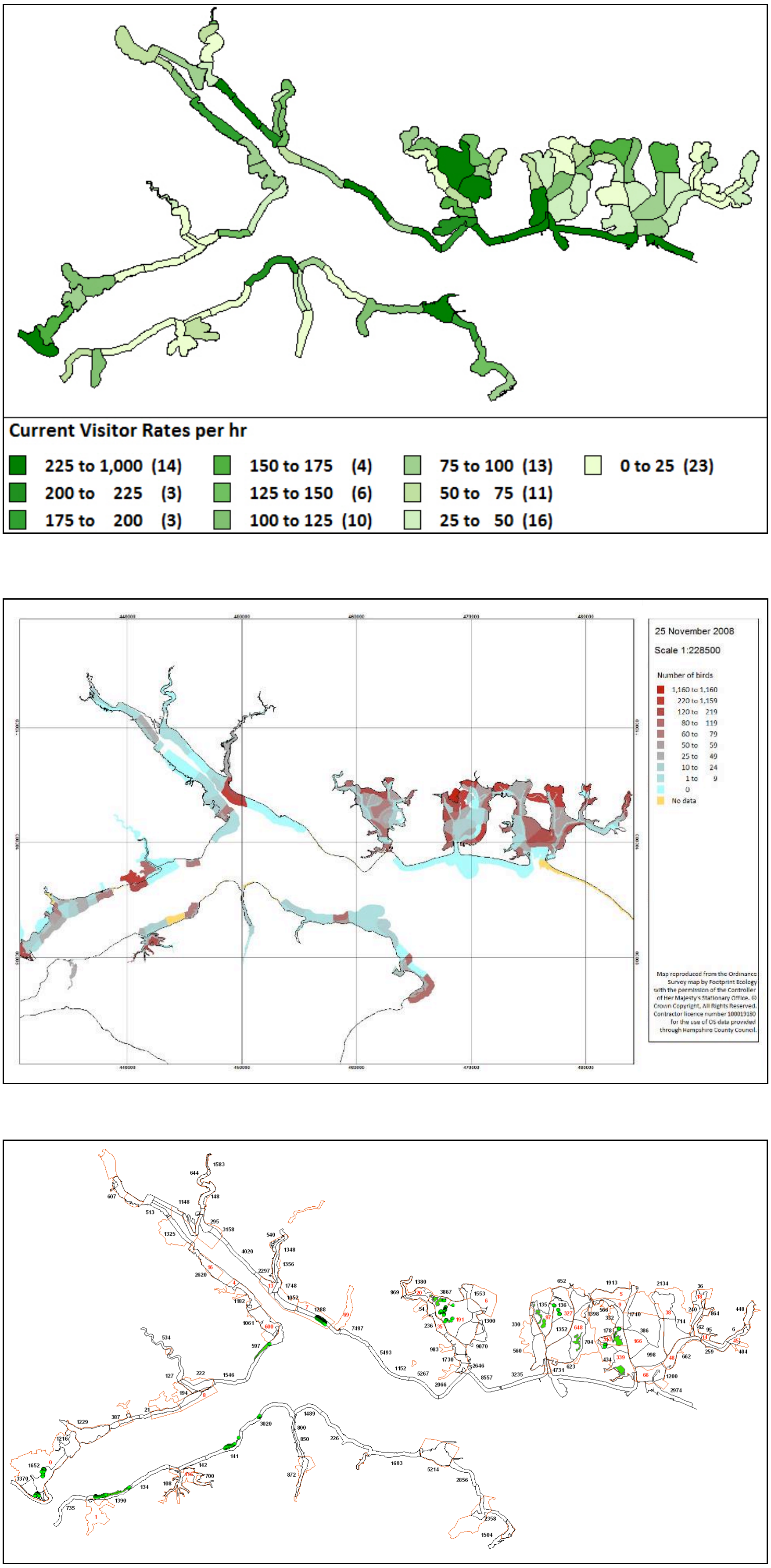


Figure 6.1 Overlap between visitors, Brent Geese and their Zostera food supplies. (a) Visitor rates from current housing. (b) Distribution of Brent Geese from WeBS low tide counts. (c) Distribution of Zostera (green patches) from Hampshire and Isle of Wight Wildlife Trust Zostera database.

Table 6.2 Policies and proposals of the Solent Waders and Brent Goose Strategy (King 2010).

Policy code	Policy statement
W & BG1	Planning Authorities will recognise the importance of the wading bird and Brent Goose sites outside of the statutory designated areas in the Solent and will use the Solent Waders and Brent Goose Strategy as a material consideration in the preparation of development plans and in the determination of planning applications.
W & BG 2	Planning Authorities will actively encourage the enhancement of existing and potential Brent Goose and wader sites, and where appropriate the creation of new sites through development control and forward planning functions.
W & BG 3	Member organisations of the Waders and Brent Goose Strategy Steering Group will continue to monitor and advise on suitable levels of feeding and roosting resource in the Solent necessary to ensure the long-term survival of the wading bird and Brent Goose populations, irrespective of natural fluctuations in population trends, in line with the Conservation Objectives for the European sites.
W & BG 4	Where appropriate, the important sites for wading birds and Brent Geese that fall outside the international and national designations should be considered for County Wildlife Site or Local Nature Reserves designation and given appropriate protection through Local Development Framework policies.
W & BG 5	Development proposals which could affect important wading bird and Brent Goose sites outside of the statutory designated areas need to demonstrate levels of impact, alone and in combination with other proposals. Where a negative impact upon an important wading bird or Brent Goose site cannot be avoided or satisfactorily mitigated, and the tests of the Habitats Regulations are met as necessary, appropriate compensatory measures will be sought.
W & BG 6	Public and private land owners or occupiers will be actively encouraged to favourably manage important Brent Goose and wader sites, and to ensure continued provision of suitable habitat in light of sea level rise predictions and other pressures on existing sites.
W & BG 7	Local Authorities, agencies and nature conservation organisations will raise awareness of the issues and develop a greater understanding of the importance of wading birds and Brent Geese amongst landowners and the general public.
W & BG 8	The Solent Forum Nature Conservation Sub-Group will reconvene the Solent Waders and Brent Goose Strategy Project Steering Group as necessary, to ensure the implementation and review of this Strategy.

Section 7 Discussion

7.1 Context of the current project

The Solent Disturbance and Mitigation Project was initiated by the Solent Forum in response to concerns over the impact of current and future levels of housing on birds around the Solent. Phase I of the project (Stillman et al. 2009) collated existing data on housing and birds in the region, assessed stakeholder opinion of the impact of disturbance and outlined a range of mitigation measures that could potentially offset any impact of disturbance. Phase II of the project has involved a programme of major new data collection to measure the distribution and numbers of visitors (Fearnley et al. 2010), predict how these are related to current housing and may change with future housing (Fearnley et al. 2011) and to predict the behavioural responses of birds to visitors (Liley et al. 2010).

The current project represents the culmination of Phase II, in which the primary data collected within Phase II are used and modelled to understand how disturbance may affect the survival and body condition of the birds. Understanding the effect of disturbance on survival and body condition is an important step because these factors can influence the number of birds that can be supported within a site, and their ability to migrate and breed successfully. Conservation objectives for protected sites (e.g. Special Protection Areas) are often expressed in terms of population size, and it is important to show, if possible, whether activities on a site are reducing the number of birds that can be supported. The previous studies measured the number of visitors to the coast and the behavioural response of birds to these visitors (e.g. the distance at which birds take flight or the time for birds to resume feeding). However, they did not predict how these behavioural responses influenced the number of birds that could be supported by a site. The overall aim of the current project was to make such predictions using individual-based models.

The aim of the current project necessarily restricted the range of bird species within the Solent that could be fully considered to waders, and the season for which predictions could be made. This was because the data required to make the predictions were only available for overwintering waders in Southampton Water and Chichester Harbour. Furthermore, the bird disturbance study conducted during Phase II was restricted to intertidally feeding waders and wildfowl. A review of the potential impact of disturbance on a wider range of species can be found in Stillman et al. (2009).

7.2 Assumptions of the project

As with any models, the predictions of the models used in this project depend on the data with which they are parameterised and the assumptions they make about the real system. This project involved a combination of detailed statistical analysis of bird disturbance data (Liley et al 2010) and computer simulation modelling. The current and future visitor rates were themselves predicted using statistical analyses of household survey (Fearnley et al. 2011) and on-site visitor data (Liley et al. 2010). Furthermore, any model is a simplification of the real system, and so it is important to recognise its limitations when interpreting its predictions. This section describes important aspects of the data used to parameterise the models and the model assumptions which should be considered when interpreting Section 7.3.

7.2.1 Disturbance and visitor data used to parameterise the models

The disturbance parameters used within models were derived from the future and current numbers of activity types throughout the Solent, the distances and time for which birds responded to visitors and the route lengths of visitors along the shore and across the intertidal. These parameters were used to calculate the area, time and energy costs of disturbance. The overall cost, and hence the chance of predicted survival being decreased by disturbance, depends on visitor numbers, disturbance distances and times, and route lengths, and so it is important to consider the way in which these parameters were measured. Visitor numbers and the frequency of different activities were estimated from the results of the household survey (Fearnley et al 2011). There was a significant correlation between the number of visitors recorded during the on-site disturbance study (Fearnley et al. 2010) and the number estimated from the household survey (Fearnley et al 2010; Fig. 10). However, observed on-site visitor rates were not predicted perfectly from the household survey. The behavioural response to disturbance was measured between December 2009 and February 2010, which included a period of exceptionally cold weather (Liley et al. 2010). It is likely that during this period birds allowed visitors to approach more closely or returned more quickly than they would have done during more mild weather (e.g. Stillman & Goss-Custard 2002). Although most likely underestimating the response to disturbance in an “average” winter, the data do probably give a better estimate of area, time and energy costs under conditions in which disturbance is more likely to affect survival. Route lengths were based on interviews conducted during the on-site visitor survey (Fearnley et al. 2010), in which a visitor marked their route on a map of the site. The accuracy of average route lengths used to parameterise the models depends on the accuracy with which the true routes were recorded and whether the visitors interviewed were a representative sample of visitors as a whole. Interviewers assisted the visitors when marking their routes to attempt to minimise errors. Steps were taken to obtain a random / representative sample of visitors (all visitors were interviewed at an access point, or a random sample interviewed when visitor rates were high; Fearnley et al 2010) and so we have no reason to expect that the survey consistently under, or overestimate route lengths.

7.2.2 Overlap of intertidal visitors and birds

Area and time costs of disturbance were calculated by assuming that intertidal disturbance events were independently distributed in space and time, and that people and birds were independently distributed over the intertidal habitat (note that shore-based activities were restricted to the top of the shore and so were separated from the birds to some extent). The assumption of independently distributed visitors and birds meant that each bird had a certain probability of being disturbed by each intertidal visitor which could be calculated with a simple formula. Simulations were run to predict the effect of birds and visitors either occurring in similar or different locations within coastal sections (Figure 4.5). These simulations showed that, as would be expected, disturbance was less likely to reduce survival if birds and intertidal visitors were found in different locations within coastal sections (e.g. birds at bottom of shore and visitors at the top). In absence of data on the co-occurrence of visitors and birds within coastal sections, it was concluded that assuming independent distributions was most appropriate, but further studies would be recommended to test this assumption.

7.2.3 Between-site variation in response to disturbance

Some simplifications were required in the analysis of the bird disturbance data. This was because it was not possible to measure the response of all bird species to all activity types in all coastal sections; some species and activity types were restricted to some sections. This meant that activity types needed to be grouped, and average responses of the birds were predicted rather than site-specific values. As result, some elements of the real system could not be incorporated. For example, the fact that birds in sites with higher visitor numbers will most likely be habituated to disturbance, and so respond less to visitors than birds in sites with lower visitor numbers, could not be incorporate. Habituation to disturbance was incorporated, in the sense that the average responses of the birds included habituation to the relatively high numbers of visitors throughout the Solent, but between-site differences were not. Therefore, model birds in sites with high visitor numbers probably experienced higher disturbance costs than real birds would have; in reality, habituation within these sites would have reduced the distance and time for which birds responded below the Solent-wide average values used in the model. However, given the restrictions of the data, it was not possible to derive site-specific values of the response to disturbance.

7.2.4 Distribution of visits during the tidal cycle.

It was assumed that visitor rates did not vary with stage of the tidal cycle. While appropriate for some activity types (e.g. shore-based dog walking) it is less so for others (e.g. bait digging). If visitor numbers are greater at low tide than at high tide, this assumption would have overestimated high tide visits and underestimated low tide visits.

7.2.5 Modelling bait digging

Bait digging was rarely observed during the bird disturbance field work (Liley et al. 2010) and so was modelled in a relatively simple way; bait diggers were assumed to represent a fixed proportion of all visits as little data were available on the frequency of bait digger visits. However, bait digging can be a common activity in some areas and depletes the prey of the birds in addition to disturbing them. The predictions for bait digging were based on an assumed low frequency of this activity and so will not apply to areas in which bait digging is more frequent.

7.2.6 Modelling rare or localised activities

Similarly to bait digging, the bird disturbance field work (Liley et al. 2010) was less able to measure the response of birds to relatively rare, or localised activities, that did not occur frequently within the 20 coastal sections studied. These include kite surfing and wildfowling. Studies directed towards such activities are recommended to better understand their effect on the birds.

7.2.7 Impacts of non-modelled species on the prey

The Southampton Water model did not include the effect of depletion by non-modelled species on the abundance of the food supply. Any additional sources of prey mortality will reduce the amount of food available to the birds, and hence their ability to compensate for disturbance. The assumption was made because field data showed that wader food supplies within Southampton Water were not depleted during the course of winter (Wood 2007). This implies that depletion due to the birds and other sources is not significant within Southampton Water, but increased depletion may occur in other sites.

7.2.8 Average conditions and pinch points

The individual-based models considered average conditions, rather than extremes of weather or visitor numbers. Simulations showed that bird survival was sensitive to their energy requirements, and so the threshold visitor density above which wader survival is reduced may be lower when energy requirements are higher due to extreme low temperatures. A policy of minimising disturbance to birds during extreme weather conditions would be supported by these predictions.

7.3 Predictions and recommendations of the project

This section highlights the major predictions and conclusions of the project. Section 7.2 explains the links between these predictions and earlier parts of Phase II of the Solent Disturbance and Mitigation Project and highlights issues that should be taken into account when interpreting the predictions.

7.3.1 Number of visits to the Solent coast

Although not an objective of the current project, one key prediction was changes in visitor rates throughout the Solent (Section A4.6). Using current housing levels the visitor models developed by Fearnley et al. (2011) were used to predict 52,000,000 household visits per year to the Solent coast (i.e. the shore from Hurst Castle to Chichester Harbour, including the north shore of the Isle of Wight). Using the housing data provided by local authorities (and assuming visits per household to be a constant over time), visitor levels were predicted to rise by around 8 million household visits, to a total of 60,000,000, an overall increase of some 15%.

7.3.2 Predicted survival of waders in Chichester Harbour

The food supply surveyed within Chichester Harbour was not predicted to be able to support the majority of wading birds modelled. With the exception of Redshank and Oystercatcher, unrealistically low survival rates of waders in Chichester Harbour were predicted. This implied that either the invertebrate survey underestimated the food intertidal supply, or that other food was available either terrestrially, or from neighbouring intertidal sites. Similar invertebrate surveys have been used to parameterise 17 other individual-based models (including Southampton Water; Stillman & Goss-Custard 2010), and in all cases birds were predicted to have survival rates close to, or higher than those expected. Wetland Bird Survey data showed that the numbers of waders feeding at low tide did not decline through winter, as would be expected if survival rates were very low, and did not provide evidence of birds roosting in the site but feeding elsewhere. Due to these uncertainties, it was decided not to use the Chichester Harbour model to predict the effect of disturbance on the birds. However, given that this was the most up to date data available it is also important to draw some conclusions as to the likely effect of disturbance. The impact of disturbance on the birds' survival and body condition will depend on their ability to compensate for lost feeding time and extra energy expenditure. Birds will be better able compensate when more food is available, and so lower food abundance in a site will tend to increase the likelihood that disturbance decreases survival and body condition. Given the importance of Chichester Harbour for waders, a priority would be a repeat invertebrate survey, based on a larger number of survey stations, to obtain a better estimate of the food supply.

