CHANGES IN THE ABUNDANCE AND DISTRIBUTION OF THE SHELDUCK (*TADORNA TADORNA*) ON THE EDEN ESTUARY, N.E. FIFE, SCOTLAND.

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I, ..., hereby certify that this thesis, which is approximately 20 000 words in length, has been written by me, that it is a record of work carried out by me and that it has not been submitted in any previous application for a higher degree.

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For Mum and Dad

ABSTRACT

This project investigates an apparent decrease in the abundance of shelduck (*Tadorna tadorna*) on the Eden Estuary, north-east Fife. Data were collected for invertebrate abundance, shelduck abundance, distribution and behaviour, and nutrient levels in the water column. The relationship between the invertebrate populations, water chemistry and macroalgal mats was explored and this led to the hypothesis that an increase in nutrients has caused macroalgal blooms on the mud flats, causing the invertebrate population to re-distribute. This, in turn, could contribute to the shelduck's decline on the estuary as its feeding methods are not compatible with areas of thick weed. Several possible sources for such eutrophication are identified and preventative measures are suggested.

CONTENTS

CHAPTER 1

LITERATURE REVIEW

1 SPECIES FIELD CHARACTERISTICS

The general appearance of the shelduck (*Tadorna tadorna*) is similar to that of geese with a conspicuous red bill, elongated head and highly patterned plumage. Mainly white, the shelduck has a dark green head and neck, a broad chestnut belt around the forepart of the body, black scapulars, flight feathers, tail tip and belly stripe and pink legs. The male develops a fleshy knob on the top of the bill in early spring and the green of the head and neck are usually brighter than in females. The shelduck averages between 58 to 67 cm in length, the body of the bird averaging 40 cm. Males weigh approximately 1 to 1.2 kg and females 0.9 to 1 kg (Patterson 1982). Males therefore tend to be slightly larger than the females, have slightly brighter green colouring on the head and neck and the rump is a darker chestnut although these are not obvious in the field. The birds have a wingspan of 110 to 133 cm (Cramp et al. 1977; Patterson 1982).

Juvenile shelducks are quite different from the adults. The top of the head, hind neck and upper parts are dark grey brown while the forehead, face, spectacles and fore neck are all white. The under parts are light grey and lack the breast band and belly stripe present in the adults. By the first winter the chestnut belt is present but tends to be mixed with black and white and the belly stripe is quite broken and narrower. Juveniles are still unmistakable by the retention of the juvenile wing with white tipped primaries and secondaries and grey greater coverts (Cramp et al. 1977; Patterson 1982).

In the field, the most useful guide to identification of juveniles proved to be the condition and colouration of the breast band and the white fringe on the primary and secondary feathers. Younger juveniles also have a white fringe on the face around the edge of the bill and the head is a very dark grey. The legs are also a dull grey colour, rather than the bright pink of the adults.

2 SPECIES PHYLOGENY

The shelduck is one of 14 living members of the tribe Tadornini, belonging to the family Anatidae and consisting of the Sheldgeese and Shelducks. The Tadornini incorporates five genera, two typical sheldgeese (*Cyanochen, Chloephaga*), two intermediates (*Alopochen, Neochen*) and the shelducks (*Tadorna*). The genus *Tadorna* is sometimes split into two groups, the typical *Tadorna* (*tadorna*, *radjah*) and *Casarca* (which includes the remaining five species) (Cramp et al. 1977; Patterson 1982). The split is due to differences in diet: the common and radjah shelducks feed mainly on molluscs and other invertebrates, while the other five species are vegetarian (Patterson 1982).

Linnaeus originally named the common shelduck *Anas tadorna* in 1758 but it has been named *Tadorna cornuta* (Saunders 1889), *Tadorna vulpanser* and *Tadorna bellonii* (Yarrell 1843). It has been known as the burrow duck, barrow duck and bar gander, skeeling goose and sly goose. It is called *Brandgans* in Germany, *tadorne de belon* in France, *Bergeend* in Holland, *tarro blanco* in Spain and *Gravand* in Switzerland.

The other species in the genus *Tadorna* are:

- Ruddy Shelduck (*Tadorna ferruginea*)
- Australian Shelduck or Mountain Shelduck (*Tadorna tadornoides*)
- Radjah Shelduck or Burdekin Duck (*Tadorna radjah*)
- New Zealand or Paradise Shelduck (*Tadorna varietaga*)
- Cape or South African Shelduck (*Tadorna cana*)
- Korean or Crested Shelduck (*Tadorna cristata*)

All seven species are large and brightly coloured, have persistent pair bonds and prolonged parental care as do geese, but also show the characteristic morphology, voice and eclipse plumage of ducks (Cramp et al. 1977; Patterson 1982).

3 Species Distribution

3.1 Biogeography

3.1.1 World

The common shelduck is confined to the Palearctic region, where it tends to favour warm, semi-arid and mild maritime climates. Its range stretches from the west of Ireland through Europe and Asia to Western China. There is a marked discontinuity in the breeding range, with two distinct groups. The first stretches from the coasts of Finland, Denmark and Sweden, along the coast of Northern Germany, around the British coast and the Atlantic coast of France and Spain. The second group ranges from Turkey through Russia and the former Soviet republics and into Eastern Asia to Western China. There are significant differences between the two groups. The European birds show a strong preference for coastal areas, their choice of breeding and moulting site governed primarily by proximity to salt or brackish waters, rarely moving further than 2 km from the coast. However, the Asian birds occur mainly on steppe and semi-desert, concentrating around brackish water lakes, often far from oceans and inland seas (Cramp et al. 1977; Patterson 1982). Lönneberg (1932) suggested that the division of the range is a product of changes in coastlines during the late Tertiary and early Pleistocene periods when the Mediterranean stretched as far as the Sarmatic Inland Sea. Overwintering ranges are similar to the breeding range in Europe with the exception of the Scandinavian populations. These birds move south to join the rest of the European birds in Britain and along the coasts of France and Spain. The eastern population moves south, concentrating in Northern India and China.

3.1.2 British distribution

In Britain, the common shelduck occurs all around the coast, both breeding and overwintering. Sharrock (1976) found the birds where there was shallow muddy water or sandy shores with suitable nesting habitats. They occur much further inland than is usual elsewhere in the range, but most are within 20 km of the coast. Exceptions to this are pairs found 30-32 km inland on the rivers Nene and Ouse in Cambridgeshire and Huntingdonshire. Sharrock found two pairs over 100 km inland in Warwickshire.

3.2 HABITAT

In Britain shelduck tend to favour areas that, while close to salt or brackish waters, also have some access to fresh water. As a voracious predator, the species needs areas of quite high biological productivity and seem to prefer sands or mud flats covered with shallow water which periodically dry out through tidal action or evaporation (Cramp et al. 1977; Patterson 1982). As the species prefers to nest in burrows, sand dunes and lighter soils are favoured. They have been found to nest at sites that have only a thick cover of vegetation rather than in a burrow, but Patterson (1982) suggests that this is due to a lack of suitable alternatives. Overhead shelter and concealment seem to be common factors in site choice (Cramp et al. 1977). Dewhurst (1930) found that the existence of a suitable 'bolt hole' (a second entrance to the nest for escape purposes), was also an important requirement of a nesting site (see also Hori 1964).

3.3 POPULATION SIZES

A global estimate of numbers is not available because the eastern population sizes are unknown. However, the European populations have been well studied and estimates have been taken from numbers in the Dutch Waddenzee / German Wattenmeer area where immense numbers of shelduck gather to moult. Goethe (1961) estimated that there were over 100 000 shelduck on the main moulting area of the Grosser Knechtsand in 1955 and Nehls (1992) counted 200 000 in 1992. In addition to this, large numbers of birds moult at Bridgwater Bay on the Severn Estuary, on the Firth of Forth in south-eastern Scotland and the Wash in Norfolk. Atkinson-Willes (1976) estimated the winter population at 130 000 with a further 75 000 birds wintering in southern Europe. It is likely that these estimates are now appreciably lower than the present, as shelduck numbers have been steadily increasing (Wingfield-Gibbons et al. 1993; Cranswick et al. 1997).

The British population has been estimated from recoveries of marked birds at Heligoland. Roughly half of the birds ringed during the moult were subsequently recovered in Britain. This suggests a figure of c. 50 000 birds (Atkinson-Willes et al. 1963). An international census of wildfowl numbers in 1967 found 113 500 common shelduck in the Palearctic, 46% of which were in Britain (Atkinson-Willes 1969). Patterson (Wingfield-Gibbons et al. 1993) estimated that there were 44 200 in Britain (10 600 breeding pairs) and 4 650 in Ireland (1 100 breeding pairs). The Wetland Bird

Survey (WeBS (Cranswick et al. 1997)) count for 1995/96 estimates the maximum population in Britain as 77 890 and 3 858 in Northern Ireland. The Wash is the premier site for Britain holding 15 000 to 20 000 birds, but counts have been lower than usual for the last three years (between 12 000 and 14 000) (Cranswick et al. 1997). Nine other sites in Britain hold internationally important numbers (more than 3 000 birds). Overall the British population has increased annually by 6.1% between 1960 and 1983, falling to 4.8% since then (Cranswick et al. 1997). The WeBS report notes that from 74 estuaries, 41 had significant increases in numbers while 10 had a significant decrease, including the Eden Estuary.

3.4 MOVEMENTS / MIGRATION ROUTES

Shelduck moult each year, becoming flightless for a period of several weeks during September to October. The majority of the British population migrates to the Dutch / German Wadden Sea area to moult. However some remain in Britain moulting on the Wash (2000+), the Forth (2500+) and at Bridgwater Bay in the Severn Estuary (3400+) (Eltringham et al. 1963; Bryant et al. 1976; Bryant 1981).

The moult migration to the Wadden Sea and Heligoland begins in early July when yearlings and young adults leave. They are followed by failed breeders and finally the successful breeders towards the end of August / September. Coombes (1949) notes that departures from Slimbridge always occurred during fine weather, with clear skies and a following wind being very important. He did not see any significantly large departures during overcast weather or against the wind. Almost all departures occurred between one hour before and one hour after sunset.

The route taken is estimated from sightings of migrating flocks and observations of birds on inland lakes. Most birds seem to follow a direct course to the moulting grounds. A female shelduck ringed at Slimbridge was found dead on the Wash almost on a direct line with Heligoland. Many birds have been seen passing east off the northern Norfolk coast. It may be that the birds from areas such as the Dee and Morecambe Bay take a rest stop on the east coast (Patterson 1982). Flying at an average speed of 96 km hr^{-1} the trip from Britain to the Wadden Sea and Heligoland should take approximately 6 to 6 ½ hours. It may be that birds congregate at focal points in Britain and then migrate as a flock. In Morecambe Bay the total number of birds leaving far exceeded the summer numbers of adults and yearlings. Birds from Ireland or other breeding areas may have moved to the bay prior to migration (Patterson 1982).

4 SPECIES DIET

4.1 MAIN PREY ITEMS

As omnivores, shelduck eat a very wide range of prey items including a small amount of plant material (7.3% by volume plant material, 92.7% by volume animal material (Olney 1965)), but show a very strong preference for a few species. The list of species shelduck has been found to eat, taken from stomach samples and dead birds, (Wingfield-Gibbons et al. 1993) is as follows:

MOLLUSCS

- *Hydrobia*
- *Cardium*
- *Macoma*
- *Mytilus*
- *Montacula*
- *Cingula*
- *Buccinum*
- *Littorina*
- *Skenea*
- *Paludina*
- *Tellina*
- *Nucula*
- *Mya*
- *Theodoxus*

CRUSTACEANS

- Small crabs, shrimps and prawns
- Sandhoppers
- *Artemia*
- *Corophium*

INSECTS

- Grasshoppers (Orthoptera)
- Beetles (Coleoptera – *Carabus nitens*)
- Fly larvae (Diptera – Chironomidae)

OTHER

- Small fish and spawn
- Annelid worms (Nereidae and *Arenicola*)
- Plant material (algae, grasses and seeds)

However, shelduck heavily favour particular prey. The diet of adult birds consists mainly of the mollusc *Hydrobia ulvae*, the crustacean *Corophium volutator*, the annelid worm *Nereis diversicolor* and the clam *Macoma balthica*. Stomach analysis of 64 shelduck from the Ythan estuary in Scotland (Buxton et al. 1981) revealed that *H. ulvae* occurred in 93.9% of samples during January to March and 90.5% in April to June. *C. volutator* was present in 6.1% of samples during January to March, rising to 33.3% in April to June, as was *N. diversicolor* which was absent from the diet in January to March but was found in 33.3% of samples during April to June. *M. balthica* showed a contrasting occurrence of 39.4% during January to March but disappeared completely from the diet during April to June.

Overall, *H. ulvae* occurred in 94% of samples. One incubating female, having fed for approximately one hour, was found to contain 11 597 whole *Hydrobia* and at least 261 apices. Buxton & Young (1981) summarised the diet of adults to emphasise the large numbers of *Hydrobia ulvae* with *Nereis diversicolor* and *Corophium volutator* becoming more important in the summer (Table 1).

The diet of ducklings differs from that of the adults. The same study analysed the stomach contents of 11 ducklings during June and July, 1981 and found that while *H. ulvae*, *N. diversicolor* and *C. volutator* were all still present, the proportions changed drastically. *C. volutator* occurred in only 18.2% of the samples, *H. ulvae* in 54.5% and *N. diversicolor* in 81.8%. Also important was *Cypris* sp., which occurred in 18.2% of samples.

Table 1. Percentages of main prey items for adults and ducklings from stomach samples (Buxton et al. 1981). Cypris refers to the larval stage of barnacles rather than the ostracod, *Cypris* spp.

	C. volutator	*H. ulvae*	*N. diversicolor*	Barnacle cypris	*M. balthica*
Ducklings	18.2	54.5	81.8	18.2	0
Ducks: Jan-Mar	6.1	93.9	0	0	39.4
Apr-Jun	33.3	90.5	33.3	9.5	0

A second study (Olney 1965) in the Medway Estuary in Kent showed that in samples from 18 stomachs taken between September and February 1962/63, *H. ulvae* comprised 89.5% of the total volume sampled. *M. balthica* and *C. volutator* were both missing from the samples. *Enteromorpha* sp. constituted a significant part of the samples at 6.4% of the total volume. A second, third and fourth set of samples taken in February to April 1963, April to May 1963 and August to October 1963 confirmed the importance of *H. ulvae* in the diet. Overall, from 46 birds, *H. ulvae* occurred in 100% of the samples taken, followed by *M. balthica* in 10.9%, *C. volutator* in 6.5% and *N. diversicolor* in 4.3%. A second species of *Hydrobia*, *Hydrobia jenkinsi* was also found in 2.2% of samples taken.

Olney concluded that the variation in numbers of snails might play an important part in where the shelduck congregate during the year. Newell (Newell 1962) described the cycle of behaviour displayed by *H. ulvae*. Split into phases, the cycle begins as the tide recedes when the snails can be seen browsing on the mud surface. As low tide approaches the snails begin to burrow in the mud, a phase which can last for several hours, before surfacing and being carried back up the shore by the incoming water. They then sink on the ebb tide at about the same mid-tide point they started from and begin to browse again. The snails are at maximum density whilst browsing on the mud and are also at their most vulnerable. This corresponds with the feeding behaviour of the shelduck, which tend to feed most intensively on the ebb tide moving down the shore and foraging in the shallow waters at the tide edge.

Diet on the feeding grounds in the former USSR is markedly different. In Kirov Bay and Magan Steppe the birds are mainly herbivorous with 8.2% of the sample volume comprising *Hydrobia* and *Theodoxus*, 16.1% seeds and 75.5% decomposing algae. Winter diet on the Ili delta was also mainly herbivorous, consisting of a large proportion of seeds, mainly Chenopodiaceae. Summer diet was dominated by the eggs of the brine shrimp *Artemia salina* (average 1 800 per stomach, maximum found 19 800), chironomid larvae (average 5 970, maximum found 63 880) and single celled algae, mainly *Aphanoteca*. On salt lakes in Uxboi, the main dietary components were crustaceans and swarming ants (Formicidae) (Dementiev et al. 1952).

This heavy dietary dependence on a single species causes the shelduck to be sensitive to the changes in populations of *H. ulvae*. After the particularly cold winter of 1962/63, 58 shelducks were found in the Wash between 26th February and 3rd March starved to death (Pilcher 1964). This was apparently due to the intertidal section of the mud freezing over, thus preventing the birds from feeding. Similar results were noted in Kent with 106 starved shelducks found in the Thames and Medway estuaries (Harrison et al. 1964).

4.2 FEEDING BEHAVIOUR

The shelduck uses various different methods of feeding from deliberate digging in the surface mud to up-ending. These are summarised in the following list:

- Scything with the bill or dabbling (Swennen et al. 1959). This method is very characteristic of the shelduck. Lamellae on the bill and tongue reject stones and large items and filter out prey from the silt and water. This technique is used on exposed wet mud, at the water's edge and probably when upending or head dipping (Patterson 1982).

- Surface digging in exposed mud. Shelduck can dig out holes of 4 to 45 cm width and 2 to 12.5 cm depth. This has been noticed particularly on the Grosser Knechtsand moulting area (Oelke 1970; Patterson 1982).
- Head dipping in 10 to 25 cm of water. Bryant and Leng (Bryant et al. 1975) found this to be the most common method of feeding.
- Up ending in 25 to 40 cm of water (Bryant et al. 1975).
- Use of foot trampling to bring prey to the surface.
- Rapid pecking of the mud surface. Incubating females and ducklings, probably targeting *Nereis* and *Corophium*, often use this method (Patterson 1982). On the Ythan estuary the birds switched from sieving to almost exclusively pecking in early May (Patterson 1982) when both species are found at the surface of the mud.

Adult shelduck rarely dive for prey but the young do so freely. The frequency with which each method is used is dependent on tidal state, on type, size, abundance and availability of prey and on substrate. Shelduck usually feed in areas where *H. ulvae* is most abundant and it has been found that birds in areas of high prey density spend less time feeding than those in areas of low prey density (Patterson 1982).

Adults show a very strong selection for particular sizes of *H. ulvae* and *C. volutator* (Buxton et al. 1981). By using forage ratios (percentage frequency of size class in stomach sample divided by the percentage frequency of size class in substrate), Buxton et al. found that shelduck seemed to select snails between 3.0 and 4.0 mm in length (forage ratios between 1.3 and 2.5) and snails of 4.5 mm in length (forage ratio 1.5). They ignored snails above and below these sizes. It is probable that smaller snails were able to slip through the bill lamellae. The birds may not be able to open the mandibles far enough to allow them to take snails larger than 4.5 mm (Buxton et al. 1981). Shelduck seemed to select specimens of *C. volutator* over 4.0 mm in length (forage ratio 1.9).

Ducklings showed a similar selection for certain size classes. With *H. ulvae* they directly selected individuals over 1.0 mm in size. Percentage frequency of *C. volutator* showed marked truncation of size classes below 3.0 mm (forage ratio 2.5). Forage ratios for *N. diversicolor* rose from 0.7 in specimens of 21 mm (mandible width 300 μm) to >6 for individuals of 50+ mm (mandible width 500+ μm) in length, indicating that the ducklings selected the largest specimens (mandible width of 350 μm and over).

5 SPECIES BEHAVIOUR

5.1 TERRITORIALITY

5.1.1 TERRITORIAL BEHAVIOUR

Agonistic behaviour in the shelduck is quite varied (Patterson 1982), from the simple alert posture (head raised, neck extended, feathers sleeked, body angled upwards slightly) to outright fights between neighbours. The most conspicuous behaviour is Inciting where the female lowers her head, waving it back and forth in the direction of the rival bird. This 'incites' her mate to approach and sometimes attack the rival bird. In general only like sexes fight but Patterson notes incidents where males attacked females (Patterson 1982). Inciting behaviour is common in ducks such as the Mallard (Eibl-Eibesfeldt 1970) but was first described in the shelduck by Boase (1935).

5.1.2 TERRITORY CLAIMING AND MAINTENANCE

Territorial behaviour in shelduck is unusual among ducks firstly because they defend territories and secondly because both the male and female show such conduct (Patterson 1982). It is difficult to define a shelduck's 'territory' since they are not consistent in their defence of areas. During February to April pairs begin to separate out across their breeding grounds. Both members become more aggressive towards conspecifics that encroach into a particular area. However, this area is not constant. Pitelka (Pitelka 1959) moved away from the conventional behavioural definition when he suggested that territories should be defined by the exclusivity of the area (the degree to which other birds are excluded from the territory) rather than just the defence of it. Young (Young 1970) followed this definition in a study on the Ythan estuary, Aberdeenshire. Using colour ringed birds he mapped the positions of the territories of each pair in the breeding flock and also the location of the neutral feeding grounds occupied by the non-breeding, non-territorial flock. Territory size varied between 1000 and 2000 m^2, mainly due to the topography of the area. The most basic prerequisite for a proposed territory was that it held at least a minimum number of mud dwelling invertebrates. Overlaying territories and densities of *H. ulvae* reveals that the birds only choose those areas where the invertebrate is present.

Once ownership had been established it did not change, unless one of the pair was injured or killed or on very rare occasions, chased from the area by a more dominant pair. Ownership also seemed to persist from year to year for many of the sites. Young found that in the second and third years of the study 52% and 69% (respectively) of birds returned to the same territory, 23% and 11% returned to different territories, 10% and 7% rejoined the non-breeding flock and 15% and 14% died or disappeared. Young also found that the time of return from moult had no bearing on when the birds took up territories or which territories were taken. Many remained vacant until the owners from the previous year returned to claim them. In all three years of the study, reclamation continued up until the end of April.

In the third year of the study, Young attempted to examine the impact of removing one or both members of the resident pair. He found that after the removal of both birds, a new pair moved into the vacant territory very rapidly (within 5 to 13 days). If the male was removed, the females acquired new mates within a week. However, if the female was removed the males abandoned the territory either to acquire another mate or to join the non-breeding flock. On the basis of this, Young suggested that the female has a stronger attachment to the territory than the male. Williams (1973, in Patterson 1982) found that 80.6% of females but only 55% of males returned to the same territories. The difference could be explained by changes of mate. Females with new mates tended to return to the same territory while males with a new mate tended to take up a new territory.

5.2 SOCIAL ORGANISATION AND BREEDING SYSTEMS

Shelduck are monogamous and pairs can persist from year to year (Patterson 1982). Peak counts of birds are usually found in December or January, by which time the winter flock is fully established. From March the flock starts to break up into a resident, non-breeding, non-territorial flock and a resident, breeding, territorial flock. By April to May territories have been established and by May to June the ducks have begun to nest. The first broods appear in July to September when the adult birds are beginning to migrate to moulting grounds, starting with the non-breeders, followed by failed breeders and finally the successful breeders. Many ducklings are left in crèches in the care of a few failed or non-breeders and some successful breeders, but some remain in parental broods until fledging. The migratory adults have usually returned to the breeding grounds by the end of October but can be delayed until the end of December (Patterson 1982).

It has been suggested that dominance relationships within the winter flock and competition for food regulates the total number of shelduck present (Jenkins et al. 1975).