7.3.3 Disturbance and survival of non-modelled waders

One species, Bar-tailed Godwit, was included in the Chichester Harbour model but not the Southampton Water model, and so no predictions were made of the effect of disturbance on the survival and body condition of this species. No data were available on the disturbance distances of Bar-tailed Godwit, but, due to its similar size to Black-tailed Godwit, it may be expect to respond in a similar way to disturbance, as response to disturbance in birds is related to body size (Blumstein et al. 2005). The survival of Black-tailed Godwit was not predicted to be reduced by current or future housing. This species was assumed to have a relatively high night-time feeding efficiency, and to be able to feed in terrestrial habitats. This meant that the species was able to compensate for the costs of disturbance by feeding with relatively high efficiency at night, and by feeding in terrestrial habitats during the day. Bar-tailed Godwit have similar foraging behaviour to Black-tailed Godwit and so may be expected to also be relatively efficient at night-time feeding, but rarely feed in terrestrial habitats. Therefore, although no survival predictions can be made, it would be expected that, everything else being equal, Bar-tailed Godwit survival and body condition would be more sensitive to increased disturbance than that of Black-tailed Godwit, as the species is not able to compensate for disturbance by feeding in terrestrial habitats. Furthermore, it should also be noted that Bar-tailed Godwit, as other species, will be less able to compensate for the costs of disturbance when their food supply is less abundant, as suggested by the invertebrate survey of Chichester Harbour. However, further studies of Bar-tailed Godwit would be recommended to test the assumptions made above.

7.3.4 Predicted effect of current and future housing in Southampton Water

In the absence of disturbance, all wader modelled species in Southampton Water (Dunlin, Ringed Plover, Redshank, Grey Plover, Black-tailed Godwit, Oystercatcher and Curlew) were predicted to have 100% survival and maintain their body masses at the target value throughout the course of winter. Disturbance from current housing was predicted to reduce the survival of Dunlin, Ringed Plover, Oystercatcher and Curlew. Future housing was predicted to further reduce the survival of Dunlin and Ringed Plover. Disturbance was predicted to have a relatively minor effect on the mean body mass of waders surviving to the end of winter, largely because the individuals with very low mass starved before the end of winter. Disturbance from both current and future housing was predicted to have a greater effect of the amount of time the model birds spent feeding. Disturbance was predicted to increase the amount of time spent feeding intertidally by Dunlin, Ringed Plover, Redshank and Grey Plover, and increase the amount of time spent feeding terrestrial by Oystercatcher and Curlew to supplement their low tide food consumption. In summary, the Southampton Water provided evidence that current and future disturbance rates may reduce wader survival in this site.

7.3.5 Predicted effect of habitat area and sea level rise

Hypothetical simulations were run to explore how changes in intertidal habitat area may influence the survival of waders within Southampton Water. The survival rates of Dunlin, Ringed Plover, Oystercatcher and Curlew were predicted to be sensitive to any decreases in intertidal habitat area. The overall area of intertidal mudflat in the Solent is predicted to change little over the next 100 years, but larger reductions in saltmarsh are expected. However, changes in the shore height of mudflat may occur in addition to changes in overall area. If, on average, more intertidal habitat is lower on the shore, then it will be exposed for less time giving waders less time to feed. The larger reductions in saltmarsh area may mean that Brent Geese become less able to compensate for the effects of disturbance when feeding in this habitat, and additionally that less roosting and terrestrial feeding habitat will be available for waders. The Southampton Water model predicted that any reduction in intertidal habitat area, whether due to an overall change in area or a change in the proportion of downshore habitat, in association with disturbance from current housing, could reduce the survival of Dunlin, Ringed Plover, Oystercatcher and Curlew.

7.3.6 Predicted effect of disturbance to roost sites

Disturbance to birds on roosting sites was not measured during the disturbance study and so it was not possible to directly predict the effect of roost disturbance on the survival of the birds. However, one of the major effects of disturbance to roosts is an increase in the energy demands of the birds. Hypothetical simulations were therefore run to determine how increasing energy demands effected the survival of the birds. Survival rates of Dunlin, Ringed Plover, Oystercatcher and Curlew were predicted to be decreased by any increases in energy requirements, suggesting that these species will be most vulnerable to increased energy expenditure due to disturbance at roosts. This prediction is in support of the Solent Waders and Brent Goose Strategy recommendation to protect roost sites throughout the Solent.

7.3.7 Predicted effect of changing the frequency of different activities

Hypothetical simulations were run to predict the effect of varying the frequency of different activities on wader survival. The largest increase in predicted survival was achieved by moving all intertidal activities to the shore. This meant that the disturbance from these activities was restricted to the top of the shore rather than the whole intertidal, and so the proportion of intertidal disturbed was reduced. This predicted would be in support of a strategy to reduce intertidal activities in areas that also provide important food resources for the birds. Reductions to the number of dogs that were not on leads were also predicted to increase the survival of some wader species. This prediction would be in support of a strategy to reduce the occurrence of off-lead dogs in areas that provide important food resources for the birds. Removing bait digging from simulations did not increase wader survival. This happened because bait-digging was assumed to be a relatively infrequent activity. This does not mean that bait-digging could not adversely affect the birds if it occurred at a higher frequency, and the simulations did not incorporate the depletion of the invertebrate prey of the birds caused by bait digging, which would be an additional effect on the birds in addition to disturbance. Further studies into the frequency of bait digging and its combined effect of disturbing birds and depleting their food supply are needed to understand the effect of this activity on the birds.

7.3.8 Disturbance and Brent Geese

It was not possible to make quantitative predictions for Brent Geese as insufficient data were available to build an individual-based model. Instead Brent Geese were considered in the light of the Solent Waders and Brent Goose Strategy. The strategy is concerned with maintaining a network of sites that is able to support overwinter populations of the birds. Important issues are the size of individual sites, their spacing and the ease with which birds can move between the sites. A high proportion of each site needs to be more than disturbance distances away from visitor access routes to ensure that disturbance to the birds is minimised. This could be achieved through a network of larger sites or by preventing visitor access through, or close to, smaller sites. Both intertidal and terrestrial food resources are important to the birds, intertidal food typically being of higher food value but dying back and / or become depleted during the autumn / early winter. Previous models of Brent Geese have predicted that the loss of terrestrial habitat typically has the highest effect on survival, and so such habitat is predicted to be particularly important for the birds. Maintaining a suitable network of saltmarsh sites will be increasingly important as the total area of saltmarsh declines as sea level rises. The findings of the present project are in general support with the recommendations of the Solent Waders and Brent Goose Strategy.

7.3.9 Scaling up to the whole Solent

Predicted current visitor rates varied widely throughout the Solent, but were relatively high within Southampton Water. Predicted future visitor rates showed a broadly similar pattern to current visitor rates, with similar differences between sites and the same coastal sections having the highest visitor rates. The lowest percentage increases (less than 10%) in visitor numbers were predicted to be to the west of Southampton Water, an area in which current visitor rates were also predicted to be relatively low. The highest percentage increases in visitor rates were on the Isle of

Wight (50-75%). Wader survival was predicted to be decreased in Southampton Water when daily visitor rates to coastal sections were greater than 30 per ha of intertidal habitat. The potential impact of visitors on wader survival throughout the Solent was inferred by comparing visitor densities throughout the Solent (expressed relative to maximum intertidal habitat area) to visitor densities predicted to decrease survival within Southampton Water. The intertidal food supplies within Chichester Harbour were insufficient to support the birds and so any disturbance (by reducing feeding area or time, or increasing energy demands) would have decreased predicted survival. There is also doubt as to the food supply within the other harbours and so some caution is appropriate when applying the results from Southampton Water to these sites. Table 5.2 lists the coastal sections with daily visitor rates over 30 per ha. The predictions of the Southampton Water model suggest that birds within any of these sections may have reduced survival due to disturbance from the visitors. Whether or not such visitor rates will reduce survival will depend on the food abundance in the coastal sections themselves as well as that in neighbouring sections.

7.3.10 Percentage of intertidal habitat disturbed

The area of overlap between an activity / development and the distribution of birds is often used as a measure of the impact of the activity on the birds, with 1% overlap often taken as the threshold for impact (note however that this 1% overlap does not necessarily mean that an activity will have an adverse effect on the survival or body condition of birds). Therefore, the percentage of intertidal habitat disturbed within each coastal section was calculated as an index of the potential impact of disturbance on the birds. Even assuming the maximum intertidal area and only including intertidal visitors, over 50% of the area of many coastal sections was predicted to be disturbed, with an average of 42%.

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Appendix 1 General description of MORPH

This appendix gives a general overview of the individual-based model (MORPH) used in the project, including the types of conservation issues to which it has been applied and ways in which the accuracy of its predictions have been tested.

A1.1 Using individual-based models to assist wader conservation

In migratory waders and wildfowl, population size is a function of the interaction between (i) mortality and reproductive rates in the breeding ranges and (ii) mortality rate in the non-breeding range, including migratory routes (Goss-Custard & Sutherland, 1997; Sutherland, 1996). Therefore, the best measure of the impact of change on population size is one which, directly or indirectly, determines these demographic rates (Goss-Custard et al., 2002). For migratory waders and wildfowl during the non-breeding season, this means that the impact should be measured in terms of its effect on two factors: (i) the storage of fat reserves needed to fuel migration in spring and to breed successfully after the birds have reached the breeding grounds and (ii) the number of birds that die during the non-breeding season (Goss-Custard et al., 2002).

Individual-based models, comprised of fitness-maximising individuals, are a means of predicting fat storage and mortality rates and hence can be used to determine the population consequences of environmental change (e.g. Norris & Stillman, 2002; Stillman & Goss-Custard 2010). Such individual-based models have been used to predict the effect of habitat loss, sea level rise and disturbance on coastal bird populations at several European sites (Caldow et al., 2004; Durell et al., 2005; Goss-Custard et al., 1995a; Goss-Custard et al., 1995b; Goss-Custard et al., 2004; Goss-Custard et al., 2006a; Stillman et al., 2000; Stillman et al., 2001a; Stillman et al., 2003; Stillman et al., 2005c; West et al., 2003). These models track the behavioural decisions and locations of all animals within a population, and predict population parameters, such as mortality rate, from the fates of all individuals. Importantly, the decisions made by model animals are based on optimal foraging theory and game theory, which are thought to provide a reliable basis for prediction (Goss-Custard & Sutherland, 1997; Sutherland, 1996). Model individuals are designed to always behave in order to maximise their own chances of survival and reproduction, no matter how much the environment changes. Therefore, model animals are expected to respond to environmental change in the same ways as real ones would (Goss-Custard & Sutherland, 1997; Sutherland, 1996). MORPH predicts how environmental change (e.g. changes in shellfishing, habitat loss, changes in human disturbance, climate change and changes in population size) affects foraging animal populations. MORPH's key assumptions are that individuals behave in order to maximise their perceived fitness (i.e. their expected survival and reproduction associated with alternative behaviours), but that perceived fitness may not always be positively related to the actual chances of survival and reproduction (i.e. animals may make sub-optimal decisions). MORPH contains a basic framework to describe animal physiology and foraging behaviour, and the distribution and abundance of resources. It can produce both general predictions (when parameterised in a simple way), and predictions for specific systems (when parameterised using system-specific data).

A1.2 Overview of the model

MORPH is an individual-based model (IBM) and tracks the foraging location, body condition and ultimate fate of each individual within an animal population. During each day, each animal in the population must consume enough food to meet its energy demands. It attempts to do this by feeding in those locations and at those times of the day where its intake rate is maximised. Although all individuals decide on the same principle, intake rate maximisation, the actual decisions made by each differ. Their individual choices depend on their particular competitive ability which depends on two characteristics. Interference-free intake rate is the rate at which an individual feeds in the absence of competition and measures its basic foraging efficiency. Susceptibility to interference measures how much interference from competitors reduces its intake rate as competitor density rises. Survival is determined by the balance between an individual's daily rates of energy expenditure and consumption. Energy expenditure depends on metabolic costs. Energy consumption depends on the time available for feeding, intake rate while feeding and the energy content of the food being consumed. When daily energy consumption exceeds daily expenditure, individuals accumulate energy reserves or maintain them if a maximum level has already been reached. When daily requirements exceed daily consumption, individuals draw on their reserves. If reserves fall to zero, an individual dies of starvation.

A1.3 Other systems to which the model has been applied

MORPH has been applied to several systems, including waders in the Exe estuary (Stillman et al., 2005a) and Poole Harbour, UK (Durell et al., 2006), the Baie de Somme, France (Durell et al., 2006; Stillman et al., 2005a) and the Bahia de Cadiz, Spain (Stillman et al., 2005a), brent geese *Branta bernicla* in western Europe (Stillman et al., 2005a) and scoter ducks in the Irish Sea (Kaiser et al., 2005). Durell et al. (2006) used MORPH to predict the effect of climate change on the survival rates of five wader species, dunlin *Calidris alpina*, redshank *Tringa totanus*, black-tailed godwit *Limosa limosa*, oystercatcher and curlew *Numenius arquata*, in Poole Harbour, UK. The model incorporated the daily exposure and covering of the birds' intertidal feeding areas, seasonal changes in temperature and the mortality of prey due to factors other than the birds. The model predicted that wader survival was very sensitive to any reduction in patch exposure time caused by sea level rise; a 20cm sea-level rise reducing survival rates of all waders from 95% to 5-70% (Durell et al., 2006). Kaiser et al. (2005) used MORPH to predict the effect of offshore wind farms on the mortality rate of common scoters in Liverpool Bay, UK. Up to 5 wind farms are proposed in the Bay, which is a key scoter wintering site (Oliver, Robinson & Harrod, 2001), and there is concern that this will displace birds into less favourable areas or alter the seabed habitat such that the ducks preferred food is no longer available. The model takes account of the changing depth of water over the ducks' food supply and the energetics of diving to reach that food. It incorporates disturbance due to shipping lanes and assumes that scoters are excluded from a 2 km buffer around windfarms. The model predicted that scoter survival rate would decrease if all wind farms were developed, but also which combination of wind farms had the least effect on scoters (Kaiser et al., 2005). Stillman et al. (2005a) used MORPH to predict changes in the distribution and survival of brent geese throughout western Europe in response to habitat loss, disturbance from people and hunting. The model showed that the geese were particularly dependent on terrestrial habitats such as grassland and agricultural fields, rather than intertidal habitats on which the geese feed early in the winter (Stillman et al., 2005a). These examples, of carnivorous waders, marine diving ducks and herbivorous geese, show how MORPH can be parameterised for a wide range of systems.

A1.4 Testing the accuracy of the model's predictions

If IBMs such as MORPH are to be of applied value they need to produce accurate predictions. MORPH has been tested as thoroughly as possible using all data available for each study system. Two questions can be asked about whether an IBM predicts real events reasonably well. One question asks whether the model captures with good precision the behaviour of real birds in the system being modelled. Because the predictions for survival are derived from the behaviour of the birds in the model, and because decision making by fitness-maximizing individuals is the fundamental feature of the model, it is vital that the model adequately represents the behaviour of real birds. The other question is whether the model accurately predicts the fitness measures (e.g. survival) that are derived from this underlying behaviour. Although the tests have varied between sites, data have been typically available to test the predicted distribution of birds throughout a site and the major prey species consumed by birds. Typically, patch selection and prey choice were accurately predicted for the majority of species (e.g. Durell et al., 2005; Stillman et al., 2005c). In some sites, data were available on the proportion of the time spent feeding each day (an important indicator of the difficulty birds are having in surviving winter) and overwinter mortality rates. Both the proportion of the time spent feeding and overwinter mortality were accurately predicted in all cases (e.g. Goss-Custard & Stillman, 2008). These accurate predictions increase confidence that the model provides a realistic description of the real world, and therefore that predictions for novel scenarios, which cannot be tested, are also likely to be accurate.

A1.5 Parameters required to apply the model to a new system

To be applied to a new system, the key parameters that need to be measured or obtained from previous studies or the literature are: (i) the distribution of the food supply and how food quality and abundance changes through the season; (ii) the tidal availability of feeding areas; (iii) the rate at which foragers are able to consume food given the abundance of food and competitors; (iv) the amount of food a forager needs to consume each day in order to avoid starvation; (v) the distribution and seasonal changes in other factors which influence the foraging behaviour and survival of foragers. In practice the only new parameters that have been measured for new wader systems have been the distribution and abundance of invertebrate prey and the availability of this prey through the tidal cycle. Typically, other parameters have been either obtained from the literature or from previous studies of the site. As a result models have typically been parameterised and applied to conservation issues using one autumn survey of prey populations (sometimes supplemented with a second in the spring), and estimates of the tidal exposure of patches either derived from local knowledge, patch heights on the shore, or existing tidal models. Once data are available, models have typically been parameterised and simulations run to address conservation issues within two months. Once a model is parameterised for a system, simulations can be run to address new issues within a matter of hours. The experience has therefore been that it has been possible to apply MORPH within a time scale that is compatible with the time constraints of coastal conservation issues.

Appendix 2 Datasets used in the project

The following datasets and sources were used in the project.

- **Bird populations of the Solent**. Wetland Bird Survey (WeBS) low tide and high tide counts were used to parameterise and test the individual-based models, and to determine overlap between Brent Geese distribution and human disturbance.
- **Wader food supply in Southampton Water**. The food supply of waders in Southampton Water was derived from an intertidal invertebrate survey conducted by Pippa Wood as part of a PhD studentship funded by Associated British Ports Marine Environmental Research (ABPmer). These data were made available to the project by ABPmer.
- **Wader food supply in Chichester Harbour**. The food supply of waders in Chichester Harbour was derived from an intertidal invertebrate survey conducted by EMU Ltd. funded by the Chichester Harbour Conservancy. These data were made available to the project by the Chichester Harbour Conservancy.
- **Food supply of Brent Geese**. The distribution of the intertidal food supply of Brent Geese was derived from the Hampshire and Isle of Wight Wildlife Trust Eelgrass Inventory. No data were available on the terrestrial food supply of Brent Geese.
- **Response of birds to human activities.** The response of birds to human activities was derived from observations at 20 sites throughout the Solent conducted by Footprint Ecology, funded by the Solent Forum and reported in Liley et al. (2010).
- **Number of people visiting the Solent coast.** The number of people visiting the coast with current and future housing was derived from a postal household survey of residences in the Solent region conducted by Footprint Ecology, funded by the Solent Forum and reported in Fearnley et al. (2011).
- **Activities of people on the Solent coast.** The activity of people on the Solent coast was derived from observations at 20 sites throughout the Solent conducted by Footprint Ecology, funded by the Solent Forum and reported in Fearnley et al. (2010).
- **Tidal exposure of intertidal habitats**. The area of intertidal habitat exposed by the tide was predicted by ABPmer using a hydrodynamic model.

Appendix 3 Chichester Harbour and Southampton Water models

This appendix gives full details of how the MORPH individual-based model was parameterised for Chichester Harbour and Southampton Water. Unless otherwise stated, the same parameters were used for both models.

A3.1 Environmental parameters

A3.1.1 Time period simulated

Model simulations ran from 1st September to 31st March, encompassing the major overwintering period of most waders in the UK, and peaks in the wintering numbers of waders in the Solent.

A3.1.2 Time step length

Time was divided into one hour time steps, during each of which environmental conditions were assumed to remain constant. Birds were assumed to occupy a single patch, and consume a single diet during each time step, but could change patches and diets between time steps. The time of day of each model time step was that for the mid-point of the time step measured in Greenwich Mean Time.

A3.1.3 Day length

Daylight was assumed to occur between sunrise and sunset. The times of sunrise and sunset each day were calculated from the duration and timing of day length cycles at Southampton water during the time period modelled. Given the close proximity between the sites, seasonal variation in day length at Chichester Harbour was assumed to be the same as at Southampton Water.

A3.1.4 Tidal cycle

The tidal cycle was based on the results of a Solent-wide tidal model simulation provided by ABPmer. See Section A3.2.2 for details of how the tidal cycle influences the area of intertidal habitat exposed.

A3.1.5 Spatial extent of the models

The models comprised the entire intertidal feeding habitat of waders in Southampton Water and Chichester Harbour. Terrestrial food resources were not included in the models as no data were available to quantify these.

A3.2 Patch parameters

A3.2.1 Model patches

Patches in the Southampton Water and Chichester Harbour models were based on the bird and visitor sections used to measure human activities on the coast (Fearnley et al*.* 2010) and the response of birds to these activities (Liley et al*.* 2010).

Southampton Water. The Southampton water model had 19 patches representing the intertidal portions of sections 13 to 32 of the bird and visitor surveys and one roost patch. Section 19 was not included as it has no intertidal feeding area contained within it. The characteristics of each patch are shown in Table A3.1.

Chichester Harbour. The Chichester Harbour model had 21 patches representing the intertidal portions of sections 64 to 84 of the disturbance survey and one roost patch. The characteristics of each patch are shown in Table A3.2.

A3.2.2 Patch area exposed by the tide

The tidal cycle was based on the results of a Solent-wide tidal model simulation provided by ABPmer. These took the form of predicted wet and dry areas for each model patch in the Solent over an average spring – neap cycle. The maximum intertidal area of each patch was defined as the area between high tide on the lowest neap tide and low tide on the lowest spring tide. This assumed that the invertebrate food supply of the birds would be absent or insignificant above high tide on the lowest neap tide as any area above this point would remain dry throughout some tidal cycles. The average spring – neap cycle was assumed to repeat throughout the winter. This approach meant that the tidal and spring-neap cycles and their effect on available feeding areas for the birds were included in the model.

Table A3.1 Characteristics of Southampton Water model patches.

Patch	Location	Maximum area (m^2)	Principal prey species
Section 13	Calshot Castle to Fawley	1040079	Marine worms, *Hydrobia*, crustaceans, bivalves<20mm
Section 14	Fawley to Cadland Creek	678179	Marine worms, *Hydrobia*, crustaceans, bivalves<20mm
Section 15	Cadland Creek to Hythe	1549984	Marine worms, bivalves<20mm
Section 16	Hythe Pier to Marchwood	657670	Marine worms, *Hydrobia*, bivalves<30mm
Section 17	Marchwood to Marchwood Industrial Park	147067	Marine worms, *Hydrobia*, bivalves<30mm
Section 18	Marchwood Industrial Park to Freemantle	545287	Marine worms, *Hydrobia*, bivalves<30mm
Section 20	Ocean Village Marina to Itchen Bridge	492301	Marine worms, crustaceans, bivalves<10mm
Section 21	Itchen Bridge to Northam Bridge	373859	Marine worms, *Hydrobia*
Section 22	Northam Bridge to St. Denys - Cobden bridge	190821	Marine worms, *Hydrobia*
Section 23	St. Denys - Cobden Bridge to Swaything	51408	Marine worms, *Hydrobia*
Section 24	Weston to Netley	542243	Marine worms, bivalves, crustaceans
Section 25	Netley to Hamble-le -Rice	494189	Marine worms, bivalves, crustaceans
Section 26	Hamble-le-Rice to Hamble Rice	641691	Marine worms, bivalves, crustaceans
Section 27	Hamble Rice to Hound - Mercury Yacht Marina	140721	Marine worms, *Hydrobia*
Section 28	Mercury Yacht Marina to Bursledon	99201	Marine worms, *Hydrobia*
Section 29	Burlesdon to Hollyhill Woodland Park	175143	Marine worms, *Hydrobia*
Section 30	Hollyhill Woodland Park to Warsash	138506	Marine worms, *Hydrobia*
Section 31	Warsash to Newton Farm	158913	Marine worms, *Hydrobia*, bivalves
Section 32	Newton Farm to Solent Breezer Caravan Site	664242	Marine worms

Table A3.2 Characteristics of Chichester Harbour model patches.

Patch	Location	Maximum area (m^2)	Principal prey species
Section 64	Black Point to Mill Rythe Holiday village	1176649	Marine worms, *Hydrobia*, cockles
Section 65	Mill Rythe Holiday Village to Tye	425347	Marine worms, *Hydrobia*, cockles
Section 66	Tye to Northney	177965	Marine worms, *Hydrobia*
Section 67	Northney to Langstone Bridge	154868	Marine worms, *Hydrobia*, bivalves
Section 68	Langstone Bridge to East side of Quay Mill	1134726	Marine worms, *Hydrobia*, bivalves
Section 69	East side of Quay Mill to Marker Point	420633	Marine worms, *Hydrobia*, bivalves
Section 70	Marker Point to Longmere Point	1401162	Marine worms, *Hydrobia*
Section 71	Longmere Point to Stanbury Point	1512017	Marine worms, *Hydrobia*
Section 72	Stanbury Point to Chidham	949466	Marine worms, *Hydrobia*, cockles
Section 73	Chidham to Cobnor Point	761325	Marine worms, *Hydrobia*, crustaceans
Section 74	Roockwood to Black Point	724961	Marine worms, *Hydrobia*, crustaceans
Section 75	West Itchenor to Rookwood	550551	Marine worms, *Hydrobia*, crustaceans
Section 76	Cobnor Point to Easton Farm	154489	Marine worms, *Hydrobia*
Section 77	Easton Farm to Bosham Shipyard	366684	Marine worms, *Hydrobia*, cockles
Section 78	Bosham Shipyard to Southwood Farm	134666	Marine worms, *Hydrobia*
Section 79	Southwood Farm to Itchenor Ferry	160601	Marine worms, *Hydrobia*
Section 80	Itchenor Ferry to Longmore Point	201763	Marine worms, *Hydrobia*
Section 81	Longmore Point to Hook Farm	205763	Marine worms, *Hydrobia*
Section 82	North Fishbourne Harbour to Dell Quay	474737	Marine worms, *Hydrobia*, cockles
Section 83	New Barn to Birdham Pool	370979	Marine worms, *Hydrobia*
Section 84	Birdham Pool to West Itchenor	203032	Marine worms, *Hydrobia*

A3.3 Food resource parameters

A3.3.1 Numerical density and mass of prey at start of winter

Southampton Water. Benthic invertebrate densities and biomasses in 5mm size classes were based on a survey of intertidal areas of Southampton Water conducted in September 2003 (Wood 2007). The survey used a stratified random sampling design and took 108 samples in total from both sides of the estuary. Lengths of individual invertebrates were measured and a sub-sample was dried and ashed to determine ash-free dry weights. Patches in the current Southampton model were based on the survey sections used in Fearnley et al. (2010) and Liley et al. (2010) and were not the same as the patches identified in the 2003 survey. Densities in the current model were adjusted to take account of this. Table A3.3 shows the start of winter density of each prey size class. Table A3.5 shows the start of winter mass of each prey class.

Chichester Harbour. Benthic invertebrate densities and biomasses in 5mm size classes were based on a survey of Chichester Harbour conducted by EMU Ltd. in October 2006, designed to assess wader prey (Emu 2007). The survey repeated the sampling design of two earlier surveys (1978 and 1987), with some sites moved to reflect subsequent changes in habitat or to move them into areas which had contained significant numbers of birds in WeBS low tide counts in 2002. Samples were collected from 45 locations across the harbour. Patches in the Chichester Harbour model were based on the survey sections used in Fearnley et al. (2010) and Liley et al. (2010). The nature of the invertebrate sampling design meant that samples were not taken from each of the model patches. To account for this, patches that did have samples were divided into groups depending on the nature of the invertebrate fauna there. Patches with no samples were then assigned to the same groups based on physical proximity to other patches and location within the harbour, e.g. near or far from the mouth. Patches within a group were then given prey densities and ash-free dry weights based on the average for all samples taken within those patches. Table A3.4 shows the start of winter density of each prey size class. Table A3.5 shows the start of winter mass of each prey class.

A3.3.2 Changes in the numerical density and mass of prey

Both models assumed that depletion by the birds was the only source of mortality of the prey. The evidence for this was that there was no detectable overwinter decline in prey abundance observed in the Southampton Water invertebrate survey (Wood 2007). The overwinter decline in the mass of individual bivalves was 28% (Stillman et al., 2000; Zwarts, 1991). Bivalve mass declined at a constant linear rate throughout winter. Individuals of all other prey species were assumed to have a constant mass throughout the course of winter.

A3.3.3 Prey energy content

Prey energy content is the amount of energy (KJ) contained in a gram of prey flesh and was 23.5 KJ g^{-1} in worms, 23.5 KJ g^{-1} in crustaceans and 22.0 KJ g^{-1} in shellfish (Zwarts and Wanink, 1993).

Table A3.3 Start of winter numerical density of prey size classes in the Southampton Water model.

	Sector									
Prey species and size	13	14	15	16	17	18	20	21	22	23
Crustacea 0-9mm	338	111	10.6	10.6	10.6	0	149	0	0	0
Crustacea10+mm	110	39.5	10.6	10.6	10.6	0	0	10.6	10.6	10.6
Bivalves 0-4mm	15.7	18.2	21.2	31.8	31.8	0	63.7	0	0	0
Bivalves 5-9mm	0	0	0	149	149	74.3	84.9	10.6	10.6	10.6
Bivalves 10-14mm	23.8	35.1	42.4	127	127	127	0	0	0	0
Bivalves 15-19mm	31.8	31.8	31.8	31.8	31.8	117	10.6	10.6	10.6	10.6
Bivalves 20-24mm	0	6.7	10.6	31.8	31.8	53.1	0	0	0	0
Bivalves 25-29mm	0	0	0	21.2	21.2	21.2	0	0	0	0
Bivalves 30-34mm	0	0	0	0	0	0	10.6	0	0	0
Bivalves 35-39mm	0	0	0	0	0	0	0	0	0	0
Bivalves 40+mm	0	0	0	0	0	0	0	0	0	0
Hydrobia 0-4mm	702	342	63.7	53.1	53.1	1210	0	10.6	10.6	10.6
Hydrobia 5-10mm	925	399	21.2	361	361	2249	31.8	552	552	552
Worms 5-15mm	0	20.2	31.8	0	0	0	53.1	74.3	74.3	74.3
Worms 15-30mm	151	61.3	10.6	31.8	31.8	42.4	31.8	127	127	127
Worms 30-45mm	79.8	205	276	149	149	63.7	127	318	318	318
Worms 45-60mm	24.2	37.4	42.4	21.2	21.2	31.8	84.9	84.9	84.9	84.9
Worms 60-75mm	55.2	58	63.7	21.2	21.2	31.8	10.6	53.1	53.1	53.1
Worms 75-90mm	0	6.7	10.6	0	0	10.6	21.2	0	0	0
Worms 90-105mm	15.7	11.4	10.6	0	0	10.6	10.6	10.6	10.6	10.6
Worms 105+mm	16.1	6.9	0	10.6	10.6	31.8	42.4	0	0	0

Table A3.3 (continued) Start of winter numerical density of prey size classes in the Southampton Water model.

	Sector								
Prey species and size	24	25	26	27	28	29	30	31	32
Crustacea 0-9mm	168	202	202	7.2	7.2	7.2	7.2	13.3	21.2
Crustacea10+mm	0	0	0	0	0	0	0	9.2	21.2
Bivalves 0-4mm	52.2	31.8	31.8	7.2	7.2	7.2	7.2	4.1	0
Bivalves 5-9mm	69.6	42.4	42.4	10.8	10.8	10.8	10.8	6.2	0
Bivalves 10-14mm	19.2	53.1	53.1	0	0	0	0	0	0
Bivalves 15-19mm	14.4	21.2	21.2	0	0	0	0	4.6	10.6
Bivalves 20-24mm	3.8	10.6	10.6	21.6	21.6	21.6	21.6	12.3	0
Bivalves 25-29mm	7.7	21.2	21.2	3.6	3.6	3.6	3.6	2.1	0
Bivalves 30-34mm	14.4	21.2	21.2	3.6	3.6	3.6	3.6	2.1	0
Bivalves 35-39mm	15.3	42.4	42.4	3.6	3.6	3.6	3.6	2.1	0
Bivalves 40+mm	0	0	0	3.6	3.6	3.6	3.6	2.1	0
Hydrobia 0-4mm	0	0	0	443	443	443	443	252	0
Hydrobia 5-10mm	20.3	0	0	346	346	346	346	197	0
Worms 5-15mm	45.4	31.8	31.8	36	36	36	36	29.7	21.2
Worms 15-30mm	35.7	42.4	42.4	28.8	28.8	28.8	28.8	16.4	0
Worms 30-45mm	120	106	106	54.1	54.1	54.1	54.1	58.2	63.7
Worms 45-60mm	88.7	95.5	95.5	7.2	7.2	7.2	7.2	59	127
Worms 60-75mm	10.6	10.6	10.6	0	0	0	0	13.7	31.8
Worms 75-90mm	13.6	0	0	0	0	0	0	0	0
Worms 90-105mm	10.6	10.6	10.6	7.2	7.2	7.2	7.2	8.7	10.6
Worms 105+mm	27.1	0	0	0	0	0	0	0	0

Table A3.4 Start of winter numerical density of prey size classes in the Chichester Harbour model.