A study carried out in Aberlady Bay (Firth of Forth) suggested that the number of shelduck resident on the bay was regulated by social behaviour, which was itself regulated by food availability, with competition for improved status causing annual reassessment and changes between breeders, non-breeders and transients (Jenkins et al. 1975). This study showed that:

1. Total population sizes and total breeder numbers remained the same throughout the 7 years of the study, regardless of changes in breeding production.
2. The number of birds that commuted to the feeding site from nest sites was stable compared with the number of transient birds.
3. Out of the total stock of ducks on the study area, 20% to 30% did not hold territories and probably did not breed.

It was suggested that birds were excluded from the field site and from breeding by a shortage of some resource and it was considered most likely that this was either food or a place to obtain food. The study suggested that:

- The number of good feeding places on the study site remained fairly constant throughout the study.
- Efficient feeding was only possible at certain times during the day when the mud was covered by a certain depth of water.
- Competition for good feeding places was high and regulated the total number of resident birds through aggressive interaction.
- As the breeding season approached, aggression became more severe excluding less dominant birds from feeding properly on richer sites at low tide.
- The submissive birds initially returned at high tide to feed on poorer quality sites, but as the aggression of the resident birds increased they were confined to neutral, non-territorial sites or left the field site altogether.

Jenkins et al. then predicted that:

a. Fluctuations in the level of breeders and resident non-breeders should be catered for by immigration of new individuals, so that selective removal of birds should have no long-term effect on the size of the two groups.

b. The release of 1-year old ducklings into the flock should not lead to more resident adults.

c. Aggressive interaction should increase as spring approaches and with increased crowding, as should the distance between feeding pairs, correlated with changes in the behaviour of submissive birds, before territories are established.

d. Birds present at high tide only should be subordinate to those also present at low tide.

e. Birds dominant in winter should become territorial.

f. Birds only present at high tide or confined to neutral ground at low tide, will not be in breeding condition by late March.

g. Birds that are more dominant should feed in richer areas than birds that are less dominant.

h. Birds that are more dominant may nest closer to the sea than less dominant breeders.

i. Changes in the social position of a bird (transient to non-territorial resident to breeder, etc.) should correlate positively with changes in the dominance of the bird and should be predictable from behavioural studies in winter.

A second study (Evans et al. 1982) which tested some of these predictions found:

- **Predictions a and b:** The size of the flock did not re-adjust to an optimum after removals and re-additions.
- **Prediction c:** Aggressive interactions did not increase through the year and a consistent dominance hierarchy was not established even when feeding in crowded groups at sites where grain had been scattered.
- **Predictions d and g:** Percentages of birds feeding at less favourable tidal states fell as time progressed, rather than increasing.
- **Predictions e and f:** Birds which fed less well during the winter, did not necessarily assume low positions in the dominance hierarchy. However, because of the limited feeding niche occupied by shelduck, mortality can increase dramatically during hard winters, but it is not suggested that this would be a regulatory mechanism.
- **Predictions h and i:** No relationship between dominance rank and territory position, continued presence in the study site or breeding success was found.

It was suggested that there was very little evidence of dominance hierarchies in the winter flock without the addition of food supplies. However, studies at the Ythan estuary (Patterson 1977) found that there are clear male hierarchies. Patterson found that the frequency of aggression increased in late winter without a change in flock density. The study used both colour marked captive-bred birds for preliminary observations and wild colour marked birds for the observations on the estuary. Captive males kept with an adult female and four juveniles showed a clear hierarchy, i.e. it was possible to assign the rank of each individual from observations. A similar result occurred with a larger group of nine hand reared juvenile males, kept with three juvenile females. All but one of the males could be ranked consistently over a series of observations (Patterson 1977). In addition, males which had previously been of low rank but which subsequently paired with one of the females moved into the top ranks. At the end of the captive study, paired males held the three highest ranks. It was suggested that this was probably due to a paired male being more ready to attack other males coming close to his mate in the confined space of the enclosures.

In the wild study, using grain as bait, it was possible to assign ranks to 28 marked birds for both 1970 and 1971. High ranking birds in 1970 tended to remain high in 1971. However, birds of middle rank in 1970 tended to lose rank relative to those that had been low in 1970. The results showed that aggressive behaviour in the winter flock was associated with a dominance hierarchy between males. There was no correlation between rank and age, rank and weight or rank and breeding success in the previous season, making it very difficult to predict dominance from physical attributes. Patterson suggested that unranked birds (those not observed enough to assign rank to) and unmarked birds formed a secondary group of subordinates. He suggested that the birds caught were likely to be individuals that were more dominant. He concluded that high ranked groups might be able to exclude subordinate groups from food sites, which could act as a regulatory mechanism on flock size and would support the hypothesis suggested by Jenkins et al. (1975).

A later study, again on the Ythan (Ingold 1991) examined the dominance relationships between pairs with broods in relation to food supply. Shelduck territories were here defined as consisting of a central exclusive area, which does not overlap the territory of other birds, surrounded by a peripheral area, which can overlap the territories of other birds. In this study, dominant pairs tended to have larger exclusive areas than subordinate pairs at high density, regardless of the order in which the birds arrived in the area. Dominance was determined by the number of encounters pairs won and the variation in distance between pairs because of those encounters. Subordinate pairs generally had smaller feeding grounds of lower quality than dominant pairs. Makepeace and Patterson (1980) showed that duckling mortality increases with brood density. It is likely that the broods of subordinate pairs suffer higher mortality, due to the increased number of attacks from higher ranking pairs and lower quality food supplies. Another factor in duckling mortality could be that because subordinates are forced into less desirable nursery areas, there is a higher chance that they will be disturbed (i.e. by predators, human activity, noise, etc.).

5.3 BROODS AND CRÈCHES

Shelduck broods usually leave the nest about 12 hours after hatching. This can be extended up to 4 days if the hatching period is very long (i.e. the ducklings take a long time physically breaking out of the egg). The hatching period is usually between 24 and 36 hours (Hori 1964). Once hatched, the young are led to the feeding territory (which can be several kilometres away) by both parents, often in a single cross country march (Patterson 1982). Once on the feeding grounds, ducklings can stray quite considerably from the parents, ranging ahead of them while foraging. Williams (1974) found that some ducklings can range up to 50 m away from the parents. This has implications for brood composition because shelduck broods often undergo mixing. Patterson et al. (1982) examined the impact of brood mixing on the shelduck's breeding output. They found that most ducklings tended to transfer from the broods of dominant birds to the broods of subordinate birds and that there was no significant difference in the number of ducklings fledged between subordinate and dominant birds. It was suggested that dominant birds tended to lose ducklings because they were more aggressive than subordinates and tended to move further from their broods when attacking than subordinates (Makepeace et al. 1980; Patterson et al. 1982). The greater the distance between brood and adult, the more likely it is that mixing of broods will occur. However, Williams (1973, in Patterson 1982) found that out of 14 incidents of mixing, only five involved aggressive interactions. Thus, the dominance of the males involved may be irrelevant to the degree or direction of mixing. Patterson and Makepeace (1979) showed that winter dominance does confer some advantage during breeding as dominant birds hatched significantly more ducklings than subordinates.

Before the moult migration shelduck congregate on mud flats with their broods, which form crèches of as many as 100 ducklings (Hori 1964; Patterson 1982). When the majority of adults leave for the moulting grounds in September, a small number of adults remain behind with the crèche. Hori (1964) suggested that these adults were mainly failed breeders with some non-breeders, accompanied by a minority of successful breeders. However, Hori later found that the adults caring for a studied crèche all had offspring within it, a finding echoed by Williams on the Ythan estuary who found that all of the mixed broods studied were accompanied by successful breeders (Williams 1974). Precisely why shelduck crèche is not clear. Tourenq et al (1995) suggest that in Greater Flamingos, *Phoenicopterus ruber roseus*, it may be an anti-predator device but this is in situations where both the parents of the crèching chicks are present and the adults do not leave the chicks until they have fledged. Adult male shelduck with ducklings often attack gulls, particularly greater and lesser black-backed *Larus marinus* and *L. fuscus*, herring gulls, *L. argentatus*, common crows *Corvus corone*, hooded crows *Corvus corone cornix* and herons *Ardea cinerea* (Davis 1975). Makepeace and Patterson (1980) found that of 92 attacks by adult males on the Ythan, 72% were on gulls and 11% on waders. Young (1964 in Patterson 1982) suggested that scattering of ducklings when attacked by gulls made them more vulnerable to predators. Patterson (1982) found that out of 554 hours of observing broods, only 2 cases of predation were seen and both were by gulls on scattered groups of ducklings.

In the Common Eider *Somateria mollisima* L. crèching behaviour has been found to be beneficial to both ducklings and adults (Gorman et al. 1972). Adult Eider feed mainly on *Mytilus edulis* and *Carcinus* sp. while the young feed mainly on *Hydrobia*, *Corophium* and *Littorina*. Thus the feeding areas of the adults and young are spatially very different with adults feeding on mussel beds and chicks feeding on mudflats. Gorman and Milne suggested that crèching has evolved to enable female eider to regain body mass lost during incubation while maintaining a reasonable level of security for the young. The value of adoption to eider females that care for crèches is probably neutral since parental effort does not seem to increase (Bustnes et al. 1991). Whether crèching has similar value to shelduck adults is unknown. No parallel work has been done on the species. The diets of shelduck adults and young are sufficiently similar to make spatial differences in feeding unlikely.

6 FIELD SITE DESCRIPTION

6.1 SITE STATUS AND QUALIFICATIONS

The Eden Estuary (N.E. Fife – NO 48' E 20'N) is a nationally or internationally important breeding and overwintering site (depending on species) for 9 species of waterfowl. It consists of shallow mudflats, approximately 4 km^2 in area. It was assigned SSSI status in 1971 followed by LNR status in 1978 for this reason. Shelduck occur in nationally important numbers, i.e. the site has a population in excess of 1% of the national population; in this case the 1% threshold is set at 750 birds. The Wetland Bird Survey 1995/96 (Cranswick et al. 1997) estimates a local population of 930 birds. This compares with an estimate of 1590 birds for 1991/92.

One of the possible reasons for this apparent decline could be a decrease in food resources. This, in turn, could be due to some sort of pollution. Various possible sources of pollution exist around the estuary (see Figure 1). At the western end of the inner bay is Guardbridge Paper Mill that has, in the past, been responsible for some leakage of pollutants into the water (L. Hatton, pers comm). In addition, there are at least five discharge points for agricultural run-off situated around the bays. A sewer discharges into the channel to the east of Coble Shore, close to the mouth of the Motray Water. The main source for nitrates in the catchment area is agricultural fertilizers while phosphorus is likely to derive mainly from sewage discharge (Caudwell et al. 1994). There are then, several potential sources for enrichment and eutrophication of the water, which has an impact on macroalgal growth and possibly, invertebrate populations.

Caudwell et al. (1994) noted that macroalgal blooms in the estuary do not appear to be a recent phenomenon, as *Enteromorpha prolifera* blooms have been recorded as early as 1939. Owen and Stewart (Owen et al. 1983) found quite extensive macroalgal blooms of *E. prolifera*, *E. intestinalis* and *Ulva* sp. Using a series of transects across the entire estuary, macroalgal biomass and percentage cover for 43 survey points was measured. It was found that macroalgal cover was never higher than 60% with a mean of just under 10% for the entire estuary (although the macroalgae are very patchy). Changes in macroalgal cover could have varying effects on invertebrates. Species such as *Arenicola marina* can occur in clear patches between macroalgal mats, but others such as *C. volutator* occur only in areas which are completely devoid of mats. Various studies have shown that *Corophium volutator* does not survive under macroalgae (Raffaelli et al. 1991; Raffaelli et al. 1998). On the Ythan estuary it has been found that patchy distributions of macroalgae are necessary for the maintenance of the *C. volutator* population, allowing them to re-populate areas which were previously covered by mats.

A study in 1978/79 (Cobb et al. 1979) showed a key species such as *H. ulvae* occurring at densities greater than 1000 m^2 over large areas of the estuary, most notably on Kincaple Flats and the southern shore of the inner bay. *C. volutator* occurred at densities over 500 m^2 and *N. diversicolor* was found at over 70 m^2. These three species, as well as *Macoma balthica* form the main components of the shelduck's diet.

7 PROJECT SUMMARY AND GOALS

This study of the Eden and its shelduck population is intended to establish some baseline data of the shelduck population and investigate whether or not there has been a real decline in numbers and if so, analyse the possible causes for such a decline. In order to gain an understanding of the system, various data were gathered:

- Behavioural and distribution data

  Data on shelduck behaviour and their distribution across the estuary were gathered to attempt to establish a baseline for further work. Changes in behaviour and distribution of species may be the first sign of a change in the environment.

- Invertebrate abundance

  A survey of the Kincaple mudflats was carried out to ascertain the potential food sources available to the birds.

- Water chemistry

  Data on water chemistry were taken simultaneously with the invertebrate abundance, to give an idea of the environmental conditions in which prey species occur and in response to a perceived increase in macroalgal mat growth.

- Back data

  Much back data on water chemistry, climate, and bird abundance was gathered from various sources to provide an historical setting for the current data.

It was hoped that analyses of these data would enable some suggestions to be made about potential causes of a decline in shelduck abundance and to generate some site specific data on the ecology of the species.

CHAPTER 2

BIRD COUNTS AND DISTRIBUTIONS

1 INTRODUCTION

Since very little work has been conducted on the shelduck population on the Eden estuary in the past, the initial section of this project was primarily to establish baseline data: how many birds are on the estuary, if there are there any long term trends in bird counts, the distribution of the shelducks across the estuary and their behaviour. This chapter examines trends in counts of shelducks in the past and the distribution of the flock across the estuary throughout tidal cycles. It will also examine the possibility of any changes in flock distribution across the estuary.

2 METHODOLOGY

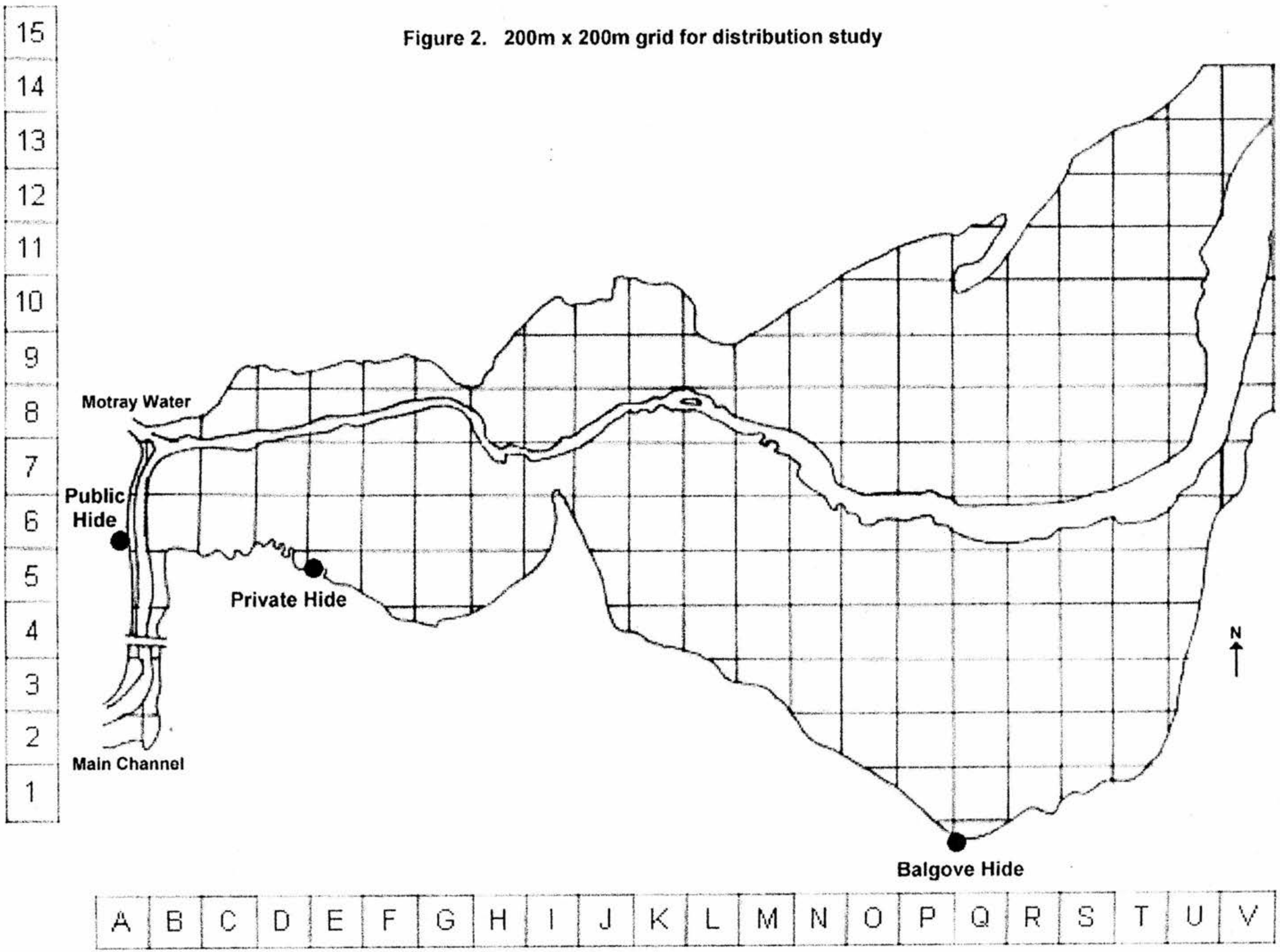
2.1 BIRD COUNTS

A daily count of the number of birds was carried out on the outer bay (Kincaple flats and Coble House Point to Shelley Spit). These were done from the Balgove hide (NO 482 182) on the south shore, using a 10 x 70 telescope scanning from west to east. It was decided to count only the birds in the outer bay because it was difficult to achieve reliable counts when counting from several different locations consecutively. The Balgove hide proved to be the most easily accessible point which could be reached without disturbing the flock. An attempt was made to include the inner bay but the discrepancy between counts made on the same day was very high and since the counts were to be carried out daily, the time needed made this impractical. Counts were made throughout the project from the beginning of December 1997 to August 1998.

2.2 BIRD DISTRIBUTION

The distribution of birds on the estuary was recorded using a 200m x 200m grid (Figure 2). The grid was marked out using bamboo canes that were marked with fluorescent

Figure 2. 200m x 200m grid for distribution study



paint to make them visible in low light conditions. Counts were then made of the number of birds in each grid square every 15 minutes through three complete tidal cycles. Due to adverse weather conditions, some of the grid canes did not remain in place and it proved necessary to use secondary methods to supplement the grid. Therefore the exact positions of the birds on the mud flats was determined first by using the grid, then by trigonometry using various landmarks on the north shore. Observations were carried out twice, once in February 1998 and again in August 1998.

2.3 OTHER DATA

2.3.1 MACROALGAL MAT DISTRIBUTION

The distribution of the main areas of macroalgal mats across the estuary was mapped using an aerial photograph taken in the summer of 1994 (Caudwell et al. 1994). The distributions shown were updated by personal observations (Figure 3).

2.3.2 SUBSTRATE TYPES

The substrate profile of the estuary was mapped using past studies (Cobb et al. 1979). The map produced was subsequently updated by personal observation and field data. Three main substrate types were identified - heavy black anoxic mud, silty grey mud and firm sand. The distributions are shown in Figure 4.

2.3.3 MONTHLY BIRD COUNTS

Past monthly peak counts from 1982 to 1998 were obtained from the local ranger, Les Hatton. Some data was missing from the data set (c. 40% before 1991), but the data could still be used to analyse long term trends. This data is shown in Figure 5. Decomposition analysis (see section 2.4.1) was used to fit missing data to the data set when required.

2.3.4 CLIMATE DATA

Monthly climate data was extracted from the Monthly Weather Report (1982 - 1993) published by the meteorological office. Data were obtained for maximum & minimum temperatures, absolute highest and absolute lowest temperature, rainfall, the frequency of snow, hail, frost and high gales and mean hours of sunshine per day. Data from 1993 to

Figure 3. Main areas of macroalgal blooms

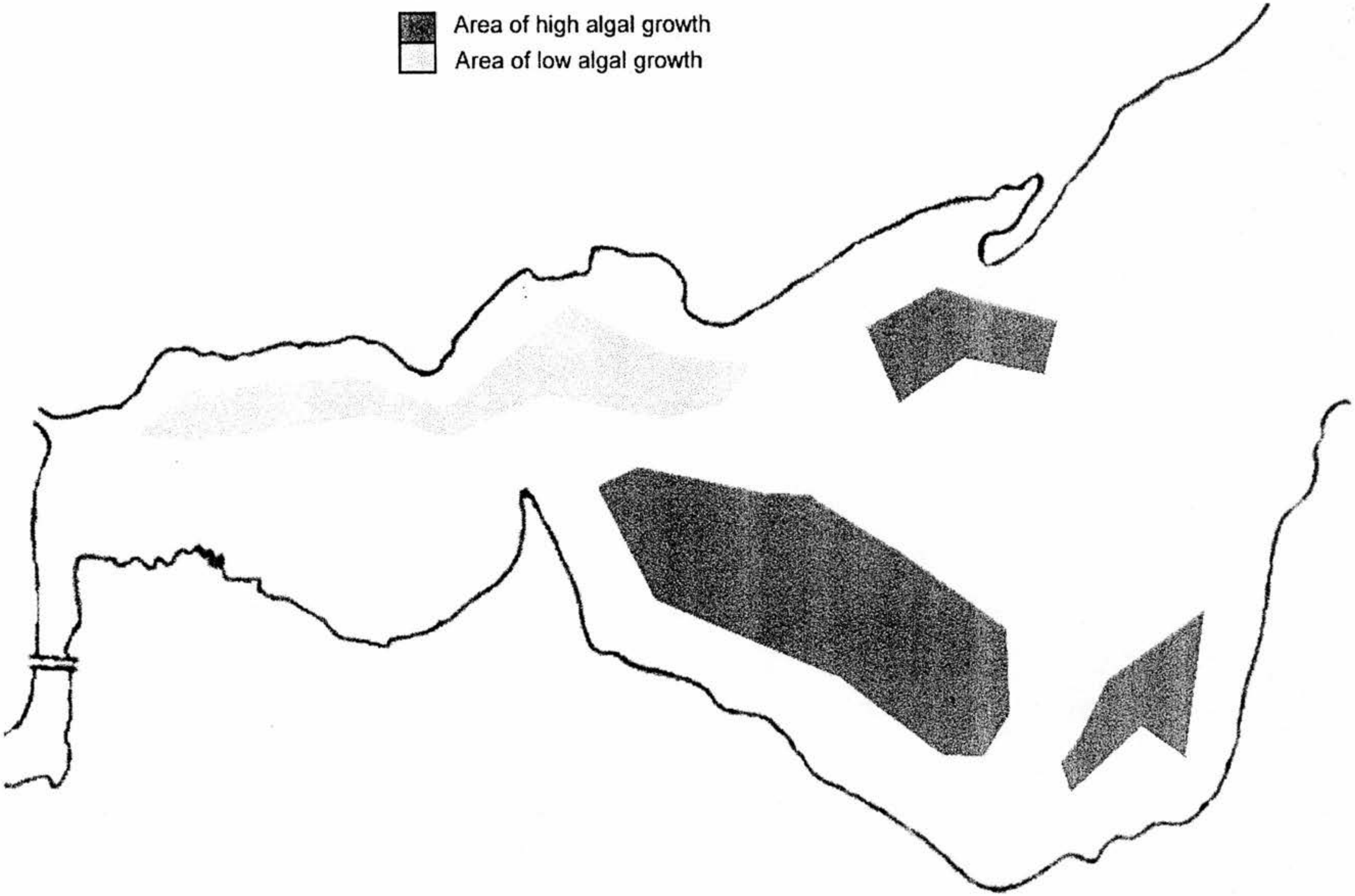


Figure 4. Distribution of three main substrate types
(updated from Cobb et al. 1979)