	Sector										
Prey species and size	82	81	83	80	84	79	78	77	76	75	74
Worms 5-15mm	9340	10577	10577	10577	10577	10577	10577	8594	10577	22758	22758
Worms 15-30mm	1017	1836	1836	1836	1836	1836	1836	1464	1836	1844	1844
Worms 30-45mm	33.3	114	114	114	114	114	114	28.6	114	25	25
Worms 45-60mm	33.3	14.3	14.3	14.3	14.3	14.3	14.3	14.3	14.3	0	0
Worms 60-75mm	0	0	0	0	0	0	0	0	0	12.5	12.5
Worms 75-90mm	0	0	0	0	0	0	0	10.6	0	0	0
Worms 90-105mm	0	0	0	0	0	0	0	10.6	0	0	0
Worms 105+mm	0	14.3	14.3	14.3	14.3	14.3	14.3	31.8	14.3	0	0
Cockles 0-4mm	0	0	0	0	0	0	0	14.3	0	0	0
Cockles 5-9mm	3.3	0	0	0	0	0	0	2.9	0	1.3	1.3
Cockles 10-14mm	0	0	0	0	0	0	0	11.4	0	0	0
Cockles 15-19mm	80	0	0	0	0	0	0	8.6	0	0	0
Cockles 20-24mm	40	0	0	0	0	0	0	15.7	0	0	0
Cockles 25-29mm	43.3	0	0	0	0	0	0	5.7	0	1.3	1.3
Cockles 30-34mm	3.3	0	0	0	0	0	0	1.4	0	1.3	1.3
Cockles 35-39mm	0	0	0	0	0	0	0	1.4	0	0	0
Cockles 40+mm	0	0	0	0	0	0	0	0	0	0	0
Hydrobia 0-4mm	19167	5386	5386	5386	5386	5386	5386	15071	5386	9650	9650
Hydrobia 5-10mm	3333	286	286	286	286	286	286	2429	286	150	150
Bivalves 0-4mm	0	114	114	114	114	114	114	0	114	0	0
Bivalves 5-9mm	0	0	0	0	0	0	0	2.9	0	0	0
Bivalves 10-14mm	0	0	0	0	0	0	0	0	0	0	0
Bivalves 15-19mm	0	0	0	0	0	0	0	0	0	0	0
Bivalves 20-24mm	0	0	0	0	0	0	0	0	0	0	0
Bivalves 25-29mm	0	0	0	0	0	0	0	0	0	0	0
Bivalves 30-34mm	0	0	0	0	0	0	0	0	0	0	0
Bivalves 35-39mm	0	0	0	0	0	0	0	0	0	0	0
Bivalves 40+mm	0	0	0	0	0	0	0	0	0	0	0
Crustacea 0-9mm	0	28.6	28.6	28.6	28.6	28.6	28.6	42.9	28.6	225	225
Crustacea10+mm	33.3	0	0	0	0	0	0	14.3	0	25	25

Table A3.4 (continued) Start of winter numerical density of prey size classes in the Chichester Harbour model.

	Sector									
Prey species and size	73	72	71	70	69	68	67	66	65	64
Worms 5-15mm	22758	8594	3696	1544	46123	46123	46123	10577	34961	34961
Worms 15-30mm	1844	1464	586	194	4213	4213	4213	1836	2417	2417
Worms 30-45mm	25	28.6	35.7	11.1	250	250	250	114	100	100
Worms 45-60mm	0	14.3	3.4	0	0	0	0	14.3	16.7	16.7
Worms 60-75mm	12.5	0	0	0	0	0	0	0	0	0
Worms 75-90mm	0	0	10.6	0	0	0	0	0	0	0
Worms 90-105mm	0	0	10.6	0	0	0	0	0	0	0
Worms 105+mm	0	0	31.8	0	0	0	0	14.3	0	0
Cockles 0-4mm	0	14.3	0	0	0	0	0	0	0	0
Cockles 5-9mm	1.3	2.9	0.8	1.1	0	0	0	0	0	0
Cockles 10-14mm	0	11.4	0.8	1.1	0	0	0	0	1.7	1.7
Cockles 15-19mm	0	8.6	0	0	0	0	0	0	13.3	13.3
Cockles 20-24mm	0	15.7	0.8	1.1	0	0	0	0	18.3	18.3
Cockles 25-29mm	1.3	5.7	1.7	2.2	0	0	0	0	3.3	3.3
Cockles 30-34mm	1.3	1.4	1.7	2.2	2.5	2.5	2.5	0	1.7	1.7
Cockles 35-39mm	0	1.4	0	0	0	0	0	0	0	0
Cockles 40+mm	0	0	0	0	0	0	0	0	0	0
Hydrobia 0-4mm	9650	15071	3381	2756	21975	21975	21975	5386	13817	13817
Hydrobia 5-10mm	150	2429	144	100	5650	5650	5650	286	417	417
Bivalves 0-4mm	0	0	52.6	33.3	75	75	75	114	167	167
Bivalves 5-9mm	0	2.9	0	0	25	25	25	0	0	0
Bivalves 10-14mm	0	0	0	0	0	0	0	0	33.3	33.3
Bivalves 15-19mm	0	0	0	0	25	25	25	0	0	0
Bivalves 20-24mm	0	0	0	0	0	0	0	0	0	0
Bivalves 25-29mm	0	0	0	0	0	0	0	0	0	0
Bivalves 30-34mm	0	0	0	0	0	0	0	0	0	0
Bivalves 35-39mm	0	0	0	0	0	0	0	0	0	0
Bivalves 40+mm	0	0	0	0	0	0	0	0	0	0
Crustacea 0-9mm	225	42.9	32.2	33.3	50	50	50	28.6	100	100
Crustacea10+mm	25	14.3	0	0	0	0	0	0	16.7	16.7

Table A3.5 Start of winter mass (g) of prey size classes in the Southampton Water and Chichester Harbour models. No cockles were included in the Southampton Water model.

Prey species and size	Mass (g)
Worms 5-15mm	0.0012
Worms 15-30mm	0.0070
Worms 30-45mm	0.0213
Worms 45-60mm	0.0445
Worms 60-75mm	0.0770
Worms 75-90mm	0.1194
Worms 90-105mm	0.1720
Worms 105+mm	0.2959
Cockles 0-4mm	0.0012
Cockles 5-9mm	0.0076
Cockles 10-14mm	0.0175
Cockles 15-19mm	0.0923
Cockles 20-24mm	0.1553
Cockles 25-29mm	0.2831
Cockles 30-34mm	0.4725
Cockles 35-39mm	0.7087
Cockles 40+mm	0.9489
Hydrobia 0-4mm	0.0008
Hydrobia 5-10mm	0.0012
Bivalves 0-4mm	0.0032
Bivalves 5-9mm	0.0094
Bivalves 10-14mm	0.0225
Bivalves 15-19mm	0.0670
Bivalves 20-24mm	0.1254
Bivalves 25-29mm	0.2240
Bivalves 30-34mm	0.3458
Bivalves 35-39mm	0.5655
Bivalves 40+mm	0.7432
Crustacea 0-9mm	0.0015
Crustacea10+mm	0.0146

A3.4 Bird parameters

A3.4.1 Population size

Southampton Water. There were seven wader species included in the Southampton Water model: Dunlin *Calidris alpina*, Ringed Plover *Charadrius hiaticula*, Redshank *Tringa totanus*, Grey Plover *Pluvialis squatarola*, Black-tailed Godwit *Limosa limosa*, Oystercatcher *Haematopus ostralegus* and Curlew *Numenius arquata*. Numbers of birds used in the model were, the WeBS 5-year winter peak mean from 2002/03 to 2006/07. The Figures for the 12 WeBS count sections covering Southampton Water were combined to make up the model bird numbers. Data from these years were used to cover a similar range of years to the invertebrate survey, and since the WeBS low tide data used to test the model were collected during 2000/01, the most recent low tide counts available. Table A3.6 shows the numbers of each bird species used in the Southampton Water model. All birds were assumed to be present on day one and remained until the final day of the simulation unless they died of starvation during the course of winter.

Chichester Harbour. The Chichester Harbour model included eight wader species; Dunlin *Calidris alpina*, Ringed Plover *Charadrius hiaticula*, Redshank *Tringa totanus*, Grey Plover *Pluvialis squatarola*, Black-tailed Godwit *Limosa limosa*, Bar-tailed Godwit *Limosa lapponica*, Oystercatcher *Haematopus ostralegus* and Curlew *Numenius arquata*. Numbers used in the model were the WeBS 5 year peak mean numbers from 2004/05 to 2008/09. More recent low tide WeBS data (2010/11) were available for Chichester Harbour than for Southampton Water. Table A3.6 shows the numbers of each bird species used in the Chichester Harbour model. All birds were assumed to be present on day one and remained until the final day of the simulation unless they starved to death.

Table A3.6 Bird species population sizes and body masses in the Southampton Water and Chichester Harbour models. Target and starvation body masses were the same in both models.

	Number of birds		Body mass (g)	
Species	Southampton Water	Chichester Harbour	Target	Starvation
Dunlin	4185	16972	50	39
Ringed Plover	138	336	68	37
Redshank	399	2039	153	88
Grey Plover	140	1754	243	127
Black-tailed Godwit	338	723	299	161
Bar-tailed Godwit	-	945	305	227
Oystercatcher	1185	1867	500	350
Curlew	676	1762	784	489

A3.4.2 Target body mass and starvation body mass

Data from The Wash were used to determine the mass of birds at the start of winter and the mean mass during winter (Johnson, 1985) (Table A3.6). The starvation mass of each species was measured from previous studies or predicted from basal body mass (Goss-Custard et al. 2006) for species with no direct measurement (Table A3.6). It was assumed that birds arrived at their target mass and attempted to maintain this mass throughout winter. Birds died of starvation if their mass fell to their starvation mass.

A3.4.3 Energy density of bird reserves

Energy density is the amount of energy (KJ) contained in a gram of bird fat reserves and was assumed to be 33.4 KJ g^{-1} (Kersten & Piersma, 1987). Bird energy density and prey energy content influenced how birds gained weight. For example, if 1 g of bivalve flesh was assimilated, only 22/33.4 g of extra fat would be stored because fat can store the energy more efficiently than the bivalve flesh.

A3.4.4 Metabolic rate

The amount of energy expended per time step by birds was based on body mass using the all bird equation of Nagy (1999). This equation excludes the energy cost of thermoregulation (as it is based on average energy expenditure).

A3.4.5 Time and energy cost of moving between patches

For simplicity it was assumed that no time and energy costs were associated with moving between patches. However, the energetic cost of disturbance was incorporated (see Section A3.5.2).

A3.4.6 Size ranges of prey consumed by the birds

The bird prey species incorporated in the Southampton Water model were crustaceans, bivalves, Hydrobia and marine worms. The Chichester model included cockles as a separate prey species from other bivalves. The prey species were divided up into different size classes based on the survey data. Any given bird species could choose to feed on any prey species it has been observed to feed on but only within the size classes within which it has been observed to feed. The size range eaten by each bird species is shown in Figure A3.1.

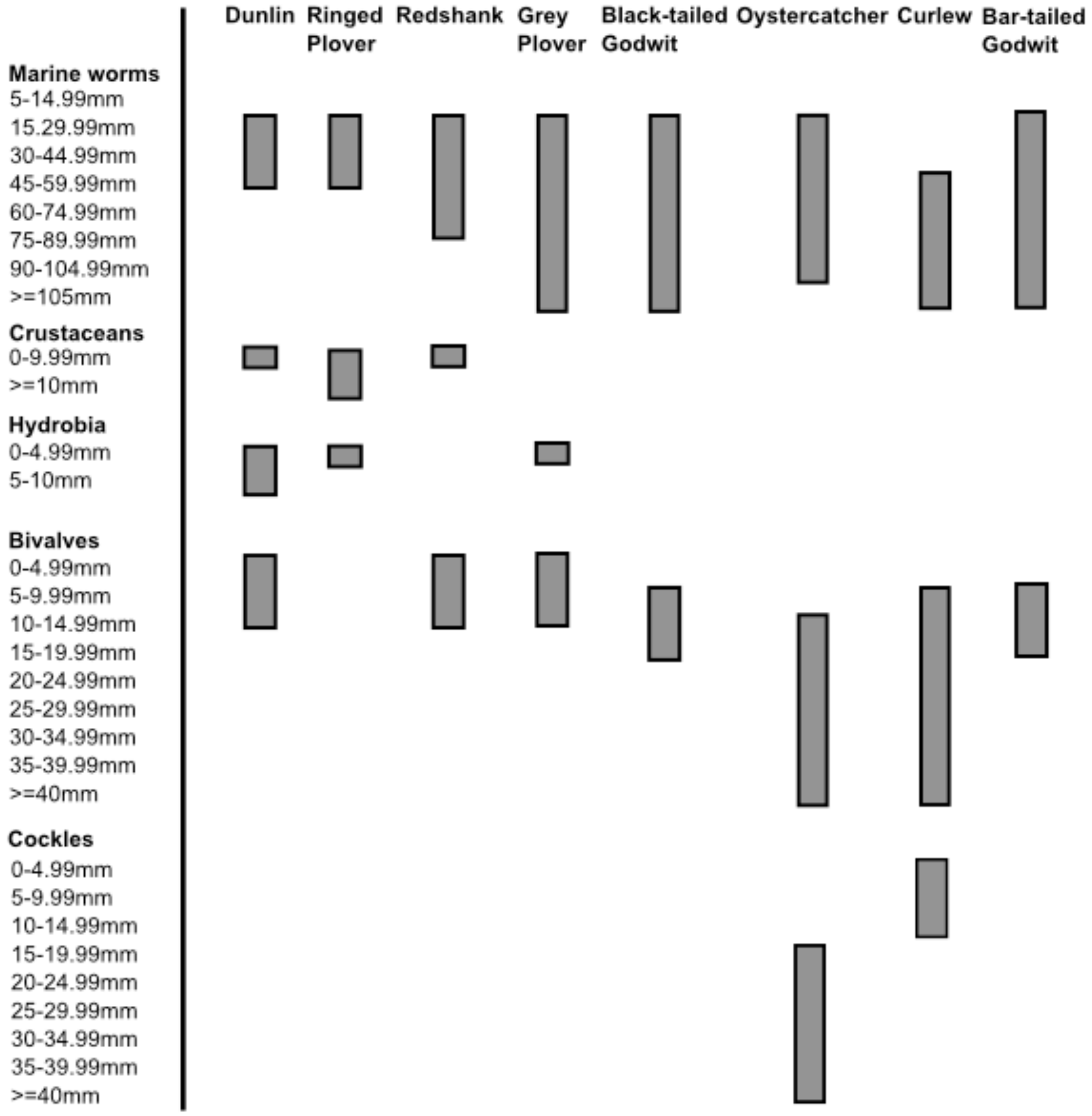


Figure A3.1 Size ranges of prey species consumed by bird species in the Southampton Water and Chichester Harbour models.

A3.4.7 Individual variation

Birds were assumed to vary in their foraging efficiency (normal distribution), which influenced the rate at which birds consumed food in the absence of competitors, and dominance (uniform distribution), which influenced a bird's susceptibility to interference from competitors. The standard deviation of foraging efficiency 0.125 (mean=1) was the average observed in oystercatchers on the Exe estuary (Stillman et al., 2000).

A3.4.8 Day and night variation in foraging efficiency

The relative rates at which waders can feed during the day and night were derived from Lourenco et al. (2008) and Sitters (2000). Figure 2 of Lourenco et al. (2008) compares the energy obtained from day and night time feeding in Ringed Plover, Redshank, Grey Plover and Black-tailed Godwit. Night time efficiency was calculated as the proportion of day time energy consumption obtained during the night: Ringed Plover (49%), Redshank (95%), Grey Plover (100%) and Black-tailed Godwit (87%). Lourenco et al. (2008) observed that Grey Plover obtained more energy at night, but a value of 100% was used as in other systems this species has either been shown to obtain more energy by day (Turpie & Hockey 1993) or by night (Kalejta 1992). Sitters (2000) measured the night and day feeding rates of Oystercatchers consuming mussels. Night time efficiency was 100% of daytime for individuals opening prey using the stabbing feeding method and 62% of daytime for individuals opening prey using the hammering feeding method, giving an average of 81%. No estimates of night time efficiency were obtained for Dunlin and Curlew and so the average of other species was used for these species (82%).

A3.4.9 Intake rate

The influence of the food supply on a bird's intake rate was calculated using the following functional response:

$$IFIR = f\frac{IFIR_{\max}B}{B_{50}+B},$$

where IFIR is the interference-free intake rate (mg s^{-1}), f is the foraging efficiency of focal individual, B is the patch biomass density of prey within the size range consumed (mg m^{-2}), $IFIR_{max}$ is the maximum intake rate when prey are superabundant and B_{50} is the prey biomass density at which intake rate is 50% of its maximum.

Foraging efficiency was normally distributed, with unit mean and a standard deviation of 0.125 (Goss-Custard et al., 1995). A literature review was used to estimate the values of $IFIR_{max}$ and B_{50} (Goss-Custard et al, 2006). $IFIR_{max}$ was predicted from:

$$\log\left(IFIR_{\max}\right) = -2.802 + 0.245\log_e\left(M_{spec}\right) + 0.365\log_e\left(rM_{prey}\right),$$

where M_{spec} is the average body mass (g) of the wader species in September, M_{prey} is the mean ash-free dry mass (mg) of prey within the size range consumed and r is the ratio of size of prey consumed to size in patch. A literature review showed that birds select the larger sized prey within the size range consumed, giving a value of r of 1.05 (Goss-Custard et al, 2006). B_{50} was unrelated to either bird or prey mass, with a mean value of 0.761 g ash-free dry mass m^{-2}. The influence of con-specific competitors on a bird's intake rate was incorporated using the following interference function (Stillman et al., 1996):

$$IR = IFIR\left(\frac{gD+1}{D_0+1}\right)^{-\left(m_{\max}-\left(m_{\max}-m_{\min}\right)d\right)},$$

where IR is the intake rate (mg s^{-1}), D is the con-specific competitor density in patch (ha^{-1}), D_0 is the con-specific competitor density above which interference reduces intake rate, g is the aggregation of birds within a patch, d is the dominance of focal individual (0–1), m_{max} is the susceptibility to interference of least dominant individual (d = 0), m_{min} is the susceptibility to interference of most dominant individual (d = 0). D_0 was set to 100 birds ha^{-1} (Stillman et al., 1996; Triplet et al., 1999; Yates et al., 2000). The aggregation factor (g) was set to 10 for all bird and prey combinations, except for cockle feeding oystercatchers where it was 6 (West et al., 2003). Interference within species consuming worms and crustaceans, which are mobile and can often rapidly escape into the sediment as birds approach, was assumed to occur through prey depression (m_{max} = 0.48; m_{min} = 0.48) with the same strength as that observed between Corophium-feeding redshank (Stillman et al., 2000a; Yates et al., 2000). For bivalves, interference was assumed to occur through prey stealing. For all species except cockle-feeding oystercatchers, relatively small prey are consumed, with short handling time (<10 s) and weak interference (m_{max} = 0; m_{min} = 0.08) (Stillman et al., 2002). The strength of interference between cockle-feeding oystercatchers (m_{max} = 0; m_{min} = 0.5) was that observed for low cockle densities in the Baie de Somme, France (Triplet et al., 1999).

A3.4.10 Maximum intake rate

Maximum intake rate was based on the maximum daily energy assimilation calculated from body mass using standard equations (Kirkwood, 1983). This assumed that birds could achieve this maximum value by feeding for just 50% of the day to allow them, if possible, to consume their daily requirements from intertidal prey alone. This maximum limited the maximum amount of food a bird could consume within a time step.

A3.4.11 Feeding in terrestrial habitats

Some wader species, Black-tailed Godwit, Oystercatcher and Curlew in particular, can feed in terrestrial habitats during the hours of daylight when food consumption from intertidal habitats is not sufficient to meet their energy requirements. The birds typically do not feed terrestrially during the night. The food abundance in terrestrial feeding habitats was not measured and so terrestrial feeding could only be incorporated in a simple way. A study of oystercatcher on the Exe Estuary showed that this species could approximately equal its energy requirements while feeding on terrestrial habitats (Stillman et al. 2000; energy expenditure = 32 KJ hr^{-1} (calculated for a 540g body mass using the Nagy (1999) all bird equation); energy assimilation = 33 KJ hr^{-1} (intake rate = 1.9 g hr^{-1}; energy content of prey (assumed to be worms) = 23.5 KJ g^{-1}; assimilation efficiency of prey = 0.75). Therefore, it was assumed that Black-tailed Godwit, Oystercatcher and Curlew were able to feed in terrestrial habitats during the hours of daylight at a rate that equalled their rate of energy expenditure. This meant that these species did not lose mass over high tide during daylight, as they were able to feed, whereas the other species did lose mass as they roosted rather than fed.

A3.4.12 Assimilation efficiency

Assimilation efficiency is the proportion of the energy within the prey consumed by a bird that is assimilated into the bird's body. It was 0.75 for marine worms, 0.75 for crustaceans, 0.85 for bivalves and 0.85 for *Hydrobia* (Goss-Custard et al, 2006).

A3.4.13 Decision rules

It was assumed that birds consumed the diet and occupied the patch which maximised their net energy assimilation during each time step (i.e. energy assimilated during a time step minus energy expended during a time step). This meant that birds patch and diet choice decisions accounted for any energy costs associated with disturbance.

A3.5 Disturbance parameters

Disturbance has three potential effects on the birds: it can prevent them from accessing potential feeding areas close to the disturber, it can cost them feeding time if they respond to disturbance by moving away and/or stop feeding, and it can cost them energy if they fly away from the disturber.

A3.5.1 Disturbance area

The number of visits to each sector per hour was predicted from the results of the household survey work associated with this project (see Appendix 4). The total areas disturbed by these visitors were also calculated from the number of each of the different types of visitor identified in the household survey. The bird survey work and associated analysis (Appendix 4) identified four bird species groups that responded differently to disturbance (group 1 = dunlin, ringed plover, turnstone and redshank; group 2 = grey plover, black-tailed godwit; group 3 = oystercatcher; and group 4 = curlew) so the area disturbed was calculated separately for each species group. Future housing data was used in conjunction with the model based on the current household survey to predict future visitor numbers and the associated areas disturbed.

The household survey divided visitors into shore-based, intertidal and water-based. The model assumed that shore-based activities only disturbed the top of the shore down to a distance from the shore determined by the disturbance distance of each species. Intertidal activities could cause disturbance throughout the whole of the intertidal area. Disturbance events were assumed to occur randomly in space and time, and the proportion of space-time (area of patch multiplied by duration of time step) disturbed within a patch during a time step calculated from.

$$P = 1 - (1 - p)^n$$

Where P = total proportion of space-time disturbed, p = proportion of space-time disturbed by a single visitor (=area disturbed multiplied by duration of disturbance) and n = number of visitors to patch during time step. Separate values of P were calculated for the upper shore area disturbed by shore-based activities and for the whole intertidal area. These were combined to calculate the proportion of the patch disturbed throughout a time step. These assumptions meant that each bird within a patch was subject to the same number of disturbances.

A3.5.2 Energy and time costs

A disturbance has an energy cost for a bird when the bird responds to the disturbance by flying away. The average distance travelled in these flights (displacement distance) was measured for some species in the model during the bird survey work (Liley et al, 2010). For species where there was no measurement available, an overall average figure was used (excluding the measurement for curlew, which was significantly larger than for all other species). These were converted into flight times using flight speeds from Alerstam et al. (2007) and adjusted to account for take-off and landing time. The energy costs associated with these flight times (Table A3.7) were then calculated using the following equation (Nudds and Bryant, 2000):

$$C = 61.718tM^{0.7902}$$

where C is the energetic cost in J, t is the duration of flight and M is the mean body mass in kg.

An analysis of the time taken to resume feeding after a disturbance based on data from the bird survey showed that there was no significant difference between bird species, and a time cost of 1.57 minutes per disturbance was used in simulations (see Section A4.4 for further details).

Since all birds on a patch are not disturbed by every visit, an estimate of the proportion of disturbances per bird was made for each patch. This was assumed to be equal to the proportion of the patch that was disturbed throughout a time step.

Table A3.7 Energy cost per disturbance for each bird species.

Species	Energy cost per disturbance (KJ)
Dunlin	0.075
Ringed Plover	0.083
Redshank	0.159
Grey Plover	0.246
Black-tailed Godwit	0.254
Bar-tailed Godwit	0.333
Oystercatcher	0.472
Curlew	0.656

A3.6 Model simulations

The model included stochastic variation in the characteristics of individual birds and so replicate simulations with the same set of parameter values produced slightly different predictions. Therefore, three replicate simulations were run for each combination of parameter values.

Appendix 4 Behavioural response of waders to disturbance in the Solent

A4.1 Quantifying the response to disturbance

Fieldwork observing bird disturbance from human activities was carried out at 20 of the 103 Solent sections during the winter period December 2009 to February 2010 (Liley et al., 2010). The fieldwork design involved roughly four visits a month to each study section each month with each visit involving a two hour observation period. Each visit involved counts of bird numbers at the start and end of the period, recording all observed recreational activity and recording detailed behavioural observations of birds within a focal area of visible intertidal habitat within a 500m radius of the surveyor. All visitor recreational events that occurred within 200m of birds within the focal area were classed as ‘potential disturbance events’. The aim was to document how birds responded to different visitor activities and the distances at which they respond and the initial data and results were summarised in the Solent Disturbance and Mitigation Project Phase II bird disturbance report of Liley et al. (2010).

Observers classified the route of each visitor into one or more of three zones: (i) sea wall / river bank, (ii) beach / mudflat or (ii) on the water. This was done for each ‘potential disturbance event’ in the on-site bird disturbance survey, when interviewing people within the on-site visitor survey, and as a question within section B of the household visitor survey. This was done to enable us to predict visitor numbers to each zone of each section and to allow for the potential effect of zone on both the (length of) route people covered on their visit and on bird disturbance rates with distance. For example, people and their dogs behind a sea wall may be less likely to disturb a bird at a given distance away than when on the intertidal area.

The overall aim of the analysis was to develop modelling procedures to use this on-site bird disturbance data, in conjunction with both the Solent coast on-site visitor survey data (Fearnley et al., 2010)) and the Solent region household survey data (Fearnley et al., 2011) to provide estimates of the effect of visitors and their disturbance to birds on the loss of intertidal habitat feeding area and feeding time for the waders at each individual coastal section. All analyses and modelling was restricted to the eight species of wading birds which rely on intertidal feeding habitat and were observed in sufficient numbers to estimate disturbance parameters (Table A4.1).

The approach taken was:

- Use the on-site bird disturbance data to estimate the probability of a ‘potential disturbance event’ resulting in a response (either a ‘minor’ response’ (i.e. alert with head up, walk/swim or short flight (<50m)) or a major flight) which temporarily stopped the bird feeding. The probability could depend on bird-to-visitor-distance, bird species, visitor activity type and zone (i.e. shore, inter-tidal or water-based activities).
- Convert the probabilities of response with distance into effective disturbance distances (EDD).
- Use the on-site bird disturbance observations to estimate the median amount of feeding time lost with each disturbance response type (major flight or ‘minor response’).
- Use the on-site visitor survey map recording of individual visitor routes with an added buffer distance based on the EDD, overlain with maps of inter-tidal

mudflat areas, to estimate the average intertidal habitat areas in which the birds are disturbed (minor response or major flight) per visitor for each differentiated combination of bird species, visitor activity type and/or zone. The buffer generated a rectangular area around the route length from which the area of disturbance could be calculated. These are referred to as 'effective disturbance areas' (EDA).

- Use predictive modelling of visitor numbers from the Solent region household survey data (Fearnley et al., 2011) to estimate the average number of visitors per hour to each of the 103 Solent coast sections and the proportions of these visitors in each major group of activity type and zone visited.
- Combine effective disturbance area (EDA) and median time disturbed per potential disturbance event with the predicted visitor numbers of each relevant visitor grouping to estimate the total feeding area by feeding time lost per hour at each of the 103 coastal sections.
- Use these estimates of lost feeding area-time as input parameters in the individual-based bird population feeding models of over-wintering feeding and survival.

Table A4.1 Percentage of major and 'minor' responses to N recorded potential disturbance events by each wader species.

Species	No Response	Alert/Head up	Walk/swim away	Minor Flight	Major Flight	Events (N)
Black-tailed Godwit	89	3	3	0	6	35
Curlew	80	7	1	1	10	297
Dunlin	81	2	1	5	12	111
Grey Plover	90	2	2	0	6	124
Oystercatcher	75	4	4	1	16	604
Redshank	80	5	2	4	10	482
Ringed Plover	75	7	0	5	14	44
Turnstone	75	3	2	5	15	244
Overall	79	4	2	3	12	1941

A4.2 Estimating probability of disturbance response

Each 'potential disturbance event' (e.g. a visitor or their dog within 200m of a bird species) could result in one of five increasing levels of response in the bird(s): no response, bird becomes alert with head up, bird walks or swims a short distance away before resuming previous behaviour, birds flew short distance (<50m) and resumed previous behaviour in general area (referred to as minor flight), or birds took flight and flew more than 50m (referred to as 'major flight'). Overall, 12.3% of all potential disturbance events led to a major flight, compared to a further 9.1% for all minor responses combined (Table A4.1).

Following initial data analyses, it was considered best to combine all responses, and model the probability of any response (i.e. 'alert with head up', 'walk/swim short distance away' or minor flight) in terms of bird-to-visitor-distance, bird species, visitor activity type and zone (i.e. shore, inter-tidal or water-based activities). The probability (P) of any disturbance response was modelled as a binary logistic regression on bird-visitor distance, bird species, visitor activity type and zone of activity using the Minitab15 statistics package.

We fitted a wide range of models for the probability of bird response involving separate relationships with distance (either untransformed, square root of log transformed) for individual species and various groupings of species, together with allowance for the zone of visitor activity (sea-wall/river-bank, inter-tidal or water) and the major activity types.

The best fitting model measured in terms of minimum Akaike's Information Criterion (AIC), was the model given in Table A4.2, involving separate relationships with the square root of distance for each of four species groups

- Group 1: Turnstone, Dunlin, Redshank, Ringed Plover
- Group 2: Grey Plover, Black-tailed Godwit
- Group 3: Oystercatcher
- Group 4: Curlew

together with terms representing:

- the lower probability of response to visitors on the sea-wall/river-bank relative to elsewhere
- the higher probability of response to dog-walkers with dog off-lead relative to other general visitors in the same zone
- the higher probability of response to bait-diggers relative to other general visitors in the inter-tidal zone

The species groupings were appropriate in terms of the general responses of birds to disturbance. In general, larger birds show a larger behavioural response to disturbance (e.g. Blumstein 2005), and the species groups contained species of increasing body mass; species in group 1 had the smallest body masses, followed by species in group 2, then oystercatcher, and curlew had the largest body mass.

Once the increased response rates for bait-digging and having dogs off-lead were allowed for, there was no statistically significant difference in probability of bird response for a given distance between other general activities on the inter-tidal zone and the group of activities which were water-based. (This is why the best fitting model only sub-divides zones in sea-wall/river-bank and elsewhere (i.e. inter-tidal and water)).