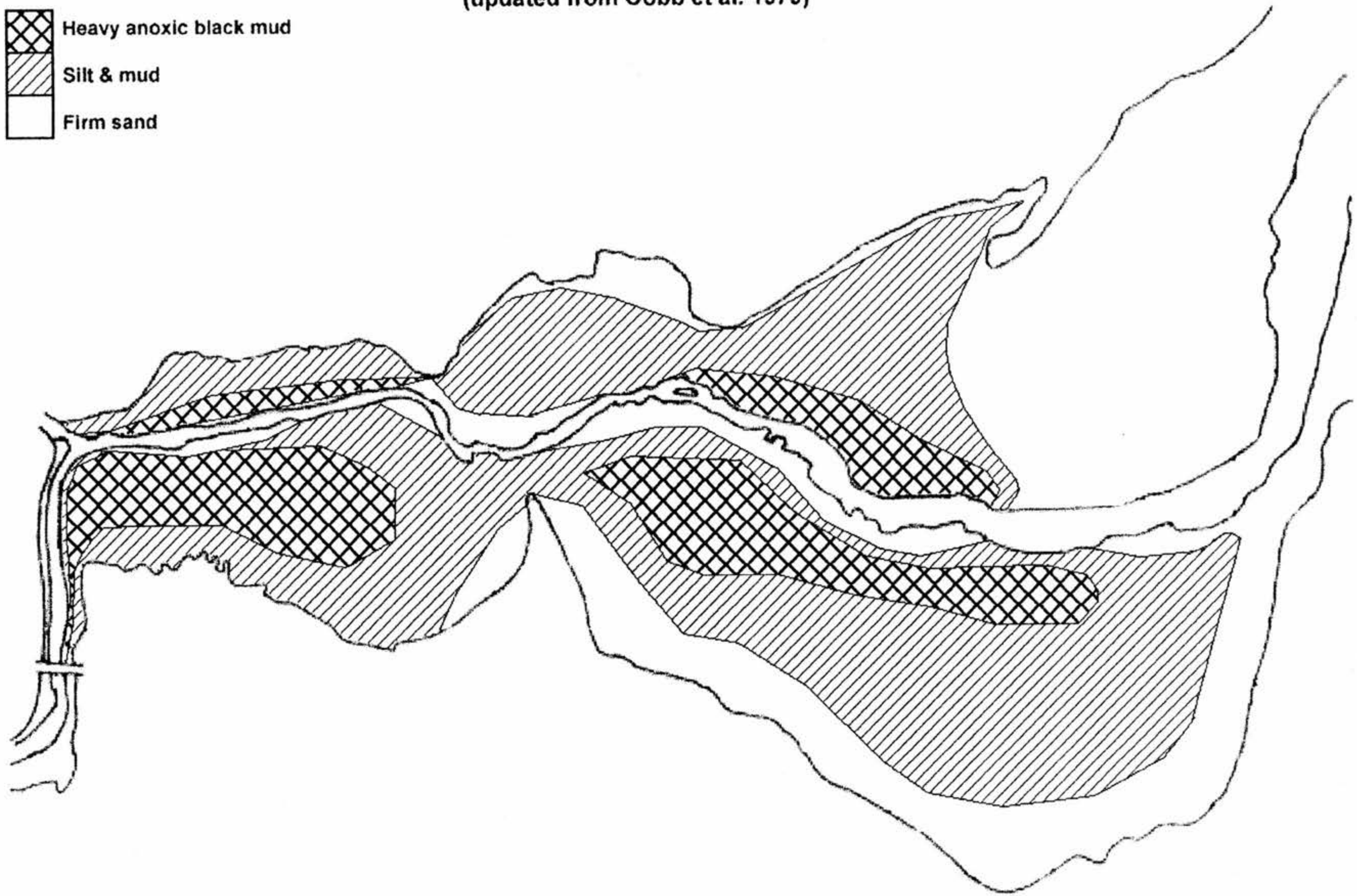
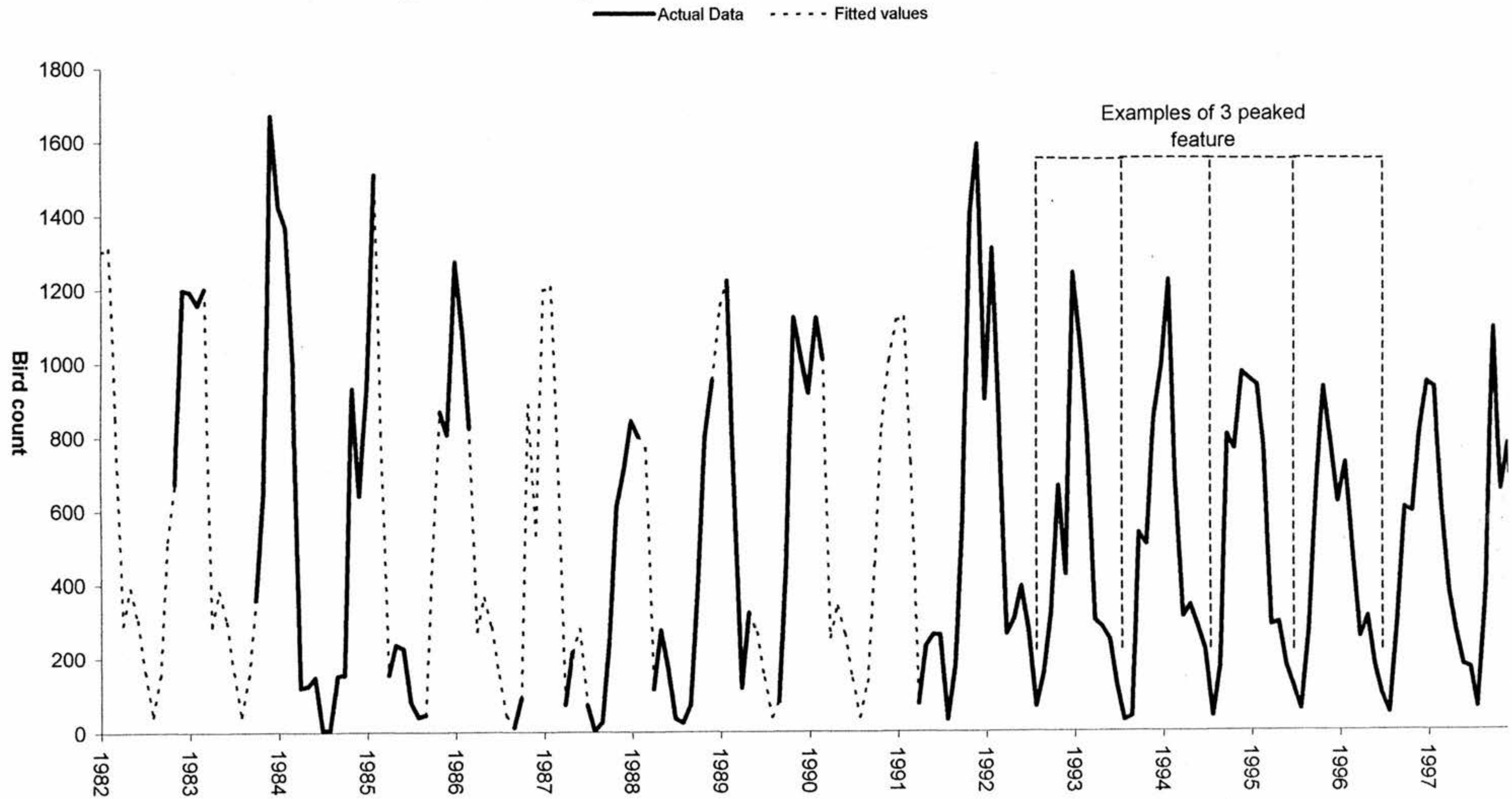


Figure 5. Monthly Peak Shelduck Counts between 1982 and 1997



1997 was obtained from the Edinburgh Meteorological Office. No data were available for the current year.

2.4 STATISTICAL METHODS

2.4.1 PEAK BIRD COUNT ANALYSIS

The monthly counts of shelduck were analysed to attempt to identify any long term trends in shelduck abundance. It was decided to do two different tests on the data to try to establish whether or not numbers were decreasing.

Firstly, the complete data set was analysed by decomposition which 'decomposes' the data into trend, seasonal and error components (Minitab Inc. 1996). Seasonal indices are calculated for each month and these are then used to calculate predicted values across the data set. A trend line is then fitted to the predictions and its accuracy is measured in three ways. Firstly, the mean absolute percentage error (MAPE) is calculated, representing the mean percentage error of the predicted values from the actual data. Secondly, the mean absolute deviation (MAD) is calculated which is the mean deviation of the predicted from actual data in the same units as the original data set. Lastly, the mean squared deviation (MSD) is calculated which is the square of the deviation of predicted from actual data. These three values give a measure of how closely the generated model fits the original data set and therefore, how trustworthy the fitted trend line is.

Secondly, a linear regression analysis was carried out using peak winter counts of birds during November to February. This period was chosen as it brackets the time after the shelducks have returned to the overwintering grounds from the moult, but before they have started to breed in spring. The data set was augmented by fitted values from the decomposition analysis. The use of peak winter counts served to remove the strong seasonal fluctuations in abundance caused by migration enabling a linear regression.

Spearman's rank correlation was used to test for associations between environmental variables and shelduck abundance.

3 RESULTS & DISCUSSION

3.1 SHELDUCK ABUNDANCE

A particularly marked feature of the data set was a repetitive three peaked rhythm through the winter and spring (see Figure 5). An initial peak in November was followed by the main winter peak in December or January and by a third peak in May or June. The initial peak may be due to the arrival and departure of transient birds which are using the estuary as a rest stop. Birds rung on the Eden which have not stayed, have been found to move on to the Solway Estuary to the south (L. Hatton, pers comm). The second peak is the main winter peak representative of the resident overwintering flock. The drop from this peak, (the lowest value of which usually occurs in April) is probably due to the dispersion of birds to nest sites. The third peak in May to June may be initially caused by failed breeders re-joining the non-breeding flock and by transient non-breeders again using the Eden as a rest stop as they begin to migrate at the end of June. Unfortunately, the nature of the data set did not allow closer scrutiny of this pattern, as many of the missing values before 1991 occurred during the middle of the year, meaning that counts for May to October or November were often missing. Counts on the Ythan estuary have also displayed some evidence of this pattern (Patterson, I.J., pers comm). The pattern was reflected in the daily counts of birds with a peak in January followed by a fall and a second peak at the beginning of June (see Figure 6 below).

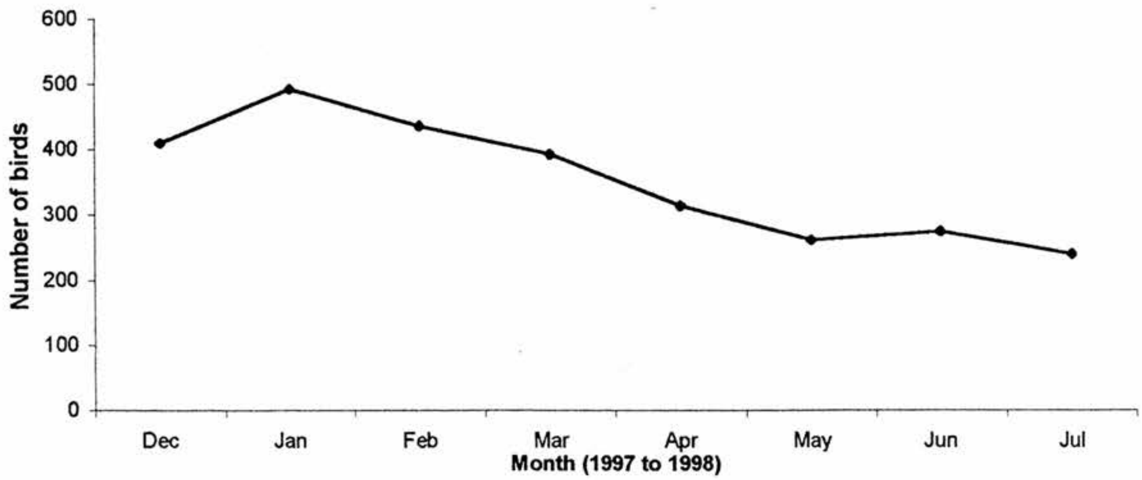


Figure 6. Peak monthly shelduck counts calculated from daily shelduck counts

The regression analysis of the peak winter counts showed a significant reduction in peak winter abundance on the estuary over time from 1982 to 1998 ($t=-2.20$, $p=0.046$, $r^2=25.6\%$). This shows a marked decline in abundance over time. Decomposition analysis showed a similar downward trend. The generated predicted values fitted the rhythm of the actual data well (MAPE = 83.6, MAD = 140.7, MSD = 39380.5, see Figure 7).

3.2 FLOCK DISTRIBUTION

Distribution maps were prepared by taking an average of the number of birds in each square across separate recording sessions at similar tidal states. This yielded maps of the mean flock distribution through the tidal cycle. There was no behavioural component to these observations. The distribution maps produced are shown in Figures 8a & 8b.

Maps of the feeding distribution of the birds were taken from Cobb et al. (1979, see Figure 9). Comparisons were possible but only at a rudimentary level as the current study mapped only the occurrence of the birds, whereas Cobb et al. mapped time spent feeding.

Flock distribution observations made in February 1998 showed the distribution of the winter flock before it began to break up prior to breeding. Flock size at this time was 363.6 (± 41.8 SD). The main roost site on Kincaple Flats was identified as a bay on the east side of Coble Shore (Figures 8a & 8b). Over half of these birds (about 150 to 200), moved to this site at high tide to roost. Some birds moved into the inner bay to roost on the salt marshes of Edenside flats but most remained in the outer bay. As the tide ebbed the birds progressively moved down through the intertidal area, following the water's edge. At low tide, the majority of the birds were seen feeding around the main channel, mainly on the northern side in an area north-east of Coble Shore. The rest of the birds spread out across the estuary with two more main feeding areas appearing, one approximately in the centre of the outer bay, north of the Balgove hide and the other east of Out Head. The birds tended to accumulate along the river channel, where thick silty mud from mussel beds predominates (Figure 4).

Distribution maps for August (Figure 8b) show the distribution of birds that have returned to the feeding grounds from breeding but have not yet migrated. The non-breeding flock has probably already migrated (see chapter 1). There is a marked reduction in birds numbers. At the start of August only 50 to 80 birds were left on the estuary and

Figure 7. Decomposition of monthly peak shelduck counts.