Table A4.2 Logistic regression model ($\text{Log}_e(P_{MF}/(1-P_{MF}))$) for the probability of any response (P_{AR}) in relation to bird-visitor distance (square root), wader species group (Group 1- Group 4), zone of activity and activity type, in terms of regression coefficients (B), standard error (SE) of B, test statistic (Z) and test probability level (*p*). Group 1 = Turnstone, Dunlin, Redshank, Ringed Plover; Group 2 = Grey Plover, Black-tailed Godwit, Group 3 = Oystercatcher, Group 4 = Curlew.

Regression term	Coefficient (B)	SE (B)	Z	*p*
Constant term (All species)	3.3665	0.4109	8.19	<0.001
Curlew / Redshank / Ringed Plover (0/1)	-2.5158	1.3337	-1.89	0.059
Oystercatcher (0/1)	5.9872	0.9441	6.34	<0.001
Curlew (0/1)	0.6063	0.9992	0.61	0.544
Square root of Distance50 (All species)	-0.5151	0.0492	-10.48	<0.001
Square root Distance * Curlew / Redshank / Ringed Plover	0.2237	0.1508	1.48	0.138
Square root Distance * Oystercatcher / Turnstone	-0.7188	0.1180	-6.09	<0.001
Square root Distance * Curlew	-0.0043	0.1120	-0.04	0.969
Sea-wall/river-bank Zone (0/1)	-1.0056	0.1542	-6.52	<0.001
Bait-Digging (0/1)	0.4924	0.1429	3.45	0.001
Dog walking with dog(s) off lead (0/1)	0.6576	0.3052	2.16	0.031

A4.3 Effective disturbance distance

In order to make use of this modelled information on the likelihood of nearby visitors and their activities causing a response in nearby birds, we needed to convert these probabilities with distance into an effective distance over which birds are disturbed. This was done by calculating the probability of response in each one metre interval up to 200m (1m, 2m,..., 200m) and then summing the predicted probabilities across all 200 metre intervals. This was done separately for each combination of species group, zone and activity involved in the logistic regression model in Table A4.2. Specifically:

If $P_R(d)$ is the predicted probabilities of any response at distance d metres, then:

$$EDD = \text{Effective Disturbance Distance for any response}$$

$$= P_R(1) + P_R(2) + ... + P_R(199) + P_R(200)$$

EDD is treated as the distance around a visitor (on that zone and activity) within which all birds (of that species group) are assumed to always be disturbed and which react with a response, each involving a loss of feeding time and energetic costs (see below). The estimates of *EDD* are given in Table A4.3.

For each species group and zone of visitor activity (sea-wall/river-bank or inter-tidal/water, Table A4.3 also gives the minimum observed bird-visitor distance at which no response was observed, the minimum observed bird-visitor distance at which a response was observed, together with the proportion of potential disturbance events in each of the three closest distance bands (<25m, 25-50, 50-75m) which resulted in a bird response.

The minimum observed distance at which no response occurred indicates that some birds will not be affected (or stop feeding) when visitors (or their dogs) are only this distance away. These minimum distances are given for each species group in Table A4.3and they are less than the estimates of EDD for each zone of activity and activity type for all species groups except the Group 2 (Grey plover and Black-tailed Godwit) (Table A4.3).

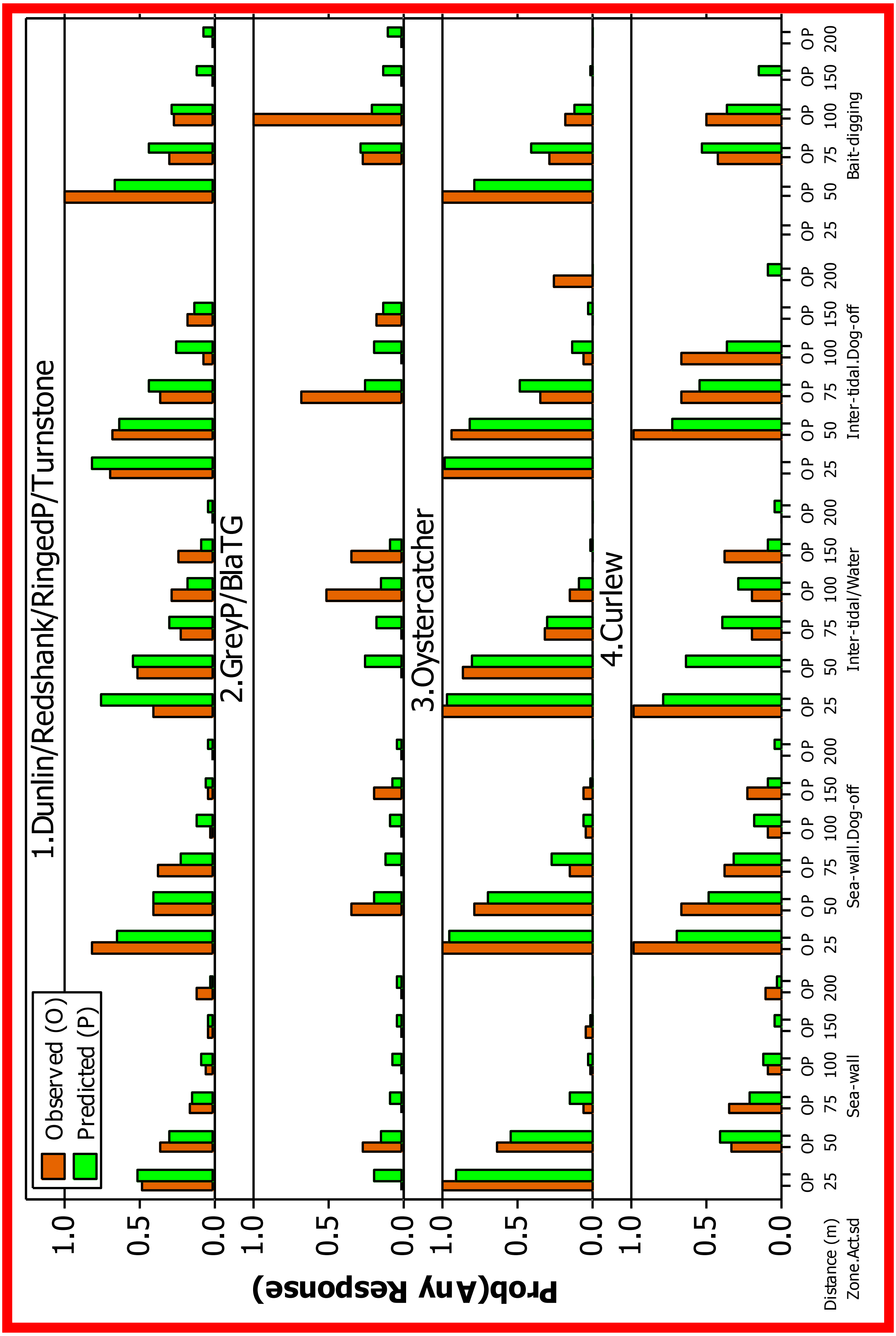
The observed proportion of potential disturbance events in each of the three closest bird-visitor distance bands (<25m, 25-50m, 50-75m) are also given for each species group and zone (Table A4.3). Species group 1 only response to events within 25m 61-63% of the time, in contrast to Oystercatchers (SG3) and Curlew (Group 4, small sample size)) which always responded to events within 25m, on both the sea-wall/river-bank and inter-tidal/water zones. In the next 25-50m distance band, the observed percentage of Oystercatchers responding falls to 72% for sea-wall based visitors and 92% for inter-tidal/water visitors, while that for Curlew drops more dramatically to 47% and 50% respectively (Table A4.3). In the next 50-75m distance band response rates drop considerably for all four species groups. Thus the EDD for Oystercatcher and Curlew should definitely be greater than 25m, which they are.

A visual comparison of the observed and model-based predicted probability of response for all distance bands, species groups, zones and critical activity types in given in Figure A4.1.

Table A4.3 (a) Effective disturbance distances (EDD) of species groups in relation to zone and activity type. (b) Minimum observed bird-visitor distance at which no response was observed, and the minimum and maximum observed bird-visitor distance at which a response was observed. (c) Observed proportion of potential disturbance events in each of the three closest bird-visitor distance bands. The following species codes are used in the table: TT = Turnstone; RP = Ringed Plover; DN = Dunlin; GV = Grey Plover; BW = Black-tailed Godwit.

			Species group			
			1	2	3	4
		Effective Disturbance Distance (EDD) (m)	Turnstone, Dunlin, Redshank, Ringed Plover	Grey Plover, Black-tailed Godwit	Oyster-catcher	Curlew
(a)						
Zone		Activity				
Sea-wall		General	31.8	15.1	47.4	43.2
		Dog-off	41.5	22.6	53.0	54.6
Inter-tidal or Water		General	53.2	33.3	59.1	68.0
		Dog-off	65.9	46.6	65.3	82.2
		Bait-digging	70.5	51.7	67.5	87.2
(b)		Zone	1	2	3	4
Min distance with no response (lowest & highest species)		Sea-Wall	16 (TT) 32 (RP)	22 (GV) 36 (BW)	38	40
		Inter-tidal / Water	20 (TT) 60 (DN)	45 (GV) 50 (BW)	40	40
Min distance with response		Sea-Wall	5	30	10	25
		Inter-tidal / Water	10	75	10	25
Max distance with response		Sea-Wall	200	200	150	200
		Inter-tidal / Water	200	200	150	200
(c)						
Proportion (out of n events) responding within :	<25m	Sea-Wall	0.63 (35)	0.00 (2)	1.00 (16)	1.00 (3)
		Inter-tidal / Water	0.61 (21)	(0)	1.00 (10)	1.00 (1)
	25-50m	Sea-Wall	0.36 (140)	0.28 (18)	0.72 (46)	0.47 (15)
		Inter-tidal / Water	0.65 (57)	0.00 (2)	0.92 (60)	0.50 (4)
	50-75m	Sea-Wall	0.30 (44)	0.00 (34)	0.09 (65)	0.37 (38)
		Inter-tidal / Water	0.21 (140)	0.21 (14)	0.33 (43)	0.44 (18)

Figure A4.1 Observed and predicted probability of a response to disturbance in relation to bird species group and distance band.



A4.4 Feeding time lost per disturbance

Whenever a potential disturbance event led to a reactive response from a bird, the field surveyors tried to record, not only the type of response, (minor response (alert/head up, walk/swim away, short flight) or major flight), but also the time before the bird returned to its previous (feeding) behaviour. Unless the bird returned within a few seconds, time to return to previous (feeding) behaviour was usually recorded to the nearest minute.

Amongst the 242 observed potential disturbance events which led to a major flight, the time the bird(s) took to resume their feeding behaviour in the same general area was observed in 61% (147) of cases and 39% were unrecorded or unobservable. Amongst the 147 timed birds, only 5% resumed feeding behaviour within 30 seconds, 50% resumed within one minute, a further 41% resumed after two minutes and the remaining 9% in 3-10 minutes.

A Kruskal-Wallis (K-W) non-parametric analysis of variance of ranked observed times did not detect any statistically significant differences between the wader species in median return times (which were two minutes for six of the eight species) (K-W test (adjusted for tied times) $p = 0.065$).

It is reasonable to assume that all of the unobserved times to return and resume feeding behaviour were longer than all (or almost all) of the observed times, but these cannot be estimated. However, with this assumption, by scaling up the observed frequency distribution of return and resume times to allow for the 39% of unobserved times, we estimated that following a disturbance resulting in major flight, 31% of birds return and resume behaviour within one minute and a further 25% in two minutes.

Therefore, the median time (50% less, 50% more) to return and resume (feeding) behaviour following a major flight is estimated to be two minutes and this estimate is used as the typical lost feeding time following each major flight of any species in the incorporation of disturbance effects within the bird population feeding models.

A similar approach was used to derive estimates of the typical feeding time lost through disturbance from visitors resulting in any form of minor response. There were 177 observed cases of potential disturbance events leading to a minor response; as the birds did not move far away (or move at all in the case of being alert and raising head), a much higher percentage (89%) of times to resume behaviour were observable and recorded, with only 11% unobserved.

Amongst the observed disturbance times, only 7% were within 30 seconds, but a further 75% were recorded as being (approximately) one minute, 10% at two minutes, 5% at three minutes and the maximum recorded time following a minor response was eight minutes by one bird.

After allowing for the 11% of unobserved times, the best estimate of the typical feeding time lost following a minor response (alert/heads up, walk/swim away or short flight) to a potential disturbance event is one minute per minor response, and this is the estimate used in the bird population feeding models.

The time cost per disturbance in the model was calculated as a weighted average of the time costs of minor (1 minute, 9% of responses) and major responses (2 minute, 12% of responses) giving a value of 1.57 minutes.

A4.5 Feeding area lost to disturbance per visitor

From the on-site visitor survey (Fearnley et al. 2010) individual routes were plotted for 774 visitors interviewed across all 20 survey locations. These routes were plotted on maps in the field as part of the face-to-face interviews, with the routes drawn on maps as part of the interview. Surveyors showed the interviewees the maps and asked about the route, checking that the interviewee was interpreting the map correctly and accurately portraying where they had walked. Various scale maps were used in the field, allowing the surveyor to select the appropriate scale for the length of route and location visited. Routes on the paper maps were transferred to GIS (MapInfo Version 10) as individual polylines, cross-referenced to the questionnaire and interview data.

Individual routes were categorised following the types of activity and zones identified in the logistic regression, namely shore (dog off lead), shore (general), intertidal (dog off lead), intertidal general / water-based and bait digger.

Intertidal habitat was mapped within the GIS using a GIS data set of mudflats, part of a series of GIS datasets showing the extent of BAP priority habitats downloaded from the Natural England website. This dataset was visually checked against the OS 1:10,000 scale raster data and sandflats added manually using the OS Raster. This intertidal habitat layer was then checked against the output of the ABPMER tidal flow model, which gave an area of intertidal habitat per section. Using the maximal area for each section from the tidal flow model there was a significant correlation with the area mapped (Pearson Correlation Coefficient = 0.915, $p<0.0011$) within each section, indicating that our GIS layer of intertidal habitat matched other data sets.

Within the GIS, a series of buffers were then drawn around the intertidal habitat, using the effective disturbance distances in Table A4.3. The average length of route, for each category of user, was then extracted within each buffered area. We took this approach – of buffering the intertidal habitat with the EDD rather than buffering the routes – as many routes involved a walk or similar that involved retracing steps and returning the same way. By returning the total line length rather than buffer area we account for this potential problem.

These average route lengths were then used to calculate an average area disturbed per visitor from the effective disturbance area (EDA) for each broad category of user. This area was calculated by assuming shore based activities only caused disturbance on one side of their route and all other activities caused disturbance both sides of their route. Average route lengths and disturbance areas are shown in Table A4.4. Only 4 routes were observed for water-based activities and effective disturbance distances were not significantly different between general intertidal and water-based activities; therefore route lengths and activity types were not calculated for this activity type, and instead the 4 water-based routes combined with the general intertidal routes.

Table A4.4 Average route length (a) and disturbance area per visitor (b) for species groups in relation to zone and activity type. The values in brackets after the activity are the number of route lengths on which calculations were based. General intertidal includes data from 4 water-based routes.

(a)		Species group			
		1	2	3	4
	Average route length per visitor (m)	Turnstone, Dunlin, Redshank, Ringed Plover	Grey Plover, Black-tailed Godwit	Oyster-catcher	Curlew
Zone	Activity				
Sea-wall	General (381)	1982	1492	2154	2127
	Dog-off (250)	1799	1505	1895	1906
Inter-tidal or Water	General (83)	4015	3829	4055	4115
	Dog-off (55)	2959	2810	2955	3165
	Bait-digging (5)	1258	1251	1257	1266

(b)		Species group			
		1	2	3	4
	Disturbance area per visitor (ha)	Turnstone, Dunlin, Redshank, Ringed Plover	Grey Plover, Black-tailed Godwit	Oyster-catcher	Curlew
Zone	Activity				
Sea-wall	General (381)	6.3	2.3	10.2	9.2
	Dog-off (250)	7.5	3.4	10.0	10.4
Inter-tidal or Water	General (83)	42.7	25.5	47.9	56.0
	Dog-off (55)	39.0	26.2	38.6	52.0
	Bait-digging (5)	17.7	12.9	17.0	22.1

A4.6 Predicted current and future visitor numbers, activities and zones

Fearnley et al. (2011) used predictive modelling of visitor numbers from the observed Solent region household survey data to estimate the current total number of visitors per year to each of the 103 Solent coast sections (see Table 50 in Fearnley et al. (2011)). These visitor models involved both general declines in rates with distance separate for visitors arriving on foot and by car, each modified by section-specific factors representing the combined effect of section characteristics.