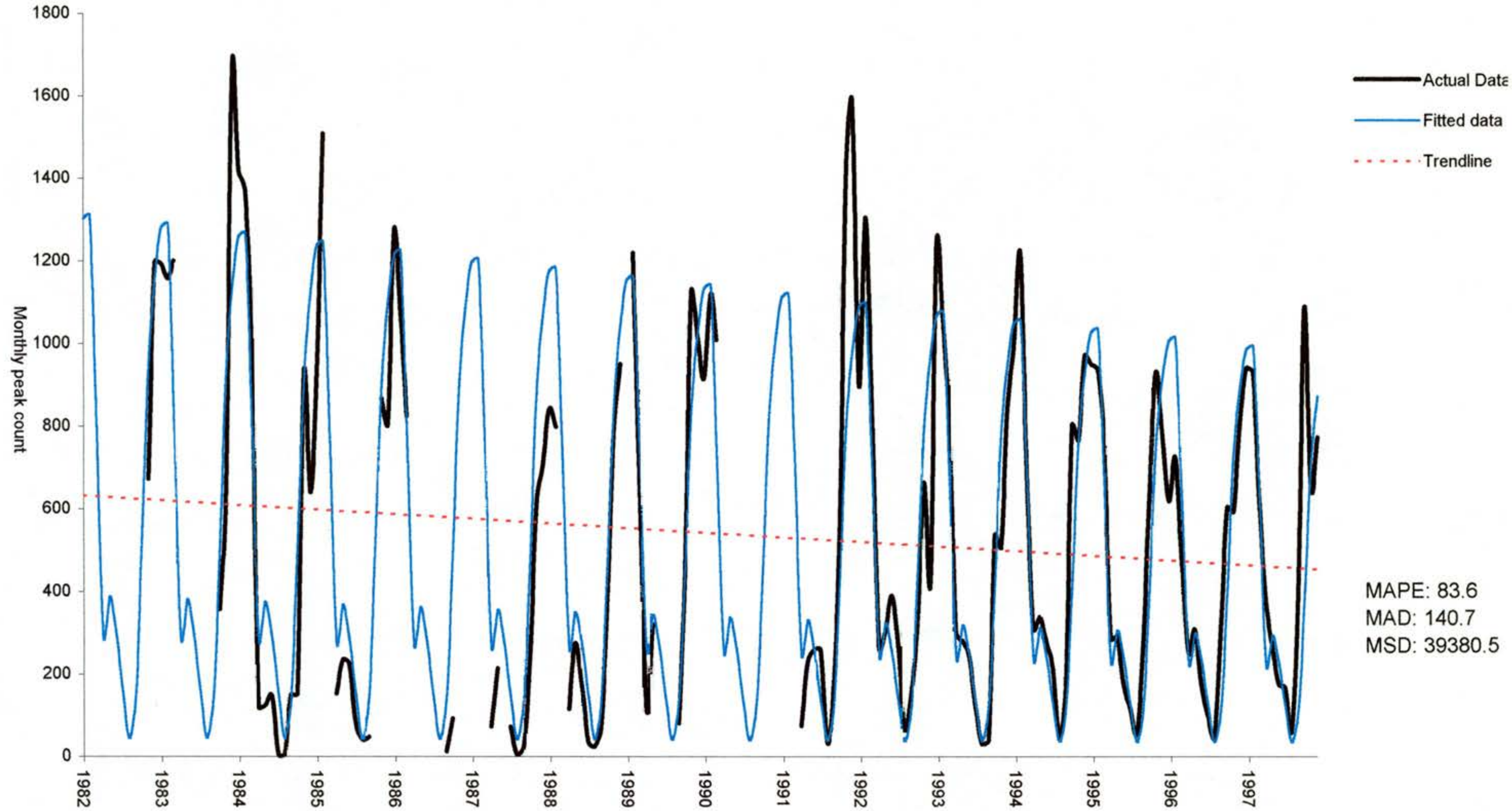


Figure 8a. Shelduck distribution in February 1998

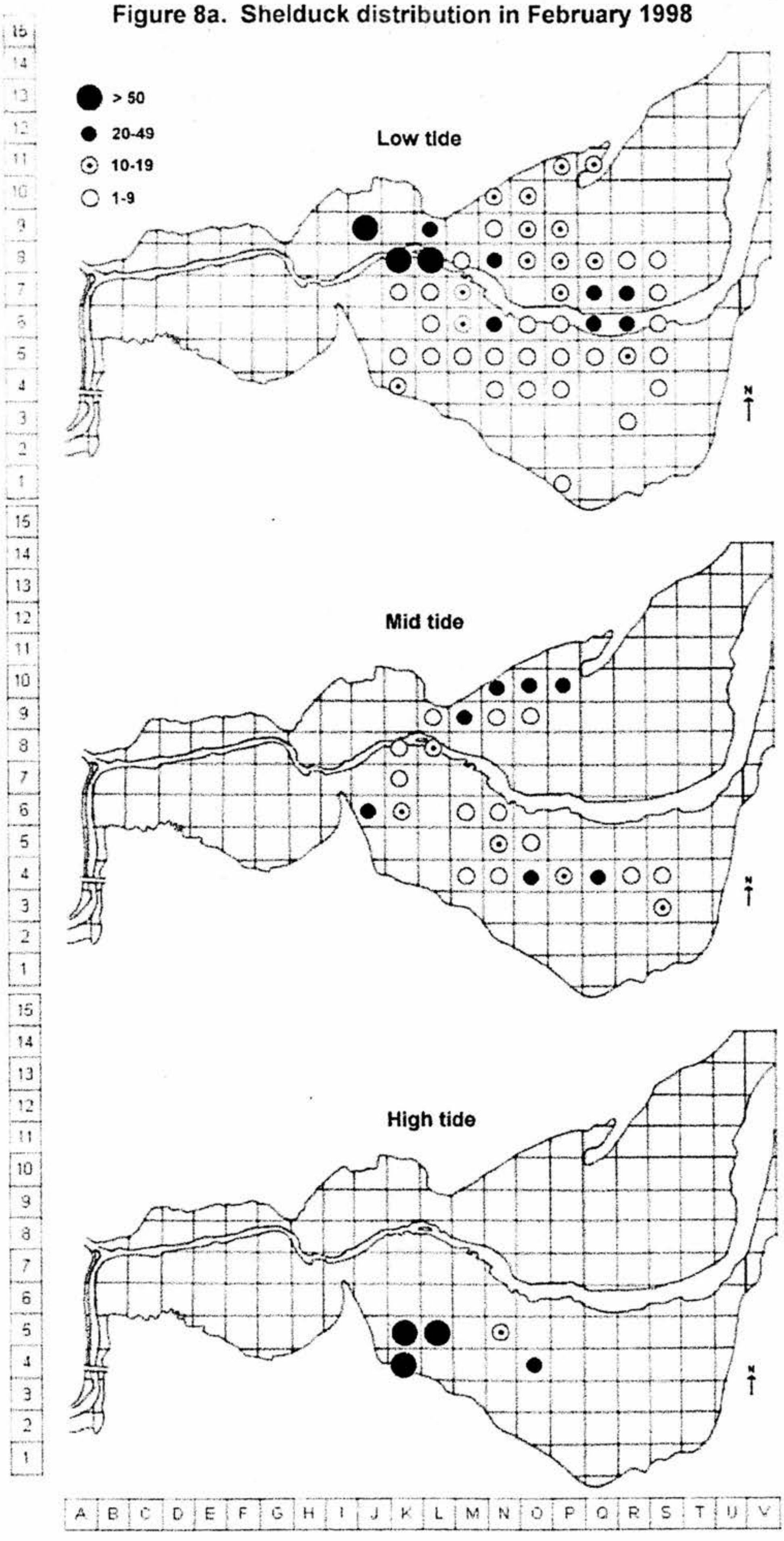


Figure 8b. Sheldduck distribution in August 1998

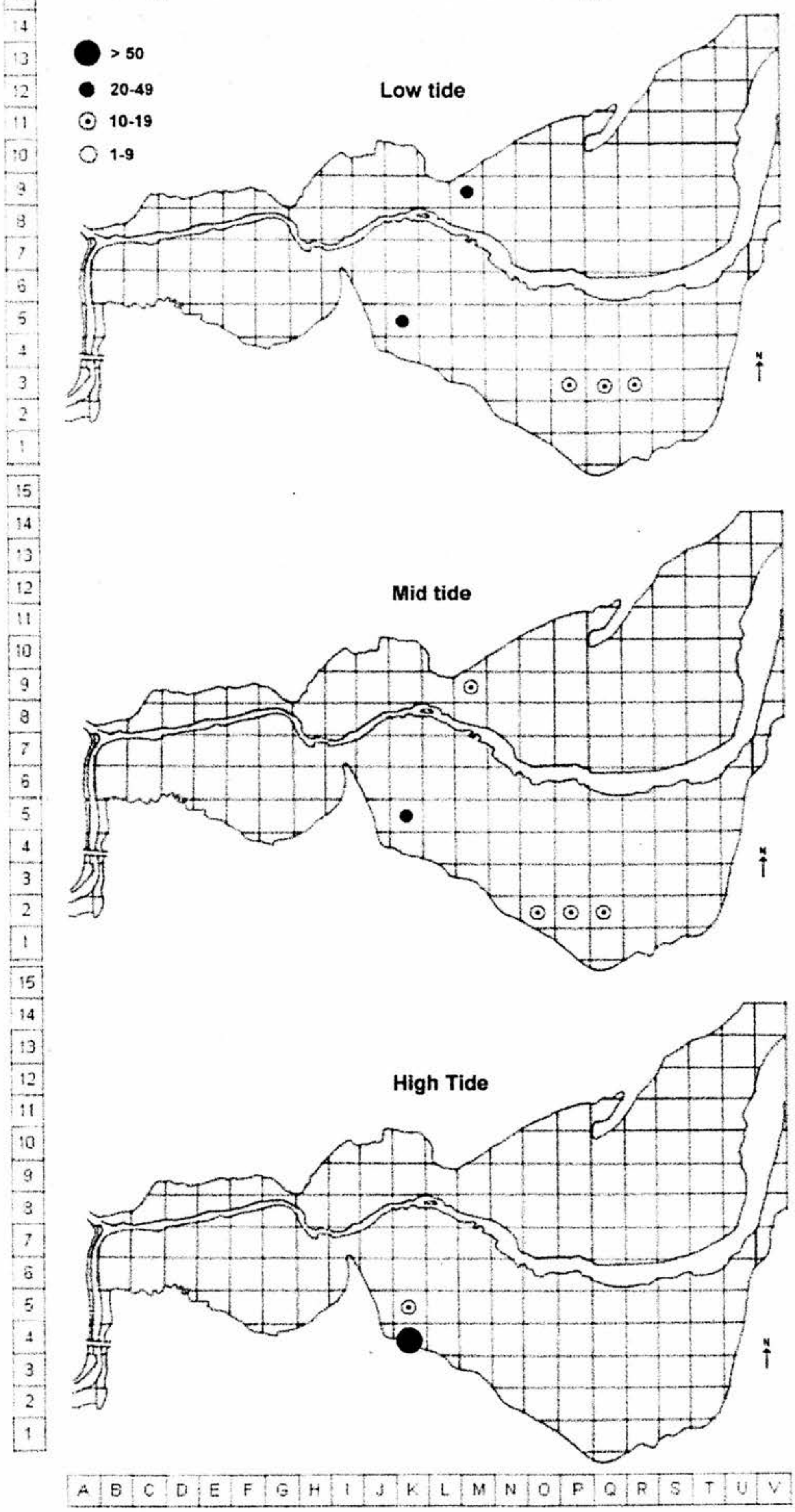
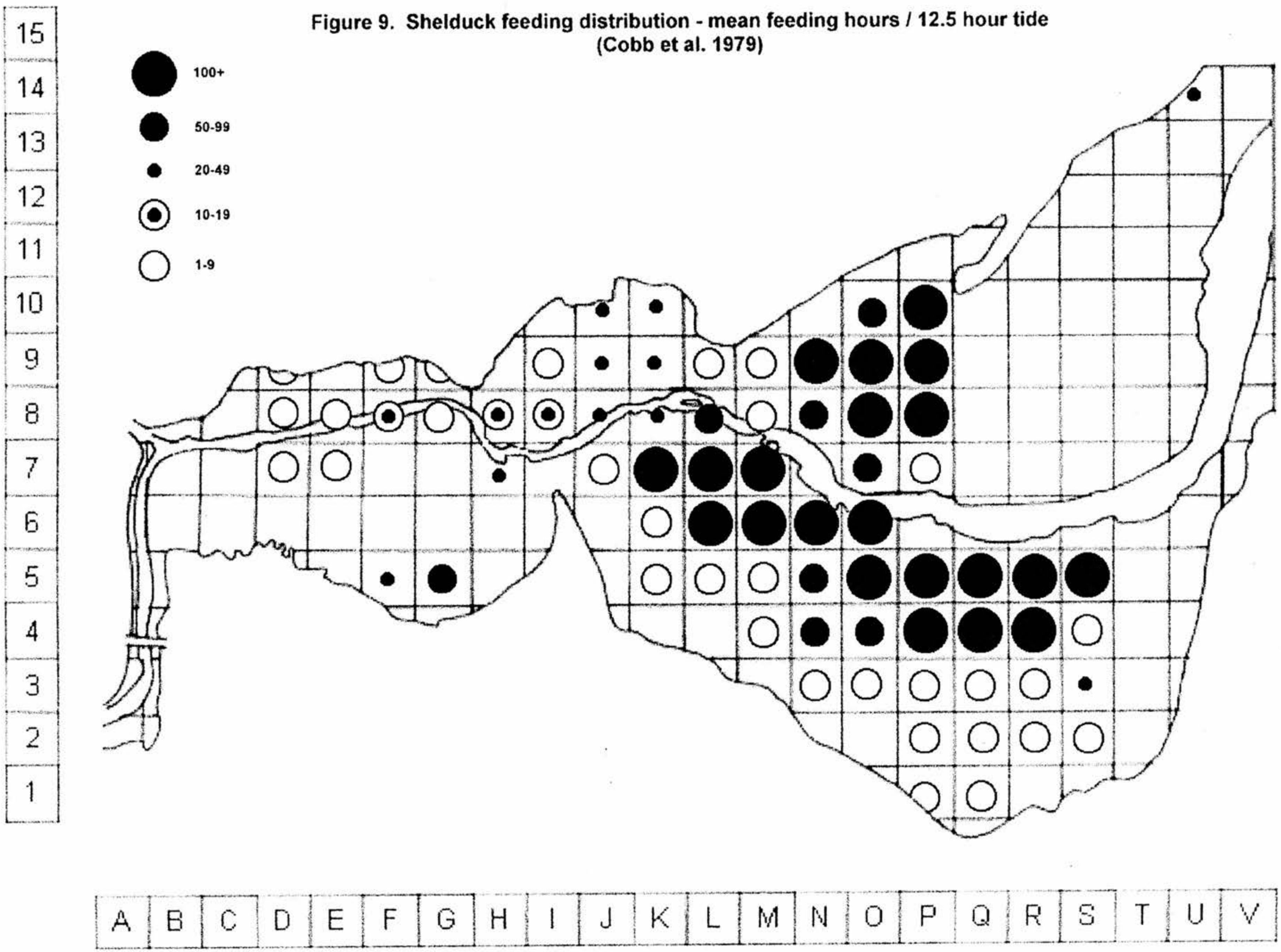


Figure 9. Shelduck feeding distribution - mean feeding hours / 12.5 hour tide
(Cobb et al. 1979)



numbers were decreasing rapidly. As can be seen the low tide distribution of the birds in August is very different to the distribution in February. Birds were seen at locations that were much further from the main channel. Most birds were seen in an area 200 to 300 metres north-east of the Balgove Hide. Distributions changed in a similar pattern to those in February with the birds being pushed back by the tide into the small bay on the eastern side of Coble Shore.

3.3 ENVIRONMENTAL EFFECTS ON SHELDUCK ABUNDANCE AND DISTRIBUTION.

Climate and macroalgal mat distribution were examined in relation to shelduck abundance. However, only climate could be examined retrospectively as no back data exists for macroalgal biomass in the estuary over the time period required.

From preliminary analysis of climate data versus bird abundance, it was decided to examine temperature effects in more detail. Lowest winter temperatures appeared to have some kind of association with peak winter counts as did rainfall (see Figures 10 and 11.).

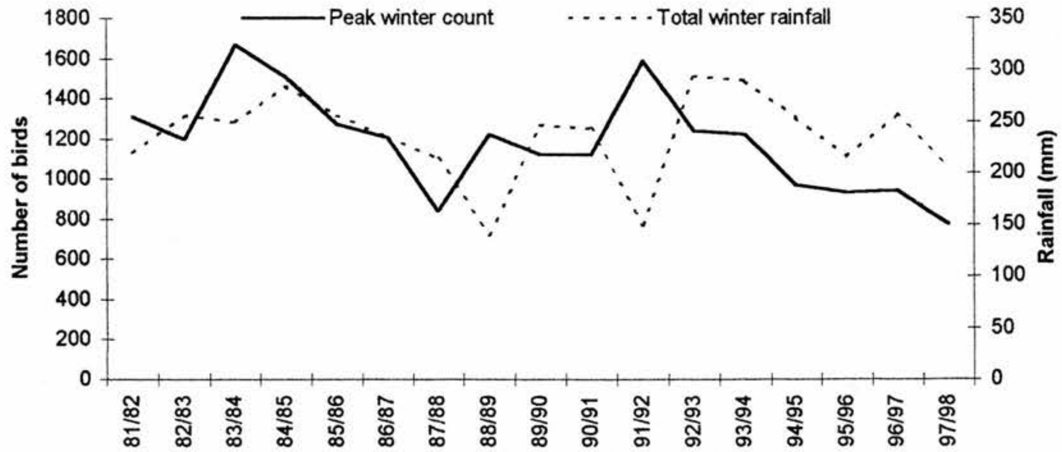


Figure 10. Total winter rainfall vs. winter abundance

It was hypothesised that if climate affected shelduck abundance, it was probably either by directly affecting food availability or by reducing breeding success. It was not possible to investigate the impact of cold on the birds' feeding directly as no data was available for invertebrate abundance over the period required. To investigate whether breeding success could be affected it was decided to use climate data from the period at the

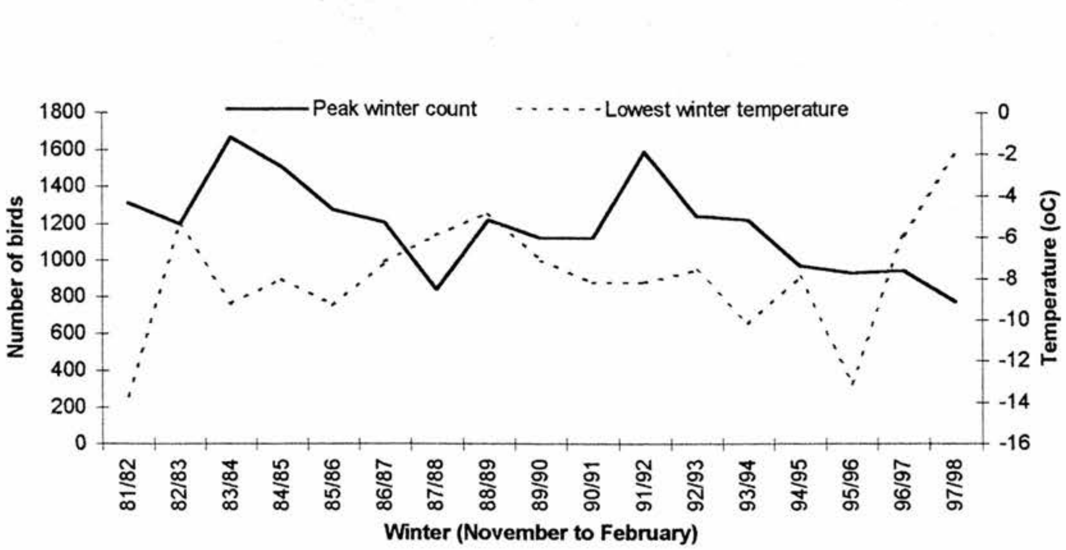


Figure 11. Lowest winter temperature vs. winter abundance

start of the breeding season. As described in chapter 1, shelduck pairs start to prospect for nest sites in March. If the birds were not in breeding condition by March, one might expect a lower breeding success for that year and this would be reflected in the counts. However, the effects would not appear until the first or second winter, when juveniles return to the flock. Lower breeding success would result in fewer juveniles returning to the estuary. Abundance would therefore decrease, unless there was a coincident increase in immigration.

There was no significant correlation between abundance and total winter rainfall. However, there was a strong correlation between the absolute lowest temperature and abundance of shelduck, but this relationship was indeed staggered (see Figure 12). Comparing the lowest temperature reached in March to the shelduck winter abundance two years later, gave a Spearman's rank correlation coefficient of $r_s = 0.753$, (DF=14, $p<0.01$). Total rainfall also showed quite a strong, significant correlation (see Figure 13) but for counts 1 year ahead ($r_s = -0.535$, DF=15, $p<0.05$). It may be that high rainfall has the more immediate effect of directly killing some birds through exposure or illness or by somehow reducing fitness sufficiently before migration to result in fewer birds returning from the moult.

3.3.1 MACROALGAL MAT DISTRIBUTION

Comparisons between the summer distribution of macroalgae and the distribution of the shelducks in August suggested that the birds were not frequenting areas of macroalgae. Although the numbers of birds were small, no birds were seen feeding over the main areas of macroalgae on Kincaple flats. The main cluster of birds was in a channel between two

Figure 12. Lowest March Temperatures vs. Peak Winter Counts

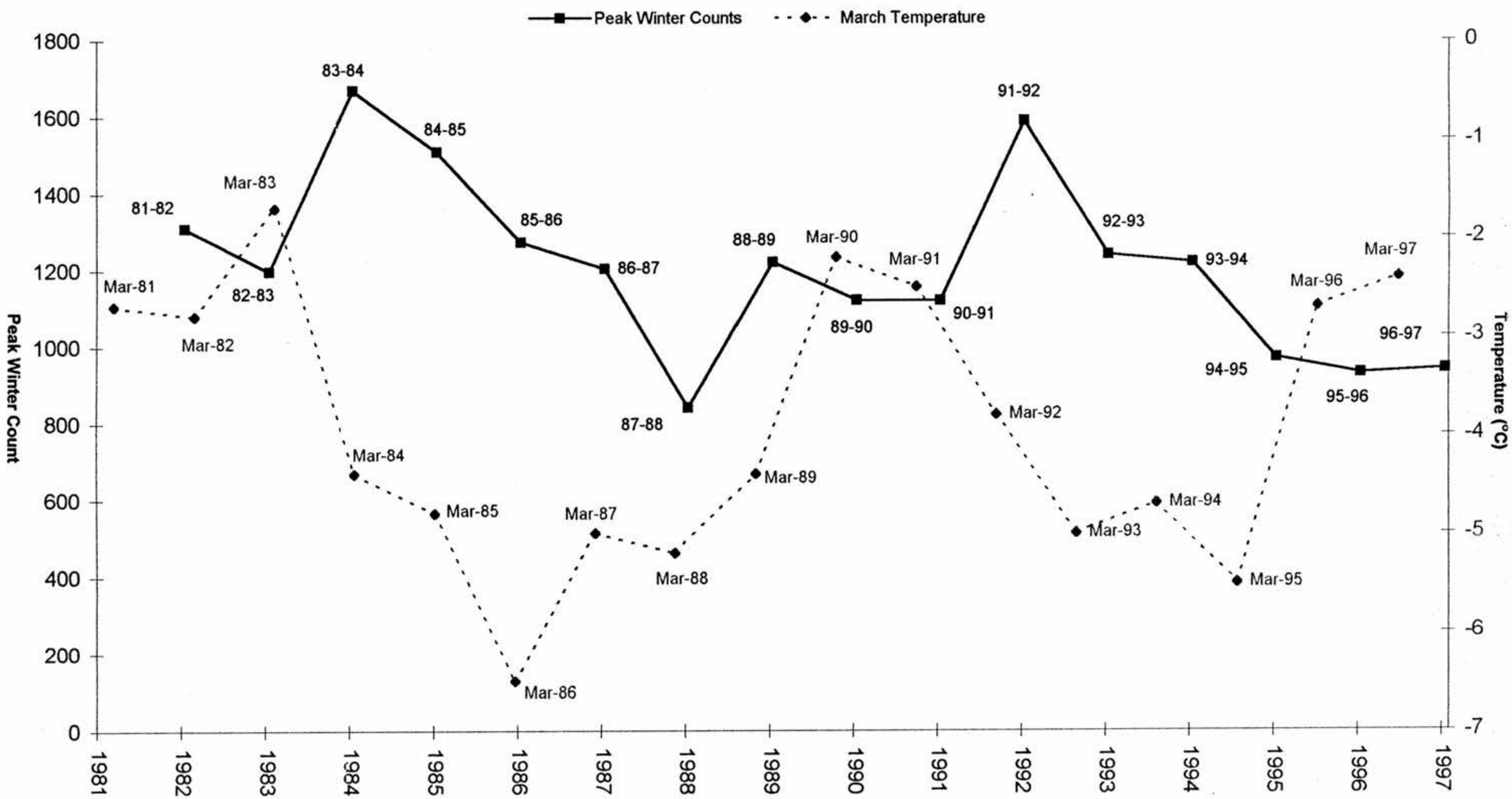
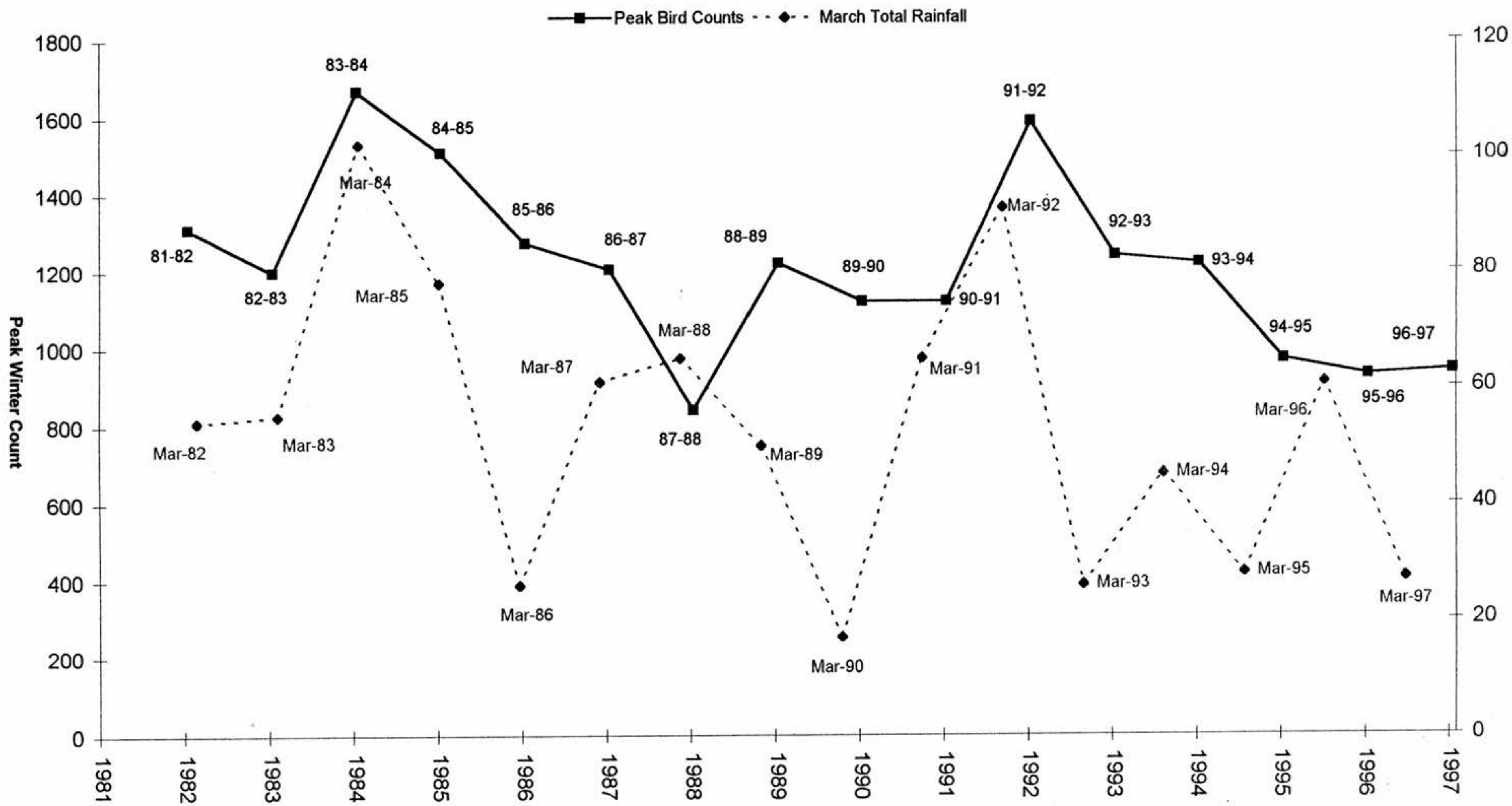


Figure 13. Total Rainfall in March vs. Peak Winter Counts



macroalgal patches on Kincaple flats. During the period when the macroalgae are not present (winter and early spring) the birds are distributed over the whole estuary.

4 General Discussion

Several authors have noted the possible connection between changes in the distribution of shorebirds and enhanced growth of macroalgae (Raffaelli et al. 1989; Raffaelli et al. 1991; Brydie 1996; Morand et al. 1996). Shorebird distributions may well be expected to change in response to a decrease in food availability. One might also expect that reduced food availability would function to increase emigration and decrease immigration in a bird such as the shelduck which has a very specialised diet. While largely free of the impact of predators, adult birds are extremely sensitive to changes in food supply (see chapter 1).

The analyses performed here suggest that, firstly, there has been a long term decline in shelduck abundance and secondly, there have been two main impacts on the population over the last two to three decades.

1. Severe cold has limited the population size, probably through the interaction of a./ reduced feeding due to mud freezing or possibly reduced prey populations and b./ reduced breeding success.
2. Rainfall may have had a role in limiting population size. Given that the birds nest in burrows or holes in the ground it may be that high rainfall causes nests to be drowned.
3. Eutrophication in the estuary may have reduced the feeding value of the mudflats, causing birds to select other sites. While this study was not able to make an examination of migration patterns or a more in depth study of the impact of macroalgae, the symptoms shown on the Eden match those shown in estuaries such as the Ythan Estuary in Aberdeenshire.

A more in depth study of the patterns and numbers of other shorebirds on the estuary and a much closer scrutiny of the migration and return of the shelduck population is warranted.

CHAPTER 3

BEHAVIOURAL OBSERVATIONS

1 INTRODUCTION

A knowledge of the behaviour and 'habits' of a species is essential if one is to make any predictions or comments about its general ecology. The behaviour of the shelduck has been described by Patterson (1977; 1979; 1982). The behavioural observations carried out here were intended to establish some baseline data, specific to the Eden Estuary, for the time spent on different behaviours. This will enable a closer monitoring of the shelduck population in the future and the effect of changes in the environment on their behaviour, specifically if the amount of time spent feeding changes.

2 METHODOLOGY

Behavioural observations were made from two main viewpoints, the Balgove hide and a hide owned by a local bird watching club situated west of Coble Shore overlooking the inner bay. In order to allow more detailed observations over time of individual birds, it was decided to catch and colour ring some birds. However, it proved difficult to catch the birds since they did not roost in consistently large numbers despite the addition of grain to several sites and proved wary of baited areas. Twelve birds were eventually caught and colour ringed using a cannon net. However, only three sightings were made of two of these birds afterwards and it is likely that the majority left the estuary after ringing.

A radio-tagging program was planned but this also proved to be impossible. I had hoped to catch females at the nest sites and radio tag them. However, repeated attempts to find sites resulted in no nests being found. No shelduck were seen at their usual breeding grounds at Earl's Hall Muir (NO 490 225) despite repeated visits. The majority of the broods which were seen later in the season did not survive to fledge and by mid to late August the shelduck had all left the estuary, an indication that breeding success was very poor.

These problems meant that data could not be gathered from the same bird over successive periods. Instead two types of observations were made. Firstly, continuous observations of a single bird for a set sampling period and secondly, observations of groups of birds. Behaviours for both types of observation were given codes (Table 2) and these were recorded using a program written in the Microsoft QuickBASIC programming language running on a Tandy portable computer.

Table 2. Behaviours and codes.

Behaviour	Roosting	Preening	Feeding	Vigilant	Aggression	Moving	Courtship
Code	1	2	3	4	5	6	7

Some of these categories were based on those described and used by Patterson (1982) and some derived from field observations of the birds as follows:

- Roosting

  Derived from field observations, this is easily seen as the bird 'lies' down with its feet tucked underneath it and its bill pushed under one wing. Occasionally birds classified as Roosting on mudflats rested on one leg but this was not usual.

- Preening

  Derived from fieldwork, this is an easily identified behaviour where the bird uses its bill to clean and settle its feathers. The shelducks often found a slight rise out of the water to preen on, making them easy to classify.

- Feeding

  Again derived from observations in the field, shelducks were deemed to be Feeding if they displayed the characteristic sieving behaviour, walking across the mud with the bill moving back and forth through the surface sediment.

- Vigilant

  Derived from fieldwork and from Patterson's descriptions (Patterson 1982), a bird was classed as being Vigilant when it paused, the head held high and feathers sleeked back. The breast band and belly stripe are usually quite visible. This is commonly described as the Alert posture.

- Aggression

  Shelduck show various types of aggressive behaviour, not all involving direct conflict. The easiest form of aggression to identify is a direct attack on another bird. However, this is most often preceded by a more ritualised threat, sometimes when the opposing bird is still some distance away. The behaviour seen most often was what Hori (1964) describes as Head-throwing. Only males were seen to display this behaviour. The head is drawn back and thrown rapidly and repeatedly upwards and forwards in a circular motion above the shoulders. The most commonly seen female Aggressive behaviour was Inciting, where the head is held low to the ground and moved from side to side vigorously. Inciting is usually followed by an attack from the female's mate on a nearby bird.

- Moving

  This category was used as a 'throw-away' category. Broadly, behaviours that did not fit into another category were classed as Moving. This was usually when the bird was simply walking across the mudflats. There were very few instances when a bird's behaviour could not be classified by one of the other categories. It was not intended to use this category in detailed analysis of scans, as it does not contain a single known behaviour type.

- Courtship

  This category was derived from fieldwork. Very little Courtship was seen during observations and it usually took the form of mutual preening by a pair. Pair status was most often identified by aggressive displays and by a conspicuous distance between the pair and other birds.

2.1 CONTINUOUS OBSERVATIONS

Continuous observations of 22 males and 15 females were made. Observations lasted for at least 30 minutes, except when the bird took flight and it was not possible to keep it in view. In this case the data were discarded. Data were gathered for a total of 18 hours 4 minutes. The longest scan period was 47 minutes. The subject bird was chosen the same way each time. The telescope was set up to point at a particular landmark. It was then panned left and the second bird seen was chosen for observation. If no birds were seen the landmark was sighted again and the telescope panned right.

Various other variables were noted at each session and these are listed below:

- Tidal state.

  Tidal state was recorded using a scale of 0 to 4, with 0 representing low tide, 2 representing half tide and 4 representing high tide. It was possible to place these quite accurately using a tidal prediction program on a computer. However, analyses of the effect of the tidal cycle on other variables were hampered by the generation of small sample sizes as the data set was manipulated. It was therefore decided to compress the data and combine tidal states 0 and 1 and states 3 and 4, to give three tidal states. This facilitated analysis by increasing the number of data points per category.

- Pair status

  This was simply whether or not the subject bird was paired or not. In cases where the bird was in a group it was sometimes necessary to observe the bird for a period before the recorded observations began to ascertain whether the bird was paired or not.

- Group size

  It was also noted whether or not the subject bird was in a group or not and how big the group was. Group size was organised into three categories. The first was 'No Group' where the bird was clearly not in a group at all, although it may have been with its mate. The second category, 'Small Group', was used when the bird was within 5 metres of up to 10 other birds. The third category, 'Large Group', was used when the bird was within 5 metres of over 10 birds. Shelduck react to the presence of conspecifics, particularly males to males, when there is still a large distance between them. Males could be seen to react to the presence of other males that were at least 100 metres away. It was decided to set a radius of 5 metres because observations showed that this was a reasonable radius at which groups became discrete from the rest of the population and could be followed reasonably easily.

- Sex

  The sex of the focal bird was also noted. Males and females were identified using the field characteristics described in Chapter 1.

The data obtained was processed using a custom program written using the Microsoft Visual Basic programming language that calculated the duration of each behaviour code within each sampling period.

2.2 GROUP SCAN OBSERVATIONS

Scans were also made of groups of birds. Groups were chosen by a method similar to that used in the continuous scans. The telescope was set up on a particular landmark and then panned left. The second discrete group of birds seen was used as the subject group. However, it proved very difficult to conduct observations for the full observation period because groups did not stay discrete. Birds seemed to be grouping by coincidence rather than by design. Therefore the group often broke up and reformed with different members. It was decided that the original group would still be considered extant if it was possible to track 5 or more of the original members. The figure 5 was chosen after some observations of pairs. Quite often two pairs of birds could be seen close together presumably on the border of territories. It was considered that 5 birds would imply the presence of a non-paired individual, which in turn would imply that the birds were not defending territories. Once a group had been chosen, scans were conducted for a target period of 30 minutes, every 5 minutes. The total number of birds in each behaviour classification was recorded at each scan.

2.3 STATISTICAL METHODOLOGY

Non-parametric analyses were used since much of the data could not be normalised successfully. A Kruskal-Wallis ANOVA was used to test for differences between tide states and group sizes. Spearman's rank correlation coefficients were used for correlations and when testing for differences between sexes or between paired and unpaired birds, a Mann-Whitney U-Test was performed.

3 RESULTS & DISCUSSION

3.1 GENERAL RESULTS

The median amount of time spent performing each behaviour was calculated from the continuous scan observations (Figure 14). Over 50% of the time within the 30-minute scan period was spent feeding and up to 20% roosting. However, although the scans were made during a period when birds were pairing up and starting to defend territories, no Aggression behaviour was recorded and there were only two instances of Courtship behaviour. In approximately 17 hours of focal observations, only 15 seconds of Courtship behaviour (0.02%) were recorded.

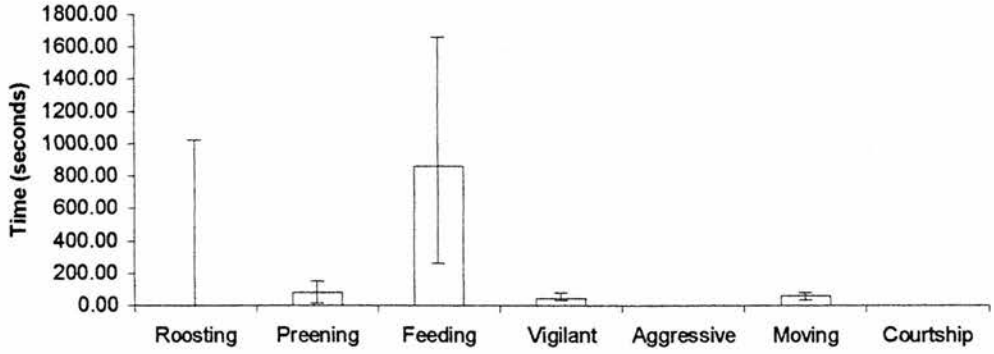


Figure 14. Time spent on behaviours calculated from continuous scan data. Medians with IQ range.

These results did not reflect the results of the group scans. Figure 15 shows the median number of birds for each behaviour code expressed as a percentage of group size calculated from the total number of birds across all group scans. It is probable that because the group scans were hampered by the problems discussed in the methodology, small sample sizes that had biases in the tide states were generated as the data set was split up during analysis. Of 13 scan sessions, 4 were at low tide and only 1 at high tide. Out of a mean of 84.4 birds per scan session, 46% of the birds seen were roosting and a third were feeding. Again, only a few birds were seen to be Aggressive and no Courtship was recorded.

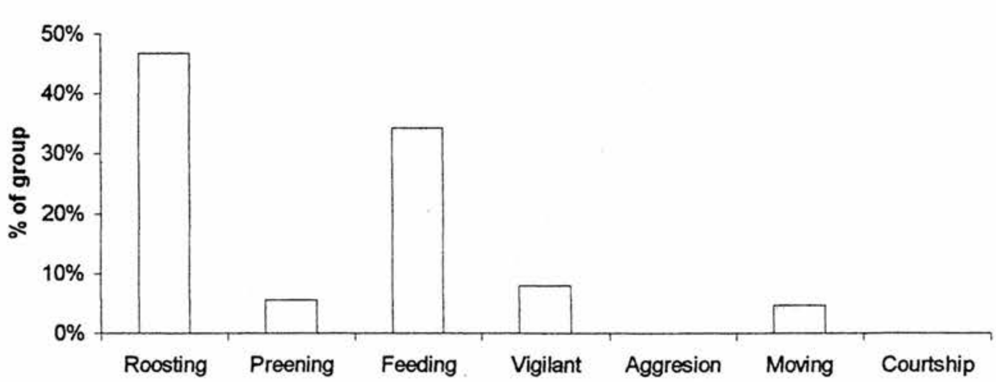


Figure 15. Number of birds per behaviour code as a percentage of group size calculated from group data.

The results of the group scans raise a question about the changes in the behaviour of the birds throughout the tidal cycle. Given that shelducks feed on the mud flats, are capable of upending only to a limited depth and that their feeding behaviour is tied closely to their prey (see Chapter 1), it is likely that the numbers of birds feeding would decrease as high tide approaches. However, the data from these scans show almost the opposite trend. Figure 16 shows the numbers of birds for different behaviours at different tidal states. Plots have not been included for Courtship (as none was seen) or Moving (as this category was not intended for analysis and does not contain records of a single known behaviour type).

As can be seen, the number of birds roosting is highest at low tide and decreases towards high tide. The peak at high tide is due to there being only a single group scan at high tide. Similarly, the pattern of feeding is the reverse of what one might expect with highest numbers feeding at high tide and lowest numbers at low tide. It is, however, difficult to attach any degree of confidence to the group scan results as the number of scans was small and the distribution of scans was biased towards low tide.

3.2 CONTINUOUS SCAN OBSERVATIONS

The results obtained from the focal scans of individual birds were more revealing. Between 6 and 9 thirty-minute scans were made at each tidal state, giving a better distribution of data. Data were first graphed to identify any overall effects of tide, group size, sex or pair status, then subjected to a more detailed analysis based on trends identified. Analysis of the time budgets was limited because the data were not independent. As each behaviour took up a proportion of the total scan period, time in one category could not increase without a corresponding decrease in other categories.

3.2.1 ANALYSIS OF TIDAL EFFECTS

Feeding times were lower at high tide than at low tide ($H=15.48$, $DF=2$, $p<0.01$, see Figure 17). Roosting and Preening times increased as the tide came in which might be expected as preening tends to be seen prior to roosting. Vigilant times did not seem to vary between tide states. Aggression and Courtship were not analysed because no Aggression was seen and there were only two instances of Courtship. Analyses of Roosting and Preening were not taken further because of the problem of independence discussed earlier.

There was no difference in the time spent Vigilant between sexes at similar tidal states ($w=253.5$, $n1=15$, $n2=22$, $p=0.3372$) or across tidal states within sexes ($H=4.23$, $DF=4$, $p=0.375$).

Figure 16. Numbers of birds performing each behaviour at varying tidal states calculated from group scan data. Medians with IQ range.

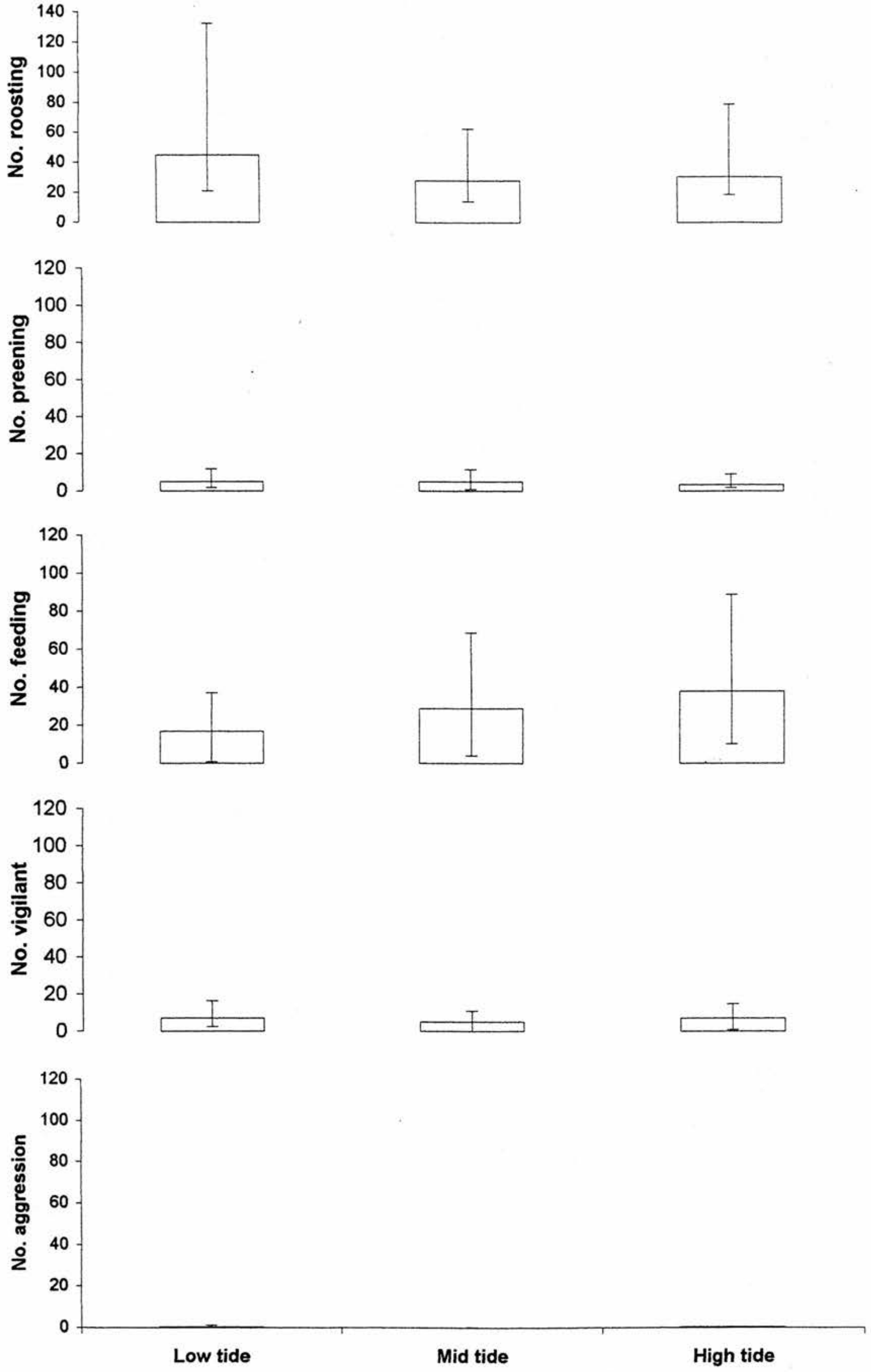
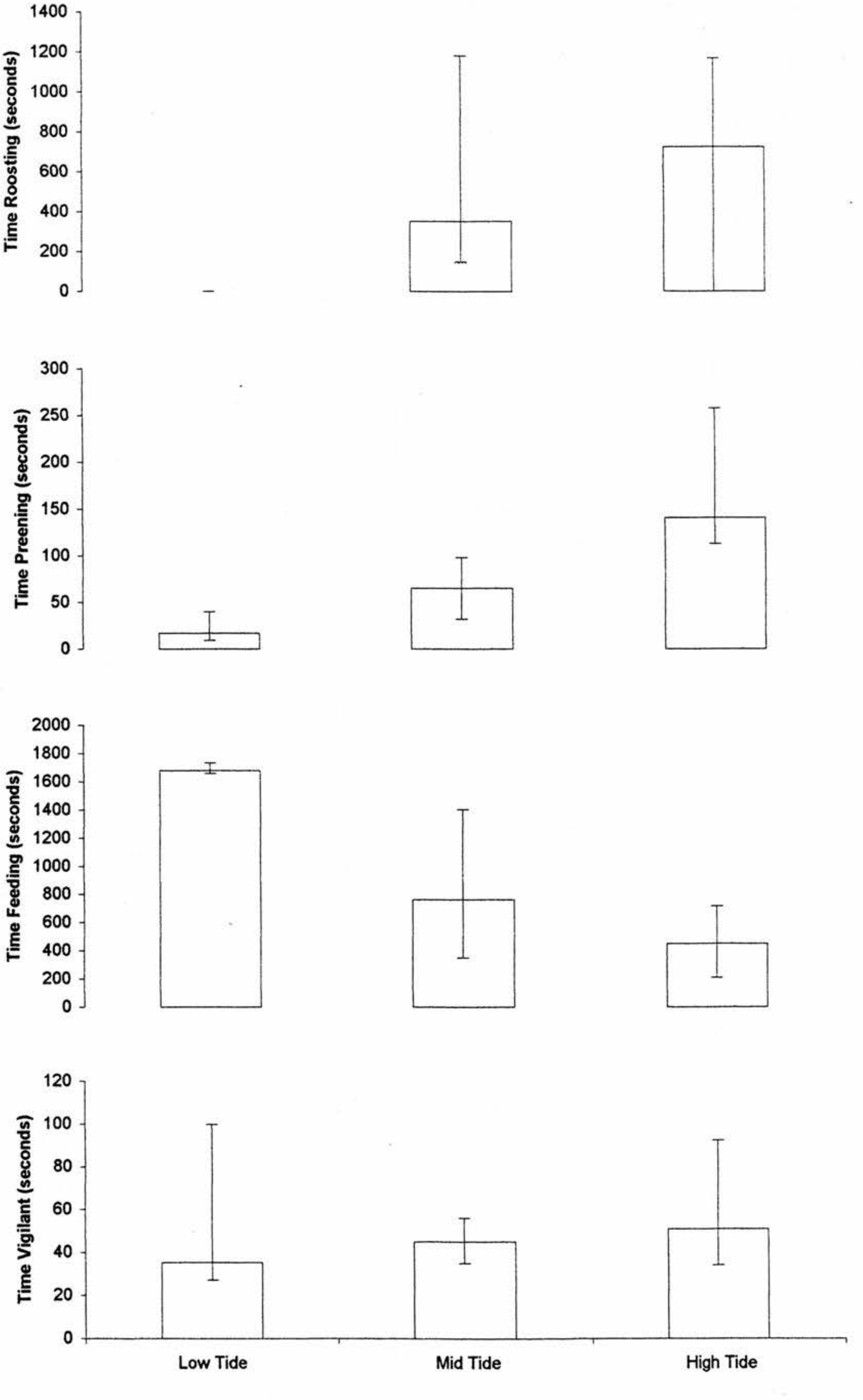


Figure 17. Times spent performing each behaviour across tidal states calculated from continuous focal scans. Medians with IQ range.



There was an interesting difference between male and female Feeding times throughout the tidal cycle. Females spent significantly more time Feeding at low than at high tide (H=13.27, DF=4, p=0.01) but males did not. There was also a significant difference in male and female Feeding times at mid tide with the males Feeding less than the females (w=35, n1=5, n2=4, p=0.02, see Figure 18).

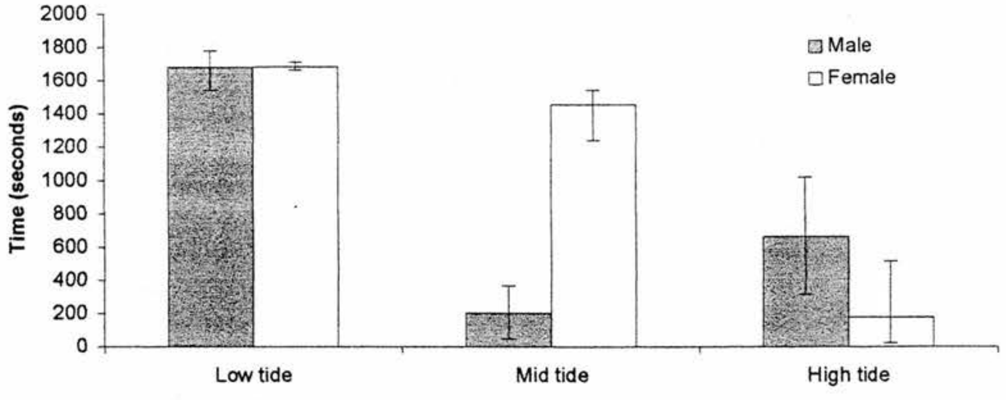


Figure 18. Times spent feeding by males and females. Medians with IQ range.

3.2.2 Analysis of Group Size Effects

There was a significant difference in time spent Feeding by males in different group sizes (H=6.11, DF=2, p=0.047, see Figure 19) with males in large groups spending less time

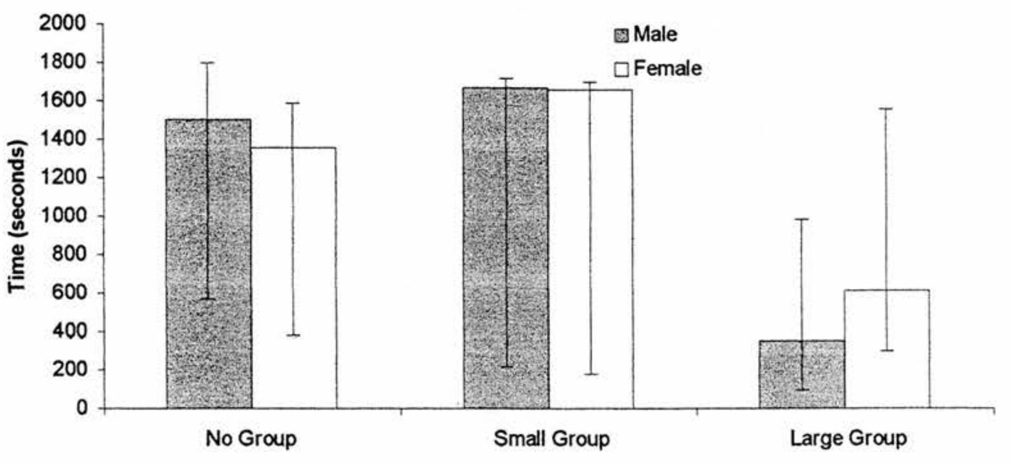


Figure 19. Feeding times in different group sizes by sex. Medians with IQ range.

Feeding than solitary males or males in small groups. Females showed a similar pattern but this was not significant.. There was no difference in Feeding times between sexes within groups (No Group: w=28, n1=5, n2=7, p=0.5160; Small Group: w=27, n1=5, n2=6, p=0.6481; Large Group: w=44.5, n1=5, n2=9, p=0.3856).

There was a significant difference across groups in time spent Vigilant by females (H=9.06, DF=2, p=0.011) with females in smaller groups spending less time Vigilant than solitary females or females in large groups. However, there were no differences in time spent Vigilant between sexes across groups (No Group: w=34, n1=5, n2=7, p=0.8708; Small Group: w=20.5, n1=5, n2=6, p=0.0996; Large Group: w=39, n1=5, n2=9, p=0.8938). Figure 20 shows the differences between male and female Vigilant times in different group sizes. Although the differences are not significant (see above) males and females showed opposing vigilance times.

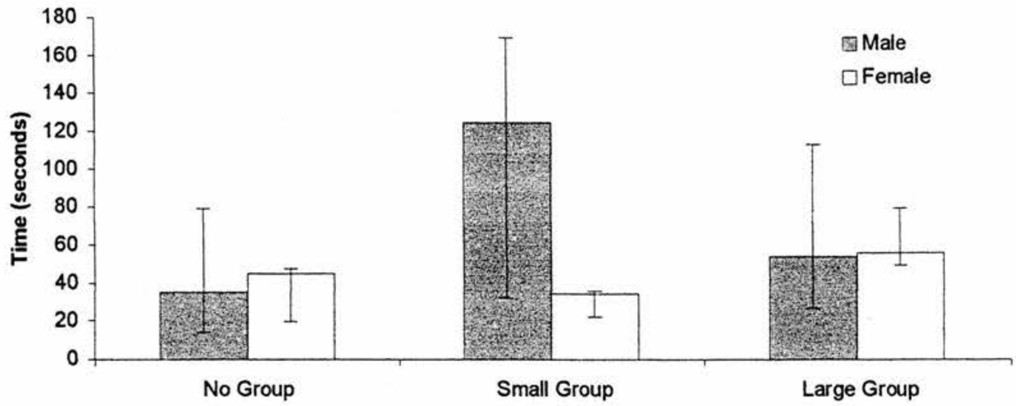


Figure 20. Times spent Vigilant in different group sizes by males and females. Medians with IQ range.

3.2.3 Analysis of Pair Status Effects

Analysis of the times for all birds by pair status did not reveal any significant trends. However, when the data was subdivided by sex and pair status it was found that paired males were more Vigilant than unpaired males (w = 97, n1=12, n2=10, p=0.0076) as might be expected as the breeding season progresses. Paired males were also more Vigilant than paired females (w = 116, n1=8, n2=7, p=0.0128). No significant difference was found between paired male and paired female feeding times or between paired and unpaired males or paired and unpaired females.

3.2.4 Problems with the Analyses

Statistical problems were encountered in the analysis of the data. Due to the lack of a reliable and powerful non-parametric 2-way ANOVA , analysis was limited to using multiple 1-way Kruskal-Wallis ANOVAs, Mann-Whitney U-Tests and Spearman's rank correlations. A Friedman analysis (a non-parametric equivalent to the 2-way ANOVA) was performed but did not prove to be accurate or powerful enough to reliably detect trends. Performing multiple tests rather than a single 2-way test increases the probability of making a Type 1 error. It is possible to apply a Bonferroni correction to the results but this makes it extremely hard to obtain significance without an extremely strong association between variables. Applying Bonferroni corrections to these results makes the majority of the tests performed not significant.

3.3 GENERAL DISCUSSION

3.3.1 TIDAL EFFECTS

The tidal cycle seemed to have a broad effect on Roosting, Preening and Feeding. One might expect that Roosting would increase and Feeding decrease as the tide covers the birds' feeding grounds. Preening seems to be positively correlated with Roosting, following much the same pattern. Vigilance did not show a tendency to vary with tidal state, which fits with the general behaviour of the birds. They group together at roost sites as the tide comes in. It is reasonable to suggest that, since the adult shelduck has no real predators on the Eden, vigilance is more a function of the breeding season and is directed at conspecifics. However, as the breeding season progresses, pairs form and leave the flock, returning to their nest sites during high tides. Therefore, it is probable that the roosting groups recorded towards the end of the sampling period were composed of non-breeders that would not be expected to vary their levels of vigilance.

The difference between male and female Feeding times at mid tide may be a function of different feeding patterns between the sexes (see Figure 18). The difference in Feeding time at mid tide is clear. The ranges are large which makes theorising difficult, but it is reasonable to suppose that females, given the investment they make in egg production, have higher energy requirements than males and would therefore feed for longer. Males, on the other hand, would need to make the choice between energy intake and vigilance. If low tide is the most profitable time for feeding , males may balance feeding with high intake at low tide against vigilance at mid tide.

3.3.2 GROUP SIZE EFFECTS

Group size primarily had an effect on vigilance. For example, females were less Vigilant in small groups than when solitary or in larger groups. This implies a link with pair status. (Figure 20 shows the median vigilance times of males and females of different size groups). Although the trend is not statistically significant, males spent more time being Vigilant in small groups compared to larger groups, the opposite of the pattern shown by females. The explanation for this is most likely to be found in the composition of the different groups. Small groups are more likely to be groups of paired birds, hence the males display higher vigilance, whereas large groups, given the timing of the sampling period, are more likely to be composed of unpaired non-breeders and juveniles. The groups of birds observed, as discussed in the methodology, were not consistent over time, tending to break up as birds moved in different directions while feeding. Smaller groups may have been pairs meeting on territory overlaps or before territories were fully established. The data set showed a tendency for paired birds to be in smaller groups and unpaired in larger but the trend was not significant.

The tendency for males to feed more when solitary or in smaller groups than when in large groups may be a function of tide. Larger groups tended to be seen at higher tide states (not significant) and therefore feeding would decrease as the mud flats were covered by water.

3.3.3 PAIR STATUS EFFECTS

Pair status was expected to be the most influential factor on vigilance times and this proved to be the case. Paired males were significantly more Vigilant than unpaired males. This suggests a strong link to breeding success with males having to invest more into vigilance in order to maintain a territory and mate. Interestingly it seems that there is a 'division of labour' between females and males in their roles on the feeding grounds. Paired males were significantly more Vigilant than paired females. Linking this with the difference in feeding pattern (described above) implies that males are responsible for territorial and mate defence while the female feeds to achieve breeding condition.

CHAPTER 4

INVERTEBRATE SURVEY

1 INTRODUCTION

The diet of the shelduck has been studied closely at several sites throughout its range (see Chapter 1). The birds' dependence on a narrow range of prey items renders them vulnerable to environmental changes which affect their food supply. In this study I decided to try to establish the abundance of these prey items according to the occurrence of the shelduck. It was hoped that this would help to establish whether the birds were using the available resources as one would expect, given their dietary requirements.

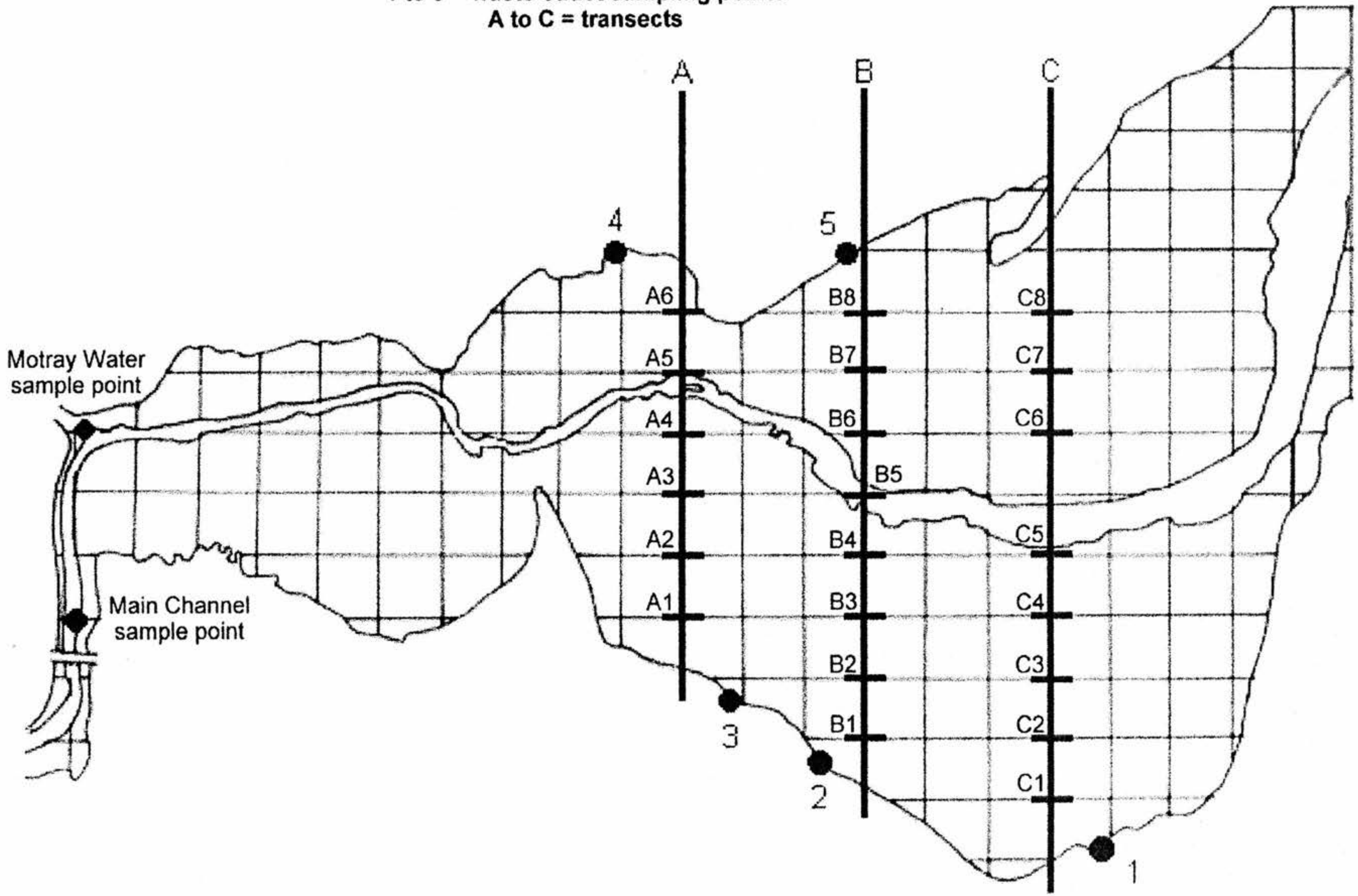
2 METHODOLOGY

A transect survey was carried out to ascertain the abundance of the main prey items of the shelduck (as Buxton & Young, 1984) and also the levels of ammonia, nitrates, nitrites and phosphates. The water chemistry methodology and results are presented in Chapter 5. It was decided to survey along 3 separate transects (see Figure 21), positioned to bisect the 3 areas of the outer bay where the shelduck fed most. The low tide distribution map for the shelducks was chosen to decide the location of the transects as the shelducks fed most on the ebb and at low tide (Bryant et al. 1975; Patterson 1982). The survey points along the transects corresponded to the grid used for the distribution maps and were therefore at 200m intervals.

Four 10cm cores were taken at each transect point to a depth of 15cm. One end of the core tube was marked with indelible marker before the sampling sessions began. The core was then thrown back over the shoulder and the core taken using the marked end. This method had two advantages. Firstly, it was easily repeatable while providing relatively unbiased samples. Secondly, it ensured that the samples were within a reasonable distance of the transect point.

Cores were sieved in the laboratory using a 1mm sieve and counts were made of *Hydrobia ulvae*, *Corophium volutator*, *Nereis diversicolor* and *Macoma balthica*. It proved impossible to make accurate counts of *M. balthica* due to a layer of *M. balthica* shells between 10 and 15 cm depth. It was found that many clams were missed or dead clams erroneously included in the counts, making reliable figures difficult to obtain and therefore it was subsequently

Figure 21. Transect locations and sampling points
1 to 5 = waste outlet sampling points
A to C = transects



decided not to count *M. balthica.* Abundance per square metre for each species was calculated from the average of the 4 core counts for each sampling site.

3 RESULTS AND DISCUSSION

Invertebrate abundance was mapped for each species and these are shown in Figures 22 to 24. It was possible to compare the distributions obtained here with maps from previous studies, enabling some investigation of changes in abundance over time.

3.1 INVERTEBRATE ABUNDANCE

3.1.1 NEREIS DIVERSICOLOR

The abundance of *N. diversicolor* was extremely low. Only one specimen was found in a sample tube, if specimens were found at all. Abundance per square metre was calculated as 78 per m^2. The presence and absence of *N. diversicolor* from the transects was quite marked as can be seen in Figure 22. Its presence was recorded at only a single point on transect C on the northern shore at one of the areas where shelduck spent the majority of their time at low tide. Its occurrence was highest along transect A where its presence was recorded 3 times.

3.1.2 COROPHIUM VOLUTATOR

C. volutator was completely absent from transect A and only occurred at low abundance on transect C at 3 points. Abundance ranged from 78 to 855 per m^2. The highest abundance was found on the northern side of the central river channel. This coincides with the area of high shelduck occurrence in the centre of the outer bay of the estuary.

3.1.3 HYDROBIA ULVAE

H. ulvae was the species found most often along the transects. Abundance ranged between c. 450 and >13000 per m^2. Mean abundance across all transects was 2645 per m^2. The presence and absence of this species was expected to coincide with the distribution of the shelducks but it was found that the areas of highest abundance were not areas frequented by the birds. The shelducks were seen in areas where the abundance of *H. ulvae* was between 2000 and 3000 per m^2. Shelduck were not recorded at all in the areas of highest *H. ulvae* abundance.

Figure 22. *Nereis diversicolor* **abundance**

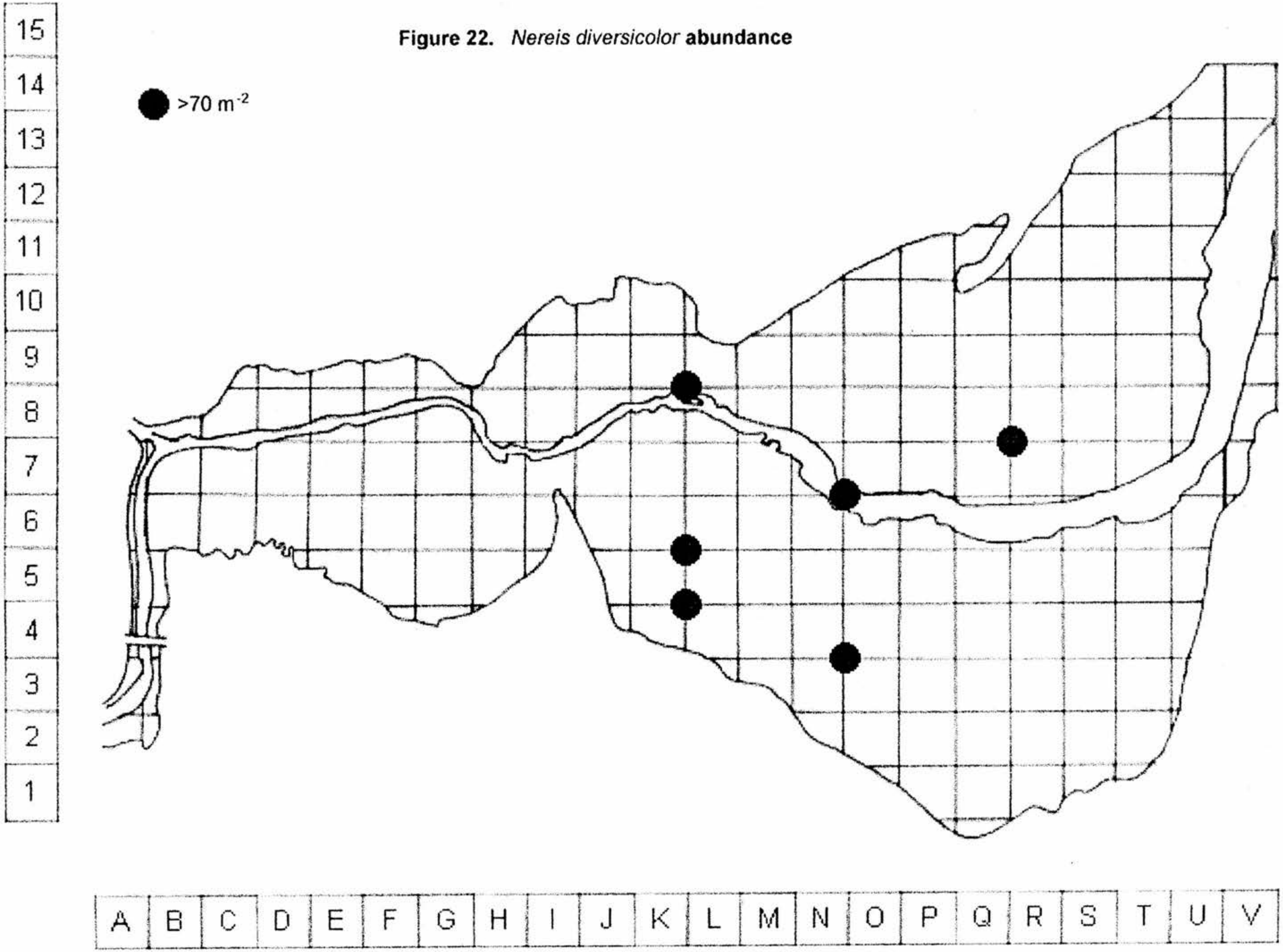


Figure 23. *Corophium volutator* **abundance**

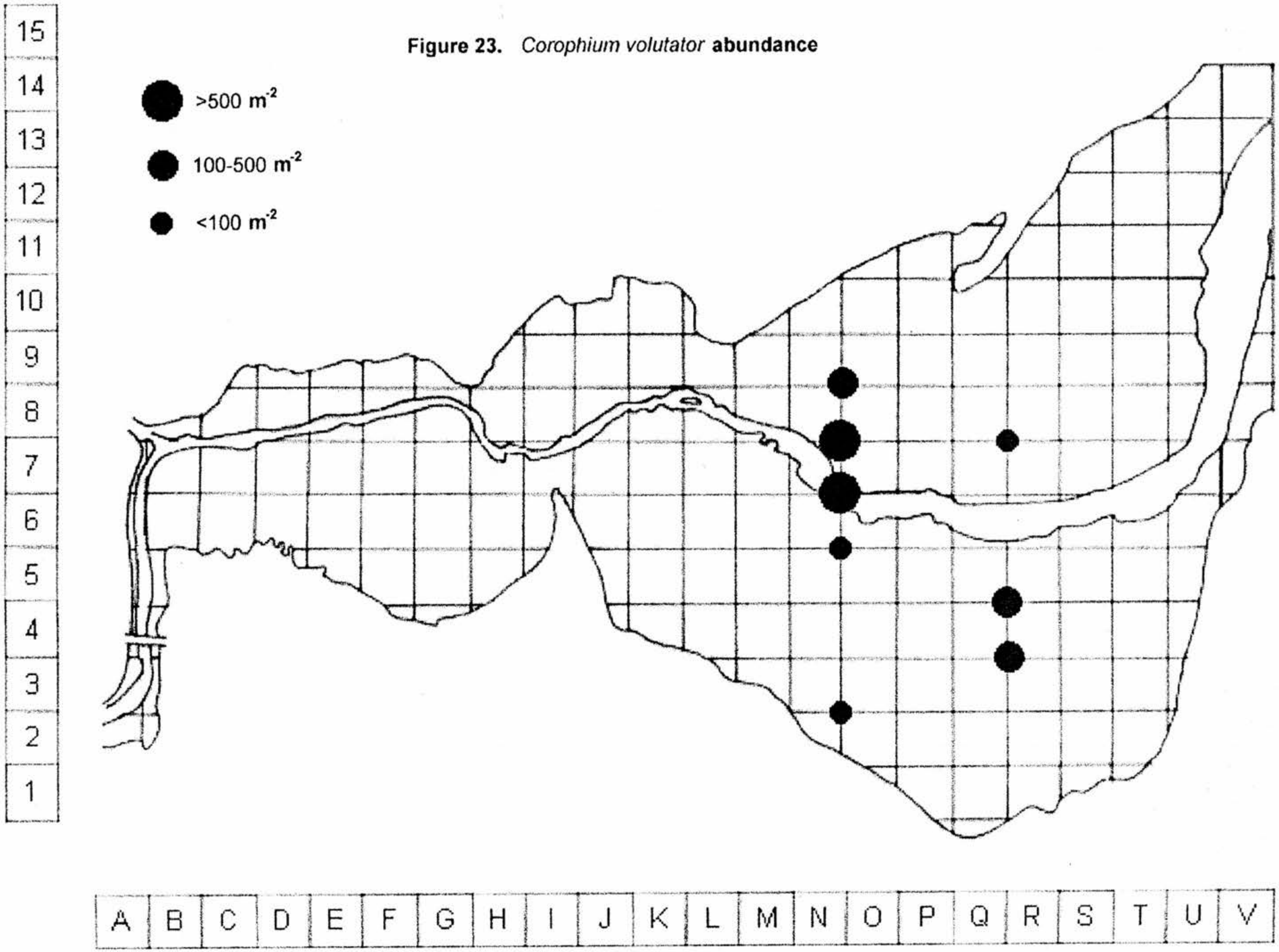
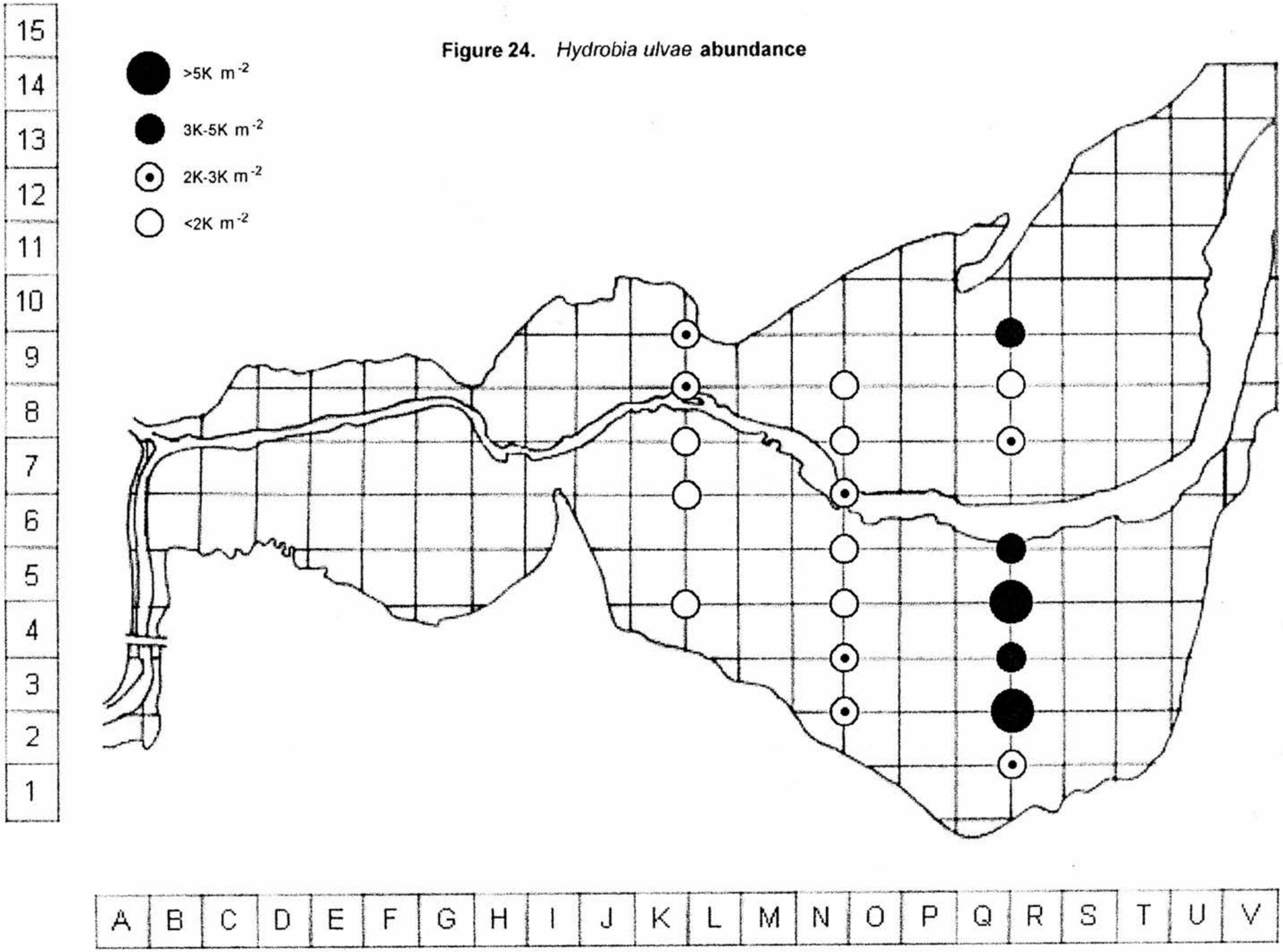


Figure 24. *Hydrobia ulvae* **abundance**



3.1.4 SUBSTRATE TYPE AND MACROALGAL MATS

It was not possible to make comparisons between abundance and algal mat distribution as the survey was carried out before the algal mats grew. Comparisons with substrate type show a tendency for *N. diversicolor* to be found in areas of silt and mud rather than sand or the thick anoxic mud around the mussel beds in the estuary. It is known that *H. ulvae* does not have a sediment preference (Newell 1962) and it was not therefore expected to find an association between *H. ulvae* and substrate type. *C. volutator* abundance did not suggest any associations with substrate type.

3.2 COMPARISONS WITH PAST DATA

Cobb et al. (1979) carried out a survey of both the feeding distribution of the shorebirds on the estuary and the abundance and distribution of various invertebrate species including *H. ulvae*, *N. diversicolor* and *C. volutator*. The distribution maps they presented are shown in Figures 25 a, b and c. The feeding distribution of the shelduck in their study corresponds with the results seen here. Shelduck fed around the centre of the outer bay. Distributions of *H. ulvae* did not match, being almost the inverse of the shelduck distribution. Shelduck feeding distribution corresponded more closely with *N. diversicolor*, *C. volutator* and *M. balthica*.

3.3 GENERAL DISCUSSION

It is well known that the distribution and population cycles of predators are strongly correlated to that of their prey. One might expect to find that predator density correlates positively with prey density. In a study on the Wash, east England (Yates et al., 1993), it was found that sediment characteristics can be used to predict densities of shorebirds as sediment type has implications on the type of feeding methods available and the type of prey available. Shorebird density has been found to be related to prey density and prey density to sediment type and inundation time (Yates et al. 1993). This would seem to suggest that shorebird feeding distributions could be expected to follow the distributions of their prey species.

Figure 25a. *Hydrobia ulvae* **distribution >1000 m^{-2} (Cobb et al. 1979)**

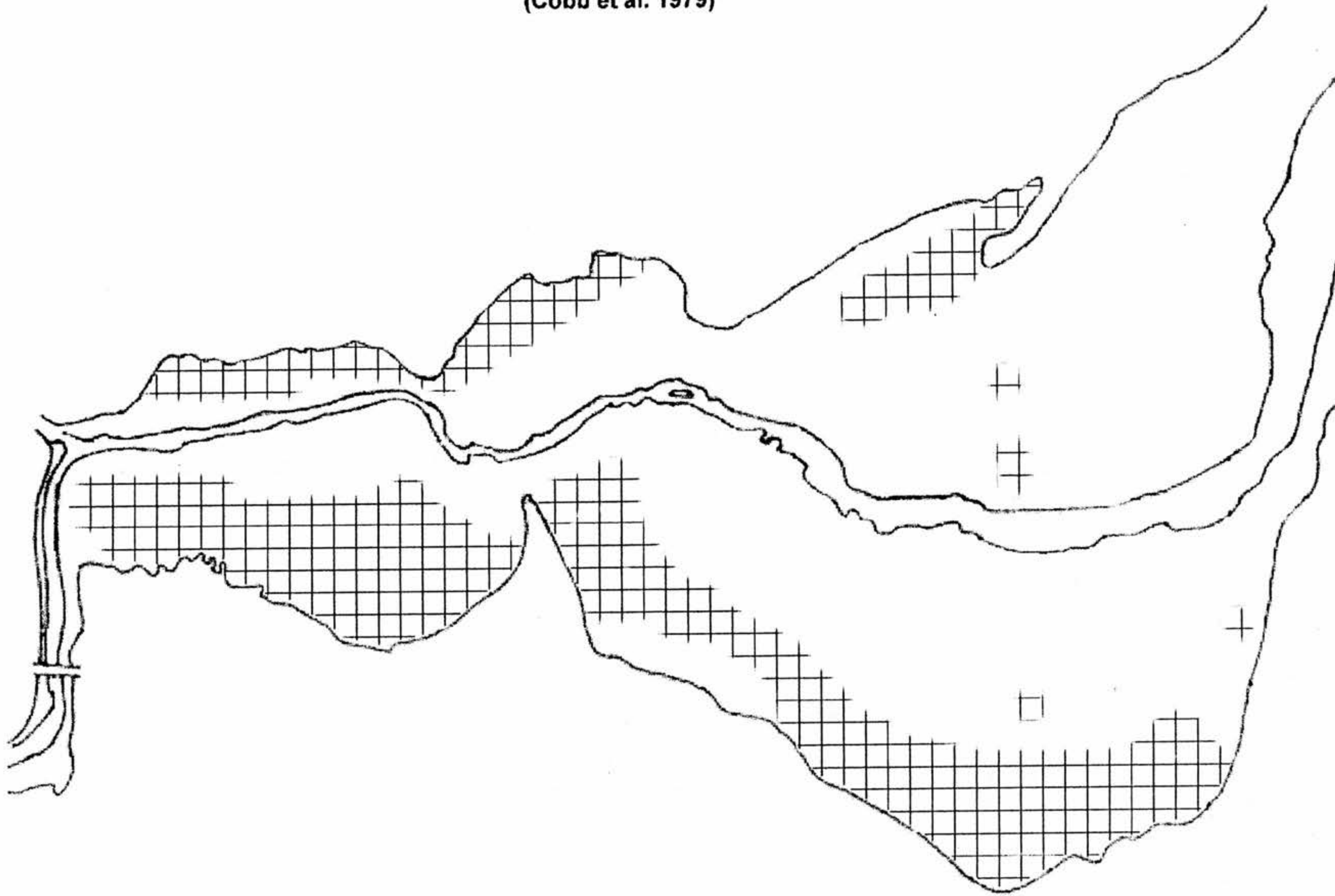


Figure 25b. *Corophium volutator* **distribution >500 m^{-2} (Cobb et al. 1979)**

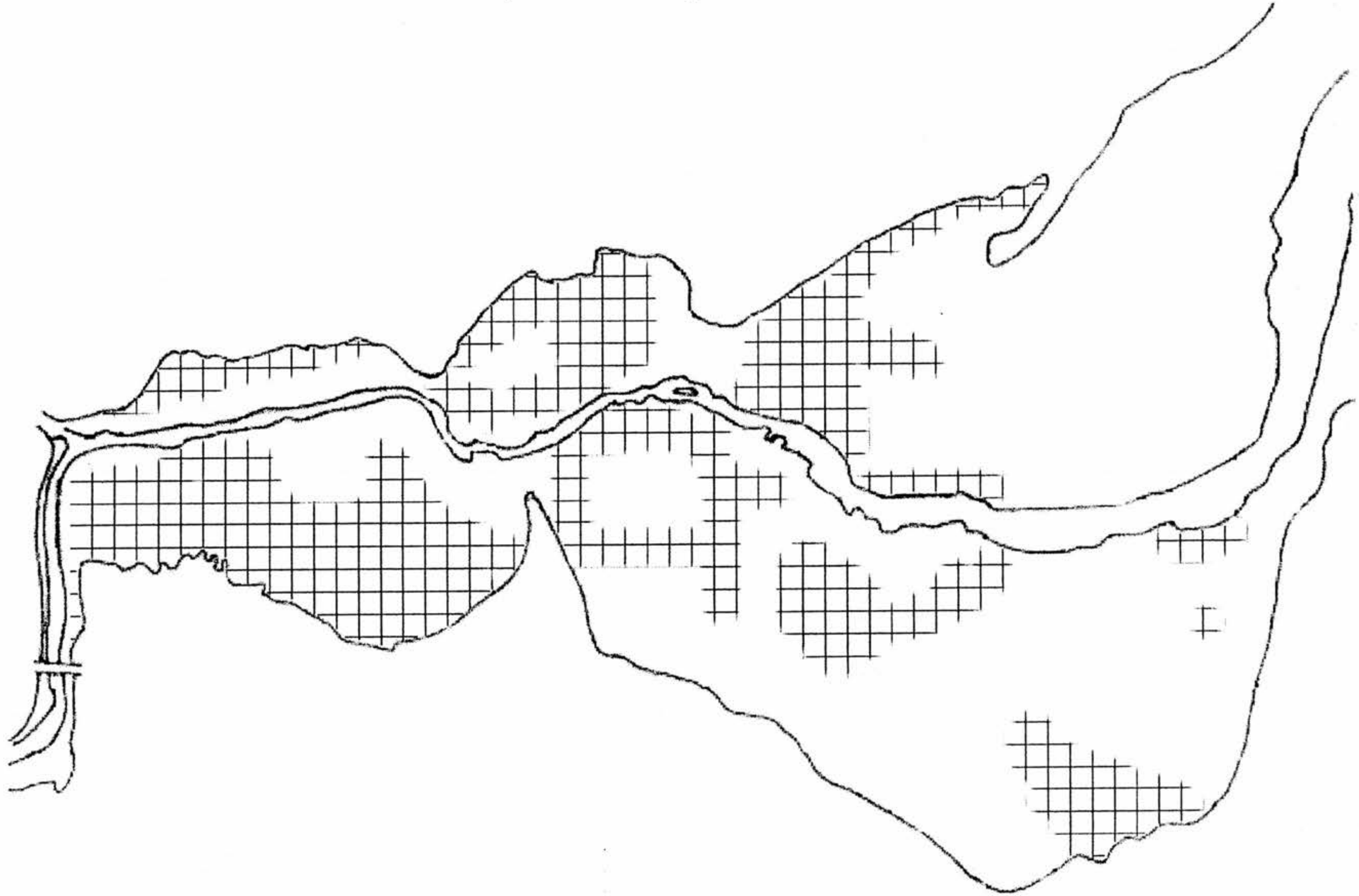
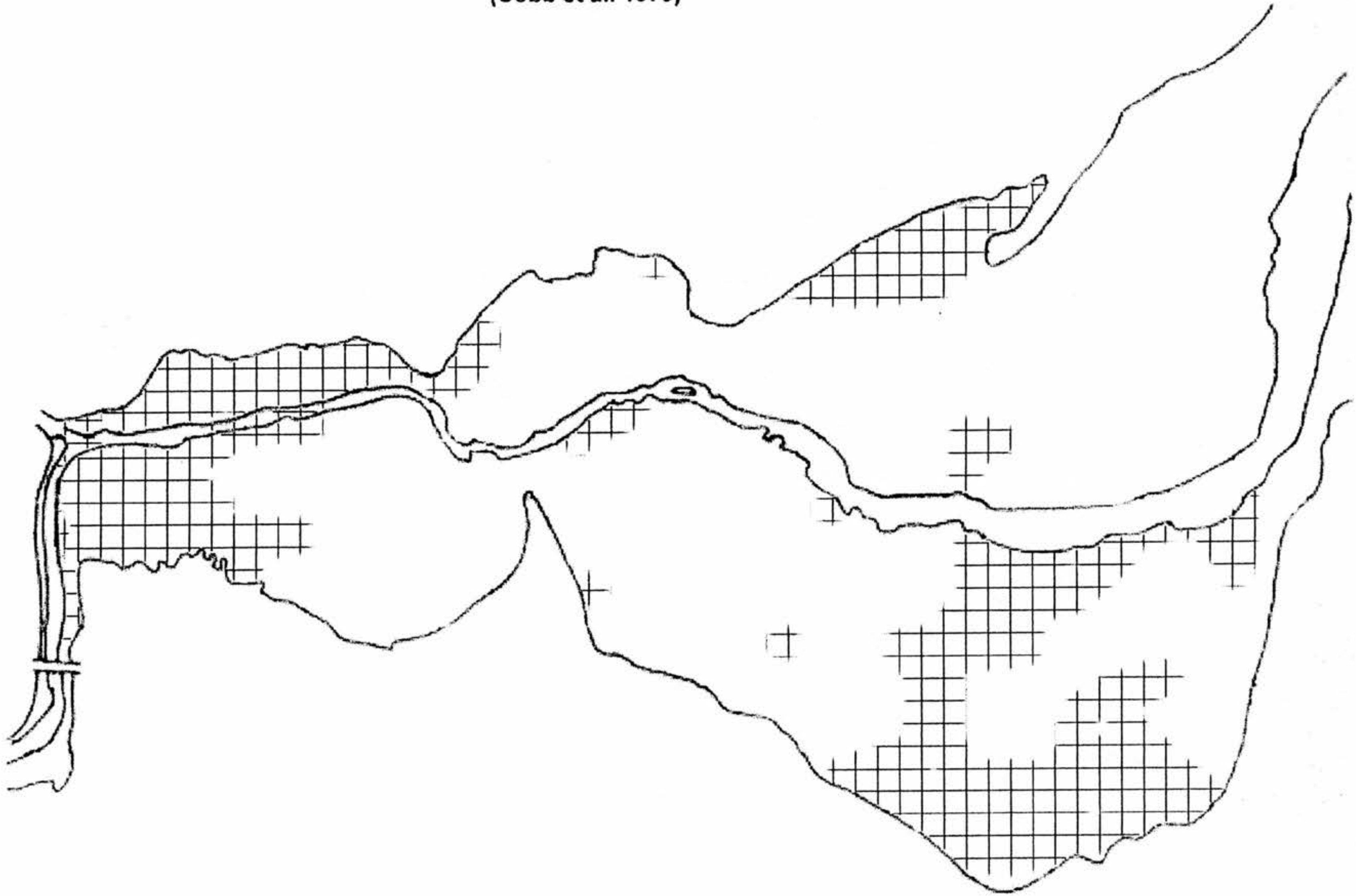


Figure 25c. *Nereis diversicolor* **distribution >70 m^{-2}**
(Cobb et al. 1979)



Various sources have noted that shelduck can be voracious predators on *H. ulvae* gathering thousands of individuals in a very short time. Since the size of the shelducks' prey items is generally very small, the birds need large numbers of prey to meet their energy requirements. It seems inconsistent therefore that the birds are not foraging in the areas where prey density is highest. This suggests that either the birds' diet is changing with the dominance of *H. ulvae* giving way to other more available species or that the birds are prevented from foraging in the areas of highest prey density by some other factor.

It seems reasonable to suggest that diet is altering as a result of external factors that prevent optimum foraging. The distribution of the shelduck in August is more closely correlated to the abundance of *H. ulvae*, with the main cluster of birds occurring on Kincaple Flats along transect C. However, by this time the macroalgal mats are fully developed and the birds distribution is more closely correlated with areas devoid of seaweed.

If the birds are being prevented from foraging in the optimum areas, there may be several factors operating. Some possibilities are:

a./ Sediment characteristics

Sediment type could affect a bird's ability to feed, particularly with the sieving method employed by the shelduck. The substrate needs to be a loose and fine grade material if it is to successfully filter through the bill lamellae of the bird. Also the substrate would need to have poor drainage in order to allow water to accumulate, enabling sediment particles to be washed through the birds' bills. The substrate types available on the Kincaple Flat range from thick, anoxic, black mud to firm sand (Figure 4). Overlaying feeding distribution onto sediment type shows that the bird are feeding on softer sediments rather than firm sands. This is particularly marked in Cobb et al. (1979) where the feeding distribution of the birds is truncated in the north-east section of the estuary, along a line coincident with a change in substrate from soft silty mud to firm sand.

b./ Algal mat distribution

Enhanced growth of algal mats across the substrate may have a similar effect to sediment type on the feeding behaviour of the birds. Raffaelli et al. (1989) suggest that large amounts of algal growth are incompatible with the sieving feeding method. They physically interfere with the filtering process in the bill lamellae. Overlaying the algal bloom map

(Figure 3) onto maps of the flock distribution and *H. ulvae* abundance suggests a negative correlation between shelduck distribution and algal bloom distribution (see Chapter 3). It should be remembered however, that the shelduck distribution maps and invertebrate abundance maps were prepared at a time when there was no macroalgae on the estuary. There will still be a large amount of filaments remaining in the sediment, however, and this may have an impact on shelduck distribution.

Various sources have shown that the abundance of the amphipod *Corophium volutator* decreases under weed mats. Hull (1987) found that *C. volutator* populations decline significantly under mats with a biomass of 1kg m^{-2} (wet weight), whilst at 3kg m^{-2} the species disappears completely. Patchy distributions allow *C. volutator* to opportunistically recolonise areas previously covered by weed mats (Raffaelli et al. 1989). Raffaelli et al. suggest that a patchy distribution of mats is crucial to the maintenance of *Corophium* populations. As seen in Chapter 1, *C. volutator*, while not as important as *H. ulvae* in the shelduck's diet, can still make up one third of their stomach contents. Enhanced growth of macroalgae could result in *Corophium* being pushed into the inner bay where there are fewer mats, but away from the feeding distribution of the birds.

It is likely that reductions in some of its prey species and an inability to forage for others would have an impact on the number of birds using the estuary for overwintering. An initial re-distribution of birds may occur, but long term changes in abundance could also appear. Shelduck from the Eden have been found at the Solway Estuary and it is possible that if food supplies are reduced, more birds will opt for different sites.

CHAPTER 5

WATER CHEMISTRY

1 INTRODUCTION

Nutrient loadings on estuarine systems are particularly important in the assessment of eutrophication problems. While enrichment of water bodies is not necessarily detrimental, occurring quite naturally in many situations, enrichment caused by human activity is frequently detrimental. Changes often occur on a very short time scale and ecosystems can be extremely vulnerable. Eutrophication is recognised as a problem by the European Commission and directives are in place with which it is possible to qualify water courses as eutrophic. Prompted by a perceived increase in the growth of macroalgal mats, an analysis of the nutrient loading on the Eden was performed in conjunction with the invertebrate survey described in Chapter 4 to attempt to assess the chemical conditions on the feeding grounds frequented by the shelduck.

2 METHODOLOGY

Water chemistry analysis ran in tandem with the survey for invertebrate abundance described in Chapter 4. Samples for water chemistry analyses were taken at the same time as the invertebrate cores.

Four sediment water samples were taken from random locations at each sampling site. Four samples were also taken from the main channel as it enters the estuary at Guardbridge, from Motray Water and from five water outlets on the edges of the estuary (Figure 21). Samples were frozen within an hour of collection at -20°C and later defrosted and decanted into Eppendorf tubes for analysis.

Assays were made by standard colorimetric methods scaled down for use with a 96 well microplate (Dynatech, M29A) and a microtitre plate spectrophotometer (Dynatech, MR5000). This enabled rapid determination of nutrient levels. An octapipette (Dynatech, S8/50) and multidispenser pipette (Eppendorf) were used to load the microplates. Mixing was achieved first by gently tapping the plate and second by the plate reader program.

Seven standards and twelve blanks were included on each microplate to minimise the effect of differences between plates. The standard curves used to calculate concentrations are included in Appendix A. Protocols for each assay are also included in Appendix A.

2.1 NITRATE-NITROGEN

$N\text{-}NO_3$- was determined using NAS Szechrome reagent (Diphenylamine Sulphonic Acid Chromogene) from Park Scientific Ltd, Northampton. 286 µl NAS Szechrome reagent was added to 14 µl substrate, giving a final volume of 300 µl. The plate was then read at 570 nm. Standards were prepared using KNO_3.

2.2 NITRITE-NITROGEN

$N\text{-}NO_2$- was determined as in Parsons et al. (Parsons et al. 1984), scaled down for use in the microplate format. 25 µl sulfanilamide solution was added to 100 µl substrate. The plate was then mixed and left to stand for 5 minutes before the addition of 25 µl dihydrochloride solution, giving a final volume of 150 µl. After a further 10 minutes the plate was then read at 550 nm. Standards were prepared using $NaNO_2$.

2.3 AMMONIUM-NITROGEN

$N\text{-}NH_4$+ was determined as in Parsons et al. (1984), scaled down for use in a microplate. 10 µl phenol solution, 10 µl sodium nitroprusside solution and 30 µl oxidising solution were added to 250 µl substrate, giving a final volume of 300 µl. Plates were then incubated in the dark at room temperature for 20 minutes and finally read at 630 nm. Standards were prepared using $(NH_4)_2 SO_4$.

2.4 ORTHO-PHOSPHATE

$P\text{-}PO_4^3$ was determined using the malachite green method (Parsons et al. 1984). 200 µl of malachite green solution was added to 100 µl substrate to give a final volume of 300 µl. The plate was then read at 630 nm. Standards were prepared using $K_2H_2PO_4$.

Maps were prepared for each nutrient using a colour bar to represent variation in concentration (Figures 26 to 29). Macroalgal mat distribution maps and maps of substrate type were overlaid to examine possible associations.

2.5 BACK DATA

Data on water chemistry for the Eden and Motray Water were obtained from the Scottish Environmental Protection Agency in Perth. These data were used to identify possible changes in the nutrient status of the estuary over time.

3 RESULTS & DISCUSSION

3.1 GENERAL RESULTS

The results of the water chemistry assays are shown in Table 3. Preliminary examination of the water chemistry maps (Figures 26 to 29) allowed some conclusions to be drawn about the nutrient status of the estuary.

- The main river channel is in good condition. Levels of all four nutrients tested were low in the mouth of the river.
- Motray Water discharges high levels of nitrates into the estuary, probably from agricultural fertilisers leaching into the water upstream.
- The highest nitrate levels (mean 20.503 mg l^{-1}) were recorded entering the estuary at outlet 3. However these high concentrations were not maintained, dropping to a mean of 9.23 mg l^{-1} at the nearest transect point.
- Nitrite levels were generally low although nitrites were recorded at 66% of sampling stations.
- The most important nitrite source found in this study was outlet 4 on the northern shore of the estuary where the mean concentration was 0.413 mg l^{-1}.
- Ammonia showed a patchy concentration distribution with particularly high concentrations in an area on the south side of the channel on transect A (mean 12.73 mg l^{-1}).
- Phosphates were generally low across the estuary but showed an area of higher concentrations, coincident with that displayed by ammonia.

Table 3. Water chemistry assay results. Mean values.

NA = concentration too low to detect using microplate assays.

	Levels of inorganic nutrients (mg l^{-1})			
Sample Point	**Ammonia**	**Nitrate**	**Nitrite**	**Ortho-Phosphates**
a1	1.36	9.23	0.30	0.38
a2	12.73	0.13	0.07	1.44
a3	*Samples damaged*			
a4	10.42	0.11	0.07	1.86
a5	2.33	0.01	0.37	*NA*
a6	1.70	*NA*	0.10	*NA*
b1	*Samples damaged*			
b2	0.31	0.59	0.07	0.60
b3	0.19	1.42	0.11	0.76
b4	0.43	1.59	0.16	0.36
b5	0.21	1.13	0.32	0.57
b6	0.61	1.09	0.19	0.67
b7	0.17	0.29	0.12	0.63
b8	2.07	*NA*	0.47	0.28
c1	0.91	0.22	0.01	0.33
c2	0.08	0.79	0.03	0.12
c3	0.12	0.45	0.08	0.67
c4	0.11	1.16	0.17	0.42
c5	0.13	0.29	0.11	0.24
c6	1.76	*NA*	0.13	0.59
c7	1.30	0.13	0.30	0.52
c8	2.07	0.00	0.18	0.93
Outlet 1	0.69	1.66	0.11	0.20
Outlet 2	0.91	4.05	0.19	1.12
Outlet 3	0.23	20.50	0.08	0.13
Outlet 4	0.83	0.95	0.41	*NA*
Outlet 5	0.43	9.11	0.30	0.22
Main Channel	0.03	*NA*	0.02	0.09
Motray Water	0.79	9.11	*NA*	0.06

Figure 26. Ammonia levels by sampling site

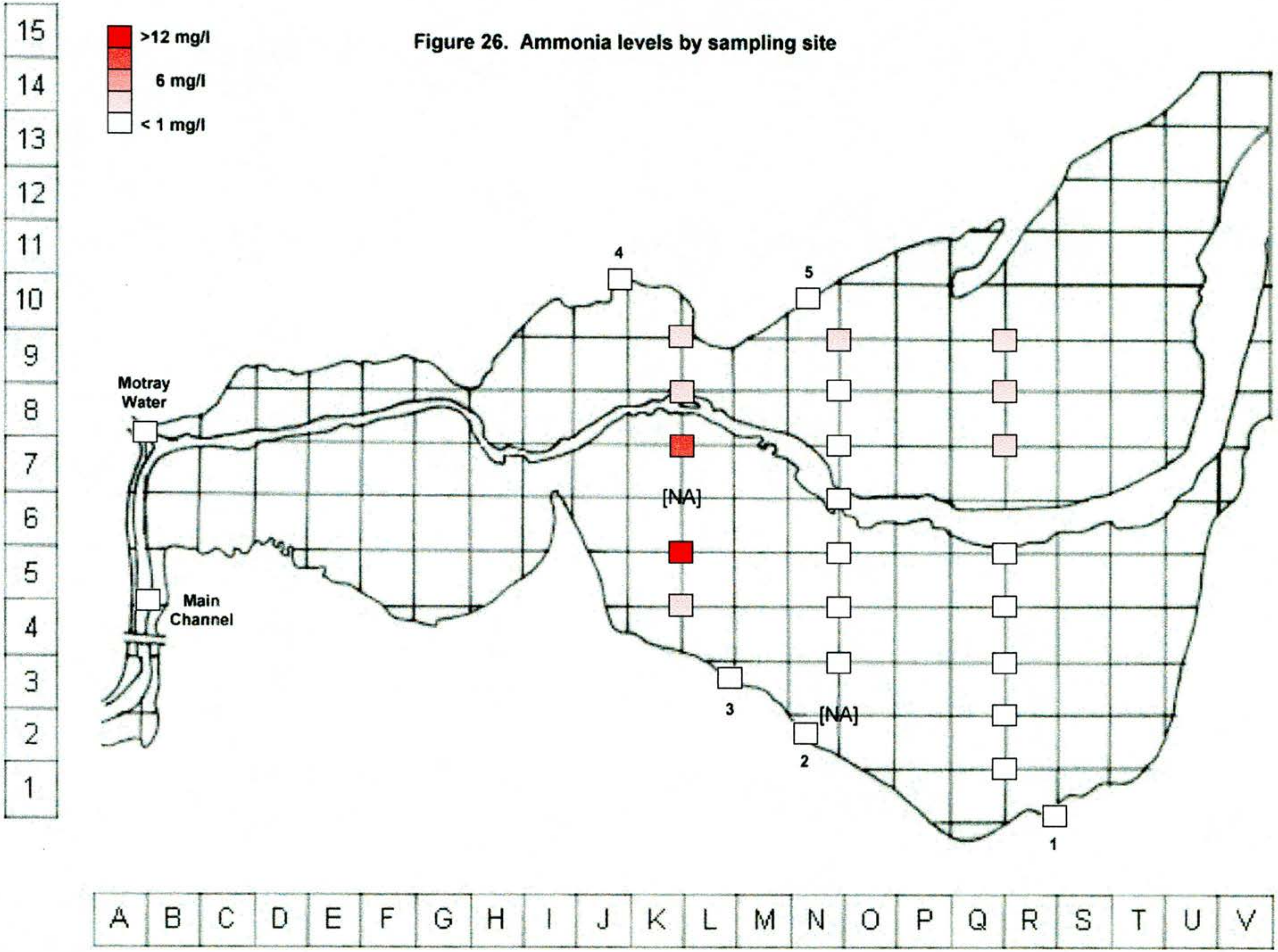


Figure 27. Nitrate levels by sampling site

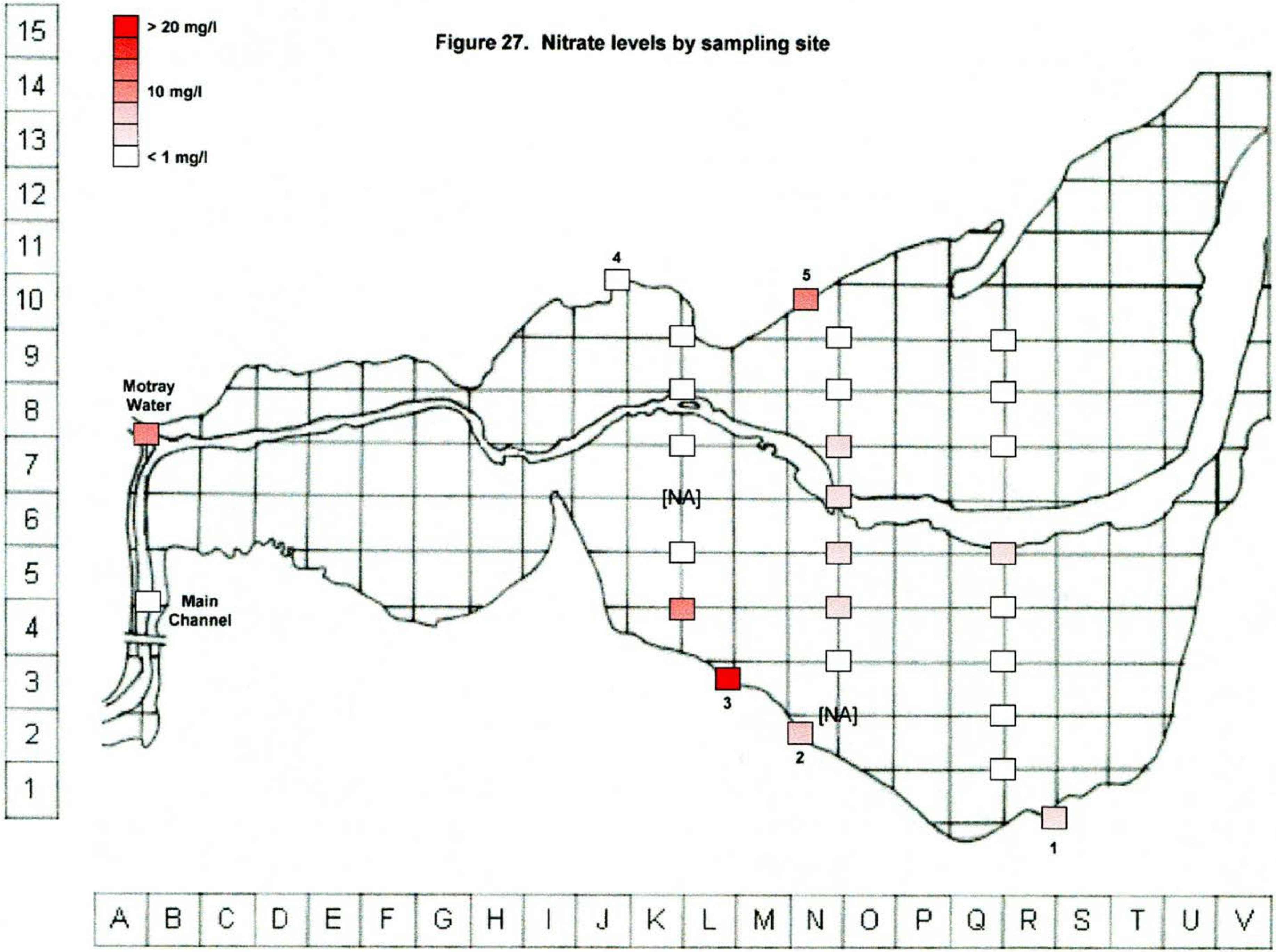


Figure 28. Nitrite levels by sampling site

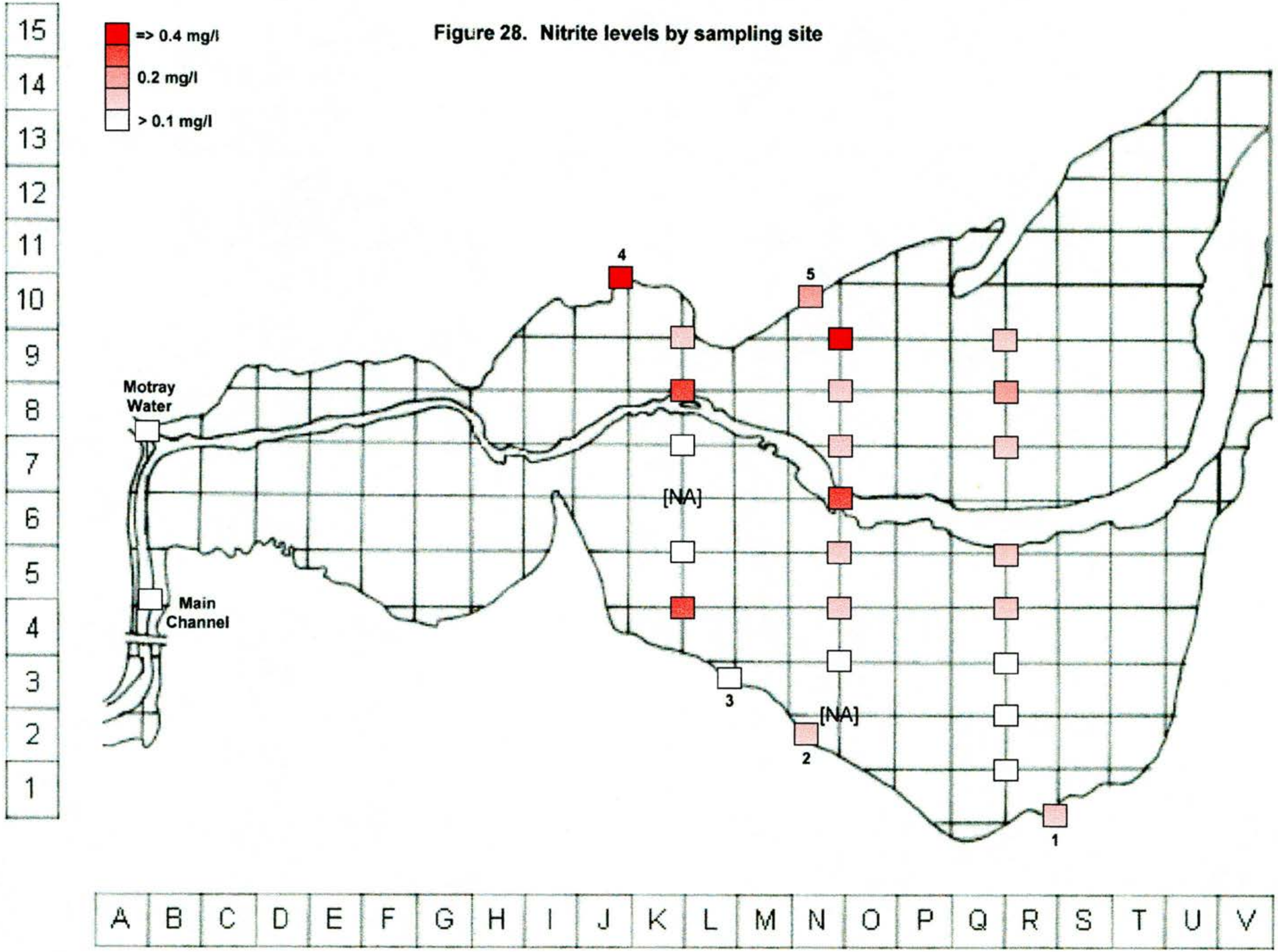
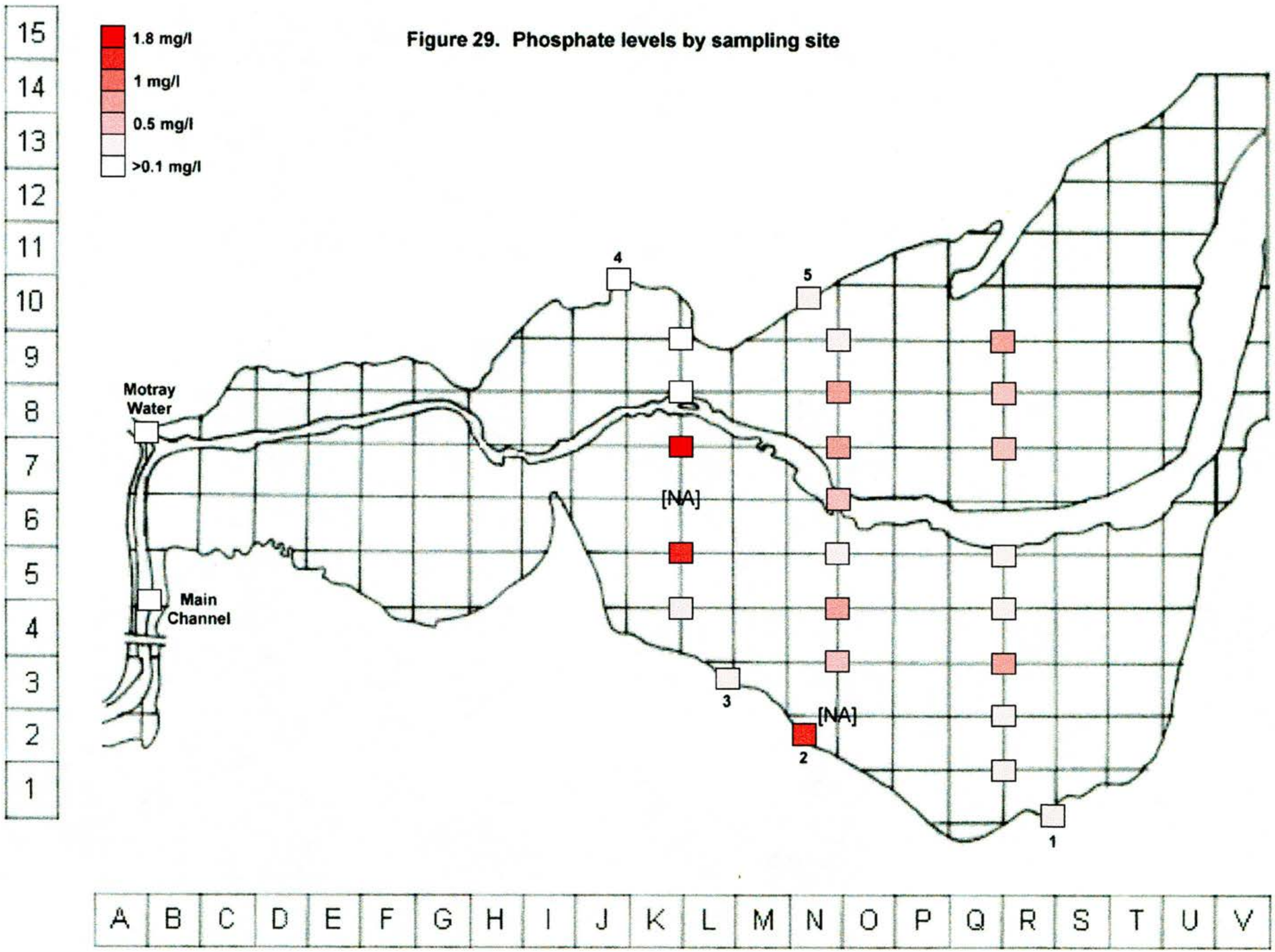


Figure 29. Phosphate levels by sampling site



In addition, examination of the available back data for the Eden estuary and for Motray Water revealed some interesting results.

For the Eden (see Figure 30):

- Concentrations of ammonia and phosphate have been increasing but neither shows a statistically significant increase.
- Concentrations of nitrates and nitrites have been decreasing. Only nitrates showed a significant decline (r_s = -0.807, DF=80, p<0.01).

For Motray Water (see Figure 31):

- Concentrations of ammonia and nitrate have been increasing. Only the increase in ammonia is significant (r_s = 0.439, DF=120, p<0.05).
- Concentrations of nitrite and phosphate have been decreasing. Only nitrite showed a significant decrease (r_s = -0.366, DF=104, p<0.05).

3.2 NUTRIENTS AND SUBSTRATE

The high levels of nitrates entering the estuary in outlet 3 may be derived from effluent from the pig farm at Coble shore. Unfortunately, the drainage patterns around the estuary are complex and it was not possible to obtain drainage maps to ascertain the precise path of this outlet. However the pig farm seems a likely contributor of such high levels, but it is probable that decomposing algae is the main cause. Nitrogen would initially be present in the effluent as ammonia but rapid oxidisation would convert this to nitrates.

Matching the data obtained in the current study with substrate type suggested that the high concentrations of ammonia and phosphates are localised to the thick anoxic black mud comprising the areas of mussel beds at either side of the channel. This is most likely to be a function of anaerobiosis in benthic organisms. The high input and sharp disappearance of nitrates into the area directly south of the highest concentrations of ammonia suggest that nitrate is fuelling the area. The subsequent conversion of nitrates back into ammonia by anaerobic respiration of organisms in the sediment would result in a peak of ammonia as nitrates decrease. It is likely that high nitrate levels from Motray Water also contribute to this area as they discharge directly into the main channel.

Figure 30. Nutrient levels over time for the Eden estuary

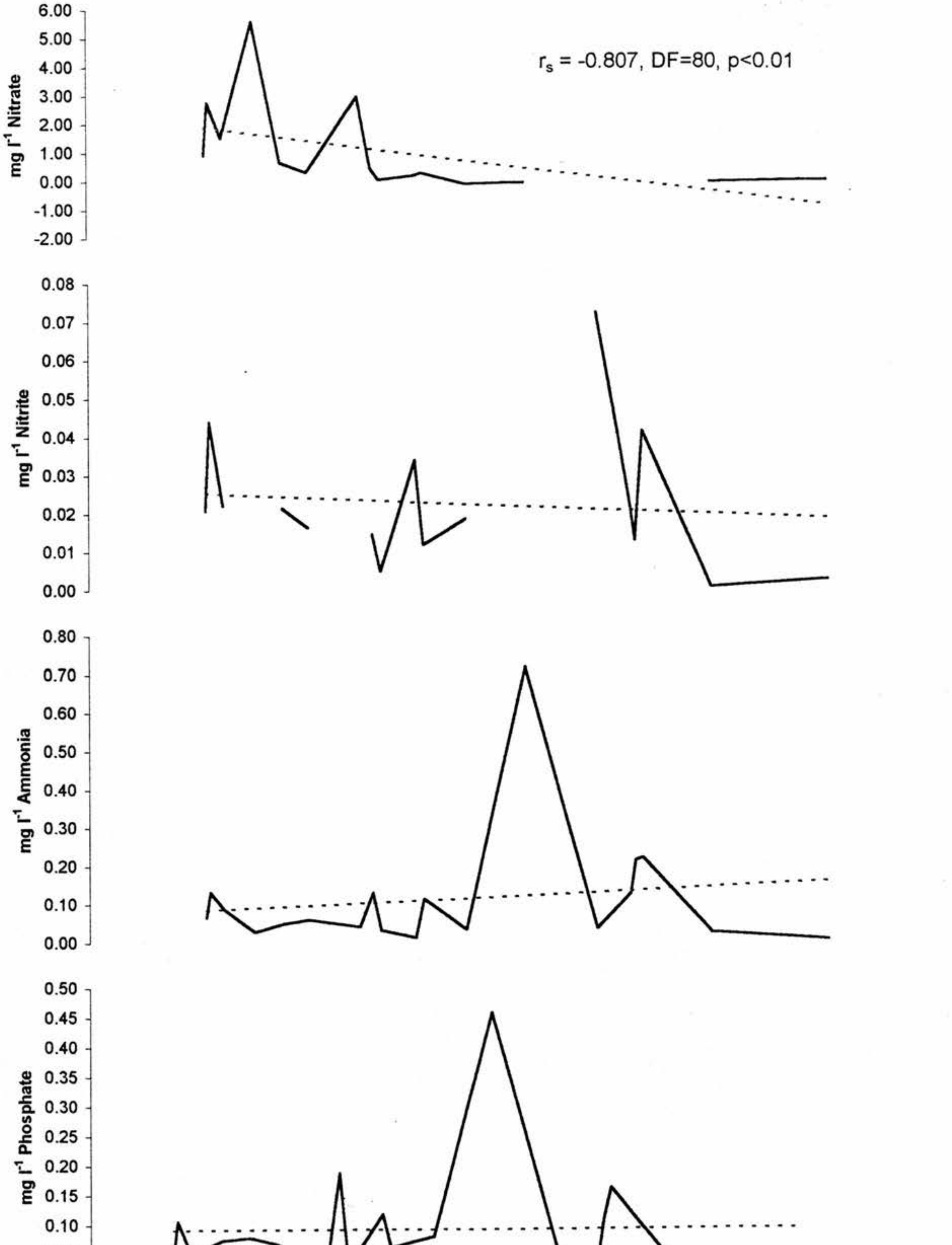