As the bird feeding population models run in one hour time steps to allow for the tidal cycle, estimates of visitor rates are needed for each hour of each day over the modelled period 1st September to 15th March.

Fearnley et al. (2011) also asked households about the diurnal pattern of their coastal visits and whether they were influenced by the state of the tide (in general, not specifically for each cited section visited). Amongst the 2053 responses on time of day of visits, 42% were for morning, 31% for afternoon, 21% for evening in daylight and only 6% for evening in darkness or night. As the vast majority of visits are in daylight, we estimated the average visit rate per hour for a section by dividing the estimated average daily visit rate for that section by 12, based on an annual average of 12 hours daylight per day. These section-specific fixed average hourly visit rates, given in Table A4.5 were used in deriving the estimates of the total feeding areas and times lost to disturbance each hour in each section during the bird feeding model simulation period.

The logistic regression modelling of probability of disturbance led to effective disturbance distances (EDD) and areas (EDA) which depended on section zone and activity of the visitors. Therefore, estimates and predictions were needed not just of the total visit rates to each section, but also the proportions (and thus numbers) of visits for each zone and critical activity. These were based on the observed section-specific proportions of total visits to each section in each of the six critical zone-by-activity classes obtained from the household survey, as given in Table A4.5.

For bait diggers, a very small proportion responded to the household survey (39 responses) or were interviewed during the face-face interviews (7 interviews in total). In the household survey none of the respondents indicated specific sections that they used. During the bird fieldwork (Liley et al 2010), 33 groups of bait diggers were recorded, such that bait digging was ranked as the 12th most frequently encountered activity. We therefore assumed that bait diggers had been undersampled in the visitor survey work, and that for some reason bait diggers had refrained from giving specific sections they visited in the household survey. From the on-site bird fieldwork bait diggers were recorded at nine different sections. On average, for these nine sections, bait diggers accounted for 1.2% of the groups recorded. In order to include bait diggers in the modelling we therefore applied this proportion to all 93 sections with mudflats, i.e. we assumed that across all sections with mudflats, 1.2% of groups would be bait digging. There was one exception, in that section 58 had particularly high numbers of bait diggers observed during the bird fieldwork (nearly 10% of observations here were bait diggers). For this section only we applied the observed percentage from the bird fieldwork, i.e.8.9% of groups).

The local authorities in the Solent region provided the project with projections of future housing developments in the region. These data were in the form of two separate data sets, representing large sites and windfall. The large sites were provided as spatially explicit data (polygons). The predicted level of windfall development was simply given as a percentage for each local authority area. In order to develop the models of visitor rates we used postcode data, where the postcodes are plotted on a 100m grid and for each postcode associated data includes the number of residential properties. We used the future housing development data to generate a modified postcode layer including the new housing layer. For the windfall data existing postcodes were increased by the given percentage for the relevant geographic area, thereby assuming that windfall development would occur in proportion to the current housing stock. For the large sites we extended the 100m grid as necessary such that new points were created on the 100m grid if there was no existing postcode falling within one of the large site polygons. The number of houses suggested for each large site was then evenly spread among all points within the polygon. The spatial models of visitor rates by distance, developed by Fearnley et al. (2011) to predict visitor numbers to each section from housing density within distance bands, were re-used with the projection additional housing in each (postcode) area to derive estimates of the model predicted percentage increase in visitor numbers to each section arising from the new housing, as given in Table A4.5. In these predictions, the pattern of behaviour in terms of visit rate, activity zones visited and general bird disturbance rates were assumed in the default predictions to be the same as for the current population. However, the bird modelling also involved simulating the effects of some altered behaviours or zone management options.

Table A4.5 Predicted visitor rates (per daylight hour) based on current housing, predicted percentage increase in visit rates with proposed future Solent region housing, and observed proportion of visits to each section by zone and activity type. See Figure 5.1 and Table 5.1 for further details of the sites.

	Predicted visitor rates per (daylight) hour		Proportion of visits to each section by zone and activity type					
			Sea wall / river bank		Beach /mudflat			Water
Section	Based on Current Housing	% increase with Proposed Future Housing	General	Dog off-lead	General	Dog off-lead	Bait-digger	All
1	365.4	4.7	0.301	0.178	0.251	0.154	0.012	0.062
2	155.8	4.4	0.357	0.266	0.160	0.082	0.012	0.121
3	83.2	4.3	0.522	0.135	0.088	0.077	0.012	0.114
4	107.1	4.3	0.548	0.118	0.046	0.072	0.012	0.156
5	16.9	4.2	0.161	0.000	0.839	0.000	0.012	0.000
6	1.6	5.5	0.857	0.000	0.143	0.000	0.012	0.000
7	2.5	6.6	0.529	0.000	0.375	0.000	0.012	0.096
8	6.4	6.7	0.440	0.000	0.215	0.000	0.012	0.251
9	38.0	7.4	0.657	0.118	0.118	0.030	0.012	0.030
10	18.8	7.4	0.126	0.036	0.048	0.051	0.012	0.721
11	131.7	7.5	0.275	0.214	0.261	0.161	0.012	0.011
12	44.4	7.5	0.266	0.091	0.325	0.180	0.000	0.124
13	93.6	7.4	0.341	0.040	0.407	0.048	0.012	0.164
14	92.8	7.5	0.409	0.019	0.279	0.019	0.012	0.275
15	196.9	9.8	0.613	0.097	0.144	0.034	0.012	0.087
16	113.4	12.6	0.672	0.132	0.064	0.007	0.012	0.063
17	57.2	18.4	0.538	0.118	0.001	0.000	0.012	0.342
18	56.9	13.2	0.459	0.152	0.163	0.091	0.012	0.026
19	81.3	22.0	0.627	0.107	0.055	0.001	0.012	0.018
20	29.8	18.7	0.715	0.000	0.088	0.000	0.012	0.000
21	16.8	15.6	0.892	0.000	0.027	0.000	0.012	0.081
22	62.7	14.5	0.339	0.189	0.006	0.000	0.012	0.466
23	137.4	10.1	0.600	0.143	0.072	0.115	0.012	0.063
24	297.8	14.7	0.370	0.129	0.233	0.259	0.012	0.002
25	363.6	13.5	0.305	0.224	0.162	0.223	0.012	0.070
26	210.7	11.3	0.372	0.147	0.207	0.091	0.012	0.175
27	119.6	13.0	0.521	0.060	0.187	0.060	0.012	0.158
28	41.7	15.2	0.331	0.121	0.269	0.109	0.012	0.162
29	136.9	14.8	0.433	0.198	0.173	0.028	0.012	0.159
30	116.2	13.1	0.493	0.162	0.214	0.069	0.012	0.056
31	130.0	12.3	0.477	0.103	0.170	0.035	0.012	0.095
32	67.8	11.9	0.246	0.049	0.362	0.055	0.012	0.144
33	91.2	13.2	0.459	0.116	0.201	0.114	0.012	0.081
34	520.3	12.2	0.384	0.095	0.351	0.087	0.000	0.035
35	422.6	11.4	0.343	0.057	0.375	0.104	0.000	0.026
36	93.2	9.9	0.194	0.180	0.409	0.156	0.000	0.003
37	401.6	8.1	0.313	0.088	0.434	0.083	0.000	0.009
38	178.0	9.9	0.313	0.092	0.216	0.150	0.012	0.078
39	218.1	10.2	0.471	0.048	0.324	0.048	0.012	0.085
40	155.0	11.5	0.419	0.152	0.090	0.082	0.012	0.207
41	53.9	12.5	0.343	0.024	0.551	0.021	0.012	0.044
42	8.4	8.7	0.835	0.000	0.148	0.000	0.012	0.000
43	0.4	14.9	1.000	0.000	0.000	0.000	0.012	0.000
44	75.4	14.6	0.129	0.275	0.167	0.017	0.012	0.034
45	110.2	12.6	0.304	0.239	0.256	0.068	0.012	0.133
46	315.3	13.2	0.342	0.224	0.213	0.073	0.012	0.147
47	143.0	16.7	0.383	0.189	0.232	0.000	0.012	0.143
48	59.4	13.8	0.537	0.306	0.012	0.004	0.012	0.005
49	94.4	13.9	0.625	0.125	0.135	0.000	0.012	0.115
50	288.9	14.2	0.466	0.196	0.082	0.039	0.012	0.116

Table A4.5 (continued) Predicted visitor rates (per daylight hour) based on current housing, predicted percentage increase in visit rates with proposed future Solent region housing, and observed proportion of visits to each section by zone and activity type.

	Predicted visitor rates per (daylight) hour		Proportion of visits to each section by zone and activity type					
			Sea wall / river bank		Beach /mudflat			Water
Section	Based on Current Housing	% increase with Proposed Future Housing	General	Dog off-lead	General	Dog off-lead	Bait-digger	All
51	698.5	11.7	0.440	0.088	0.280	0.050	0.000	0.091
52	706.8	10.6	0.383	0.078	0.332	0.096	0.000	0.083
53	252.9	12.0	0.330	0.138	0.294	0.081	0.012	0.142
54	50.4	11.9	0.276	0.072	0.261	0.108	0.012	0.282
55	31.5	13.6	0.580	0.142	0.233	0.020	0.012	0.024
56	10.2	13.4	0.214	0.100	0.340	0.100	0.012	0.247
57	8.5	15.4	0.403	0.036	0.403	0.036	0.012	0.123
58	61.7	14.9	0.125	0.378	0.124	0.373	0.089	0.000
59	117.0	12.3	0.411	0.259	0.293	0.015	0.012	0.017
60	116.2	13.2	0.138	0.111	0.257	0.183	0.012	0.308
61	38.6	13.8	0.422	0.177	0.396	0.005	0.012	0.000
62	28.7	12.0	0.356	0.000	0.499	0.000	0.012	0.124
63	348.2	12.5	0.145	0.008	0.488	0.194	0.012	0.098
64	33.7	13.4	0.309	0.034	0.321	0.026	0.012	0.301
65	11.7	10.8	0.228	0.683	0.067	0.000	0.012	0.000
66	29.6	14.7	0.012	0.000	0.256	0.732	0.012	0.000
67	50.2	13.0	0.717	0.000	0.194	0.000	0.012	0.088
68	163.4	13.1	0.436	0.148	0.234	0.047	0.012	0.135
69	106.2	11.6	0.437	0.107	0.185	0.093	0.012	0.172
70	31.7	11.4	0.226	0.323	0.111	0.340	0.012	0.000
71	77.8	12.3	0.289	0.155	0.235	0.145	0.012	0.168
72	154.5	15.6	0.170	0.250	0.143	0.358	0.012	0.078
73	46.5	14.2	0.190	0.184	0.170	0.170	0.012	0.280
74	78.4	17.8	0.252	0.020	0.363	0.073	0.012	0.237
75	33.2	16.7	0.197	0.068	0.145	0.007	0.012	0.357
76	24.3	16.2	0.252	0.034	0.286	0.105	0.012	0.324
77	2.9	16.4	0.577	0.090	0.278	0.000	0.012	0.056
78	86.1	13.2	0.238	0.147	0.177	0.183	0.012	0.251
79	0.8	18.2	0.065	0.000	0.468	0.000	0.012	0.403
80	6.5	17.9	0.365	0.051	0.359	0.051	0.012	0.132
81	0.0	18.7	0.066	0.045	0.733	0.045	0.012	0.111
82	27.8	21.3	0.643	0.015	0.306	0.008	0.012	0.028
83	44.7	20.8	0.236	0.325	0.106	0.301	0.012	0.031
84	12.6	18.1	0.212	0.176	0.266	0.007	0.012	0.323
85	244.4	22.1	0.195	0.117	0.359	0.123	0.000	0.154
86	64.8	26.7	0.310	0.099	0.326	0.099	0.012	0.145
87	111.9	36.2	0.288	0.048	0.223	0.092	0.012	0.237
88	4.6	49.0	0.357	0.014	0.260	0.014	0.012	0.050
89	2.3	56.2	0.335	0.125	0.305	0.035	0.012	0.201
90	67.7	59.3	0.048	0.021	0.300	0.181	0.012	0.450
91	9.1	60.6	0.737	0.000	0.221	0.023	0.012	0.019
92	8.7	60.7	0.323	0.287	0.321	0.069	0.012	0.000
93	216.2	38.5	0.379	0.019	0.356	0.111	0.012	0.132
94	44.9	59.6	0.546	0.001	0.278	0.000	0.012	0.161
95	23.2	83.6	0.475	0.005	0.379	0.003	0.012	0.116
96	43.1	54.5	0.373	0.000	0.284	0.000	0.012	0.323
97	95.1	49.6	0.524	0.014	0.179	0.014	0.012	0.064
98	19.2	49.4	0.353	0.000	0.377	0.043	0.012	0.227
99	110.1	29.9	0.306	0.096	0.263	0.293	0.012	0.037
100	271.1	28.5	0.384	0.078	0.333	0.086	0.000	0.115
101	182.4	36.2	0.435	0.033	0.347	0.044	0.000	0.133
102	143.0	31.8	0.450	0.037	0.354	0.037	0.012	0.117
103	96.0	25.0	0.442	0.027	0.351	0.030	0.000	0.146

A4.7 Estimating seasonal pattern of visits

The individual-based models needed an estimate of the proportion of the (estimated) total annual visits to each section that occur during the different seasons of the year and especially, the proportion of visits during the period 1st September to 31st March covered by the over-wintering bird modelling.

In Section A of the Solent Household Questionnaire Survey (Fearnley et al 2011), households were asked (Question A3) 'how frequently do you or your household visit this coast ?' with the options given in Table A4.6 below. Fearnley et al (2011) converted these visit frequency categories to an estimated number of visits, as also given in Table A4.6.

In question A2, households were asked 'when do you or your household tend to visit this coast ?', with the reply options either being more in one specific season (spring, summer, autumn or winter) or 'equally all year'.

Table A4.6 (a) gives a cross-classification of all responding households by visit frequency and visit season(s). (Note: these row and column totals differ very slightly from those in Table 9 and 10 of Fearnley et al (2011) summarising the two questions A2 and A3 separately because not quite all households responded to both questions).

It is immediately apparent (and expected) that almost all of the households which claim to visit the coast 'almost every day (equated to 300 visits per year) responded to question A2 by saying they "visit equally all year". This was also true for the vast majority of households which claim they visit the coast '2-4 times a week' and 'about once a week'. Therefore, the almost 40% of households which said they visited more in summer contributed relatively few visits compared to year-round visitors.

When a household says they visit more in one season, it could just be that they visit in all or some other seasons, but just more in that one season. However, in estimating the total number of visits made to the coast by each group of households, we assumed that a household quoting 'more in summer' made all of its annual visits in summer, and similarly for the other seasons. For households specifying 'visit equally all year', we allocated one-quarter of the total visits from such households to each of the four seasons, as seen in Table A4.6 (b).

The total visits in a season is then the visits from all households who visit more (assumed only) that season plus a quarter of all visits from all households who visit 'equally all year'. The totals are given in Table A4.6 (c).

Using this approach, the estimated percentage of all visits to the Solent coast made in each season is spring (21.2%), summer (37.0%), autumn (20.8%) and winter (21.1%).

Thus the estimated proportion (P_{AW}) of annual visits made during the autumn-winter (September to February) half-year period is 0.419. It was not possible to determine whether the proportion of visits during the autumn and winter varied throughout the Solent.

Table A4.6 Classification of responding households by annual frequency of coast visits and season of most visits, together with ensuing calculations of the estimated numbers and proportions of total visits made in each season.

(a)	A3. Annual frequency of visits to Solent coast						Responding Households	
	About once per year	A few times per year	About once a month	About once a week	About 2-4 times a week	Almost every day	Total	%
	1	4	12	50	150	300		
A2. Season tend to visit								
“equally all year”	0	72	119	174	157	134	658	57
“more in spring”	2	15	4	3	1	0	26	2
“more in summer”	25	193	115	83	31	12	463	40
“more in autumn”	0	5	1	1	0	0	7	1
“more in winter”	0	2	2	0	2	0	6	1
Total	27	287	241	261	191	146	1160	100

(b)							
Season of visit							Total visits
equally all year	0	288	1428	8700	23550	40200	74166
more in spring	2	60	48	150	150	0	410
more in summer	25	772	1380	4150	4650	3600	14577
more in autumn	0	20	12	50	0	0	82
more in winter	0	8	24	0	300	0	332
Total	27	1148	2892	13050	28650	43800	89567

(c)	Contribution from households visiting:		Annual visits	
Season	more(only) that season	equally all year	Total	%
spring	410	18542	18952	21.2
summer	14577	18542	33119	37.0
autumn	82	18542	18624	20.8
winter	332	18542	18874	21.1
Total			89567	100.0

A4.8 Estimating diurnal pattern of visits

The individual-based models needed an estimate of the proportions of (estimated) total visitors to each section that visit during each part of the day and especially, the proportion that visit during hours of darkness relative to during daylight.

In the Solent Household Questionnaire Survey (Fearnley et al 2011) households were asked (question A4 in questionnaire section A) “Are there particular times of day when you or your household visit the coast ?” and were asked to tick one or more of the following four categories: ‘morning’, ‘afternoon’, ‘evening in daylight’, ‘evening/night in darkness’. This question was only asked about their visits to the Solent coast in general; it was not about their visits to specific individual Solent coast sections (in section B of the questionnaire) due to a constraint on overall questionnaire length to maximise questionnaire completion and return. This information has been used to derive estimates of the overall percentage of visits to the Solent coastal sections which are made at different periods of the day.

To allow for the possibility that diurnal patterns of visits may be different in spring/summer than autumn/winter (bird modelling period), separate estimates were made using all data and also excluding those households who indicated (Question A2) they visited the coast “more in spring” or “more in summer”. In both of these cases, two methods were used to estimate the percentage of visits at each period of the day:

(i) Count number of households ticking each period and express as percentage of all ticks.

(ii) Allocate the total annual coastal visits by a particular household equally amongst all of the periods of the day ticked as the periods of the day that household tends to visit the coast. Sum these estimated annual visits during a diurnal period across all households to get estimates of total visits to the coast during each diurnal and express these as a percentage of their sum (i.e. the total visits during the whole day).

Method (ii) allows for the possibility that households making more coastal visits per year may have some tendency to visit at different times of the day relative to households which only visit the coast once or a few times per year. The results of these four methods are summarised in Table A4.7.

The estimates which give more weight to households making more visits per year give higher estimates of percentage of visits made in the morning (37-39%) than un-weighted household estimates (30-33%); this may be due the frequent visits by regular early-morning dog-walkers.

However, most importantly the four estimates of the percentage of all visits to the coast which are made during the hours of darkness are similar (range 5.6% to 7.2%).

For use in the over-wintering bird modelling, the recommended estimate is that based on weighting households by their annual visit frequency and excluding households which visit more in the spring or summer.

Therefore, for the individual-based models, the best-available estimate of the percentage of coastal visits which are made during the hours of darkness in the evening is 6.2%.

The Household Questionnaire Survey did not ask households the time at which they visited the coast, and yet visitor rates will not remain constant during the hours of darkness. For example, more visits would be expected early in the evening than in the middle of the night. The individual-based models needed an estimate of the times of darkness during which most visits occurred. In the absence of any data from the Solent, data from a neighbouring site, Poole Harbour, were used (Natural England 2009). Figure A4.2 shows that in Poole Harbour most evening visits occurred before 22.00.

Therefore, for the individual-based models all evening visits during darkness were assumed to occur before 22.00.

The data from Poole Harbour showed that visitor rates remained low up to at least 4.00 in the morning, but did not indicate the time at which visitor rates would increase during the morning. However, consultations with Solent Forum members familiar with the Solent suggested that visitor rates would increase after 6.00 in the morning.

Therefore, for the individual-based models daylight visitor rates were assumed to occur between 6.00 and 18.00, approximately the average times of sun rise and sunset. In mid-winter this meant that morning disturbance started during darkness, whereas at the start and end of winter morning disturbance started during daylight.

Table A4.7 Percentage of visits occurring during different stages of the day calculated for all responding households and excluding households that who visit the coast “more in Spring” or “more in Summer”.

	All responding households				excluding households who visit coast “more in Spring” or “more in Summer”			
Period of the day for coastal visits	Households ticks for visiting		Estimated total visits		Households visiting coast		Estimated total visits	
	N	%	N	%	N	%	N	%
Morning	627	30.5	31187	37.3	424	33.2	26664	38.6
Afternoon	870	42.4	31327	37.5	488	38.2	24908	36.1
Evening in daylight	429	20.9	16350	19.6	272	21.3	13235	19.2
Evening/night in darkness	127	6.2	4716	5.6	92	7.2	4283	6.2

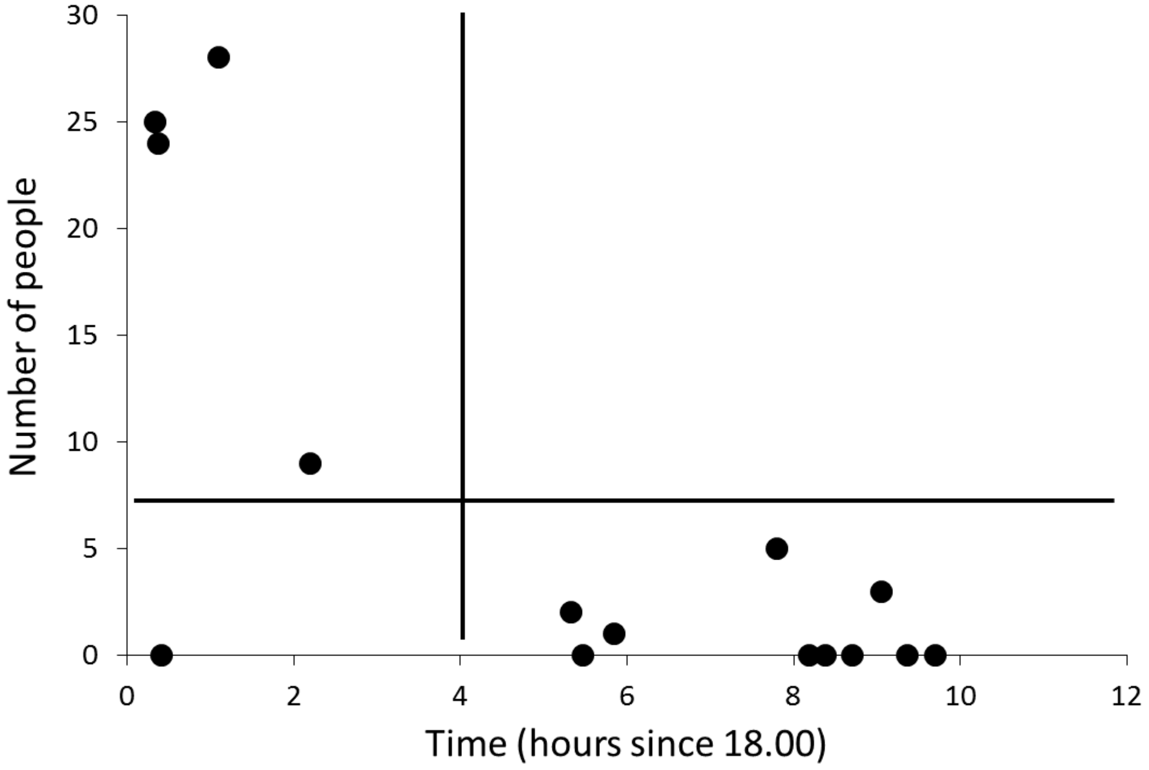


Figure A4.2 Relationship between time of day and number of people visiting coastal sections of Poole Harbour. Data from Appendix 6 of Natural England (2009). The horizontal bar is the mean number is people observed. The vertical line is at 22.00. In the individual-based models all evening visits in darkness were assumed to occur before this time.

A4.9 Estimated total feeding area lost per hour per section

The bird population feeding models simulate over-wintering feeding in one hour time steps to allow for changes in exposed feeding areas throughout the tidal cycle.

We have described how we estimate the average feeding area-by-time (hectare-minutes) lost per visitor (in relation to visitor zone, activity and bird species group).

To combine these space-time estimates across visitors requires assumptions about the collective distribution of visitors to each section in both space and time (within each hour). It seems reasonable to assume that the visitors arrive and spend their time independently within any one hour period. We considered how best to model where visitors go within a section, the extent to which they can be regarded as independent in space, or at the other extreme all take the same route.

The chosen approach was to sub-divide predicted visitors to each section by the observed proportions using each zone (shore, intertidal) to take account of the major differences between sections in use of zones. However, within zones, because the individual responses last only one or two minutes, the individual visitor disturbance responses are treated as independent in space and time.

The resulting summed estimates were in space-time units of hectare-minutes. For use within the bird population models, these estimates were divided by 60 to estimate the feeding area of mudflat assumed to be lost to disturbance per hour.

Appendix 5 Disturbance issues and management in the Solent

This appendix provides an overview and justification for the individual-based modelling scenarios used in this project. The basis of the scenarios was a Solent Forum workshop held during November 2010 which derived a set of potential mitigation measures to offset any negative effects of disturbance. This appendix describes which of these options have been explored, including an overview of the simulations that have been run, and explains why certain mitigation options were not be explored within the simulations.

A5.1 Process for selecting scenarios simulations

Each of the scenario simulations compared model predictions within an altered environment to those in the baseline (e.g. comparing predictions with increased sea level rise with those for the present day, or comparing predictions with reduced shore access by dogs to that with present day levels of access). To achieve these changes in environmental conditions, the values of parameters within the model were changed. Therefore, whether or not a particular scenario was simulated depended on whether the model had an appropriate parameter value to be changed. In respect to disturbance, the range of parameters that could be altered was related to the statistical analysis of the responses of birds to human disturbance (Appendix 4). As part of the analysis different types of human activity needed to be combined, which meant that scenario simulations could only be based on changes to these combined activity types (e.g. it was not possible to separate the effects of bird watchers and walkers because these activity types were combined in the analysis). The following parameters could potentially be altered in the scenario simulations.

- Area of intertidal habitat
- Duration of tidal exposure of intertidal habitat
- Size of bird populations
- Abundance of bird prey species
- Distribution and frequency of disturbance from the follow combined activity types
  - General activities on the shoreline (excluding dogs off lead)
  - Dogs off lead on the shoreline
  - General activities on the intertidal (excluding dogs off lead and bait digging)
  - Dogs off lead on the intertidal
  - Bait digging on the intertidal
  - Water-based activities

A consideration for the scenario simulations was whether changes were made to parameter values in specific parts of a site (to simulate local changes) or made throughout a site (to simulate site-wide changes). Preference was given to making changes throughout a site to help understand the overall implications of changes (e.g. site-wide changes in the amount of disturbance rather than changes in one or two places). Another consideration was whether relatively small or larger changes were made to parameter values. Preference was given to making larger changes as this approach can often help to understand the key parameters in models (e.g. completely removing a particular type of disturbance to understand its influence on the birds). However, all-or-nothing changes of parameters was kept to a minimum. Instead, percentage changes were applied to parameters (e.g. 25%, 50%) so that the potential impact of smaller changes could also be determined by interpolation (e.g. the effect of a 5% change could be estimated as 20% of the effect of a 25% change).

A5.2 Scenarios simulations

The following sections describe the scenario simulations run in the project and how the influence of sea level rise was incorporated. These simulations are summarised in Table A5.1.

A5.2.1 Current and future housing

Previous household and visitor surveys (Fearnley et al. 2010; Fearnley et al. 2011) have estimated current and predicted future access to the coast. Simulations could therefore be run to predict the effect of current and future housing.

A5.2.2 Sea level rise

Sea level rise could either have been simulated through changes in the sea level within the model (which would then predict changes in habitat area and tidal exposure) or through a direct reduction in intertidal habitat area. The first option would also have been associated with the assumption that the position of the high tide line remained unchanged (i.e. coastal squeeze occurred throughout the Solent, and no set-back schemes were implemented). These options were discussed at a Solent Forum meeting. Given the limitations of assuming sea level rise directly, it was decided that sea level rise would be simulated by reducing habitat area by the percentage values expected in the Solent.

A5.2.3 Change in habitat area

Factors other than sea level rise may influence, either positively or negatively, the area of habitat available to the birds and hence the potential impact of disturbance (e.g. changes in the rate of erosion, port / marina development). Simulations were run to determine the sensitivity of model predictions to changes in the area of intertidal habitat. These simulations were intended to give an indication of sensitivity to changes in habitat area rather than model any specific sources of change.

A5.2.4 Changes in numbers and distribution of visitors to the coast

The influence of changes in the overall number of people visiting the coast was simulated by making percentage changes in the number of people throughout the modelled sites. Changes in distribution and numbers could be associated with new housing developments, preventing access to sensitive parts of the coast or other factors that may influence the distribution of people.

A5.2.5 Influence of dog walking

Two categories of dog walking were identified in the statistical analysis of the response of birds to disturbance (dogs off lead on the shore and on the intertidal). Furthermore, the frequencies of dog walking (on lead) within the general on shore and intertidal disturbance categories were known. Simulations were therefore run to determine the effect of dog walking (whether on or off lead) on the birds. Simulations were run in which the frequency dog walking was altered throughout a site and in which dogs off lead were converted to dogs on lead.

A5.2.6 Influence of bait digging

The influence of bait digging on the birds could be simulated as bait digging was a category identified in the statistical analysis of the response of birds to disturbance. The influence of changing the frequency of bait digging (including removing bait digging) was simulated.

A5.3 Scenarios that could not be simulated

The following sections describe the mitigation options derived from the workshop that could not be simulated, and explains the reasons for this. These were either because the option was outside of the scope of the model, or because the model did not contain a suitable parameter that could be altered to simulate the mitigation option.

A5.3.1 Disturbance to roost sites

Disturbance to roost sites could not be simulated directly as no data were collected on the influence of disturbance on roosting birds.

A5.3.2 Response to unusual / unmeasured activities

The response of birds to unusual activities could not be distinguished statistically from responses to more frequent activities (Appendix 3). As a result, the responses to unusual activities were combined with the responses to more frequent activities. This meant that simulations could not be run to determine the effect of unusual activities. The response to disturbance was not measured for all potential sources of disturbance (e.g. kite surfers, low flying aircraft, effect of boat speed). Therefore, simulations could not be run to determine the effect of these activities.

A5.3.3 Provision of alternative green spaces

The influence of alternative green spaces on visitor numbers on the coast could not be simulated directly as previous household and visitor surveys (Fearnley et al. 2010; Fearnley et al. 2011) did not measure the influence of such locations on the behaviour of people. The influence of changes in the overall number and distribution of visitors to the coast was simulated however (see Section A5.2.4).

A5.3.4 Control measures, education and funding mechanisms

Most control measures, education and funding mechanisms could not be simulated as they are outside of the scope of the model. Incorporating changes to car parks (e.g. parking fees, or number of car parks) was also outside the scope of the model, as the influence of car parks on the distribution of people could not be identified in an analyses of visitor numbers (Fearnley et al. 2010; Fearnley et al. 2011).

Table A5.1 Scenario simulations included in the model. Each scenario was simulated for both Chichester Harbour and Southampton Water models. Each was repeated three times and the results averaged.

Scenario	Simulations
Current and future housing	Visitor numbers set to those for current or future housing.
Sea level rise	Habitat area reduced by the percentage expected in the Solent.
Change in habitat area	Habitat area reduced from current value.
Changes in numbers and distribution of visitors to the coast	Number of visitors – number of visitors increased from current value.
	Distribution of visitors – the distribution of visitors varies between the simulations for current and future housing due to regional differences in housing growth.
Influence of dog walking	Off-lead dog walking removed throughout each site.
	All off-lead dogs converted to on-lead dogs.
Influence of bait digging	Bait digging removed throughout each site.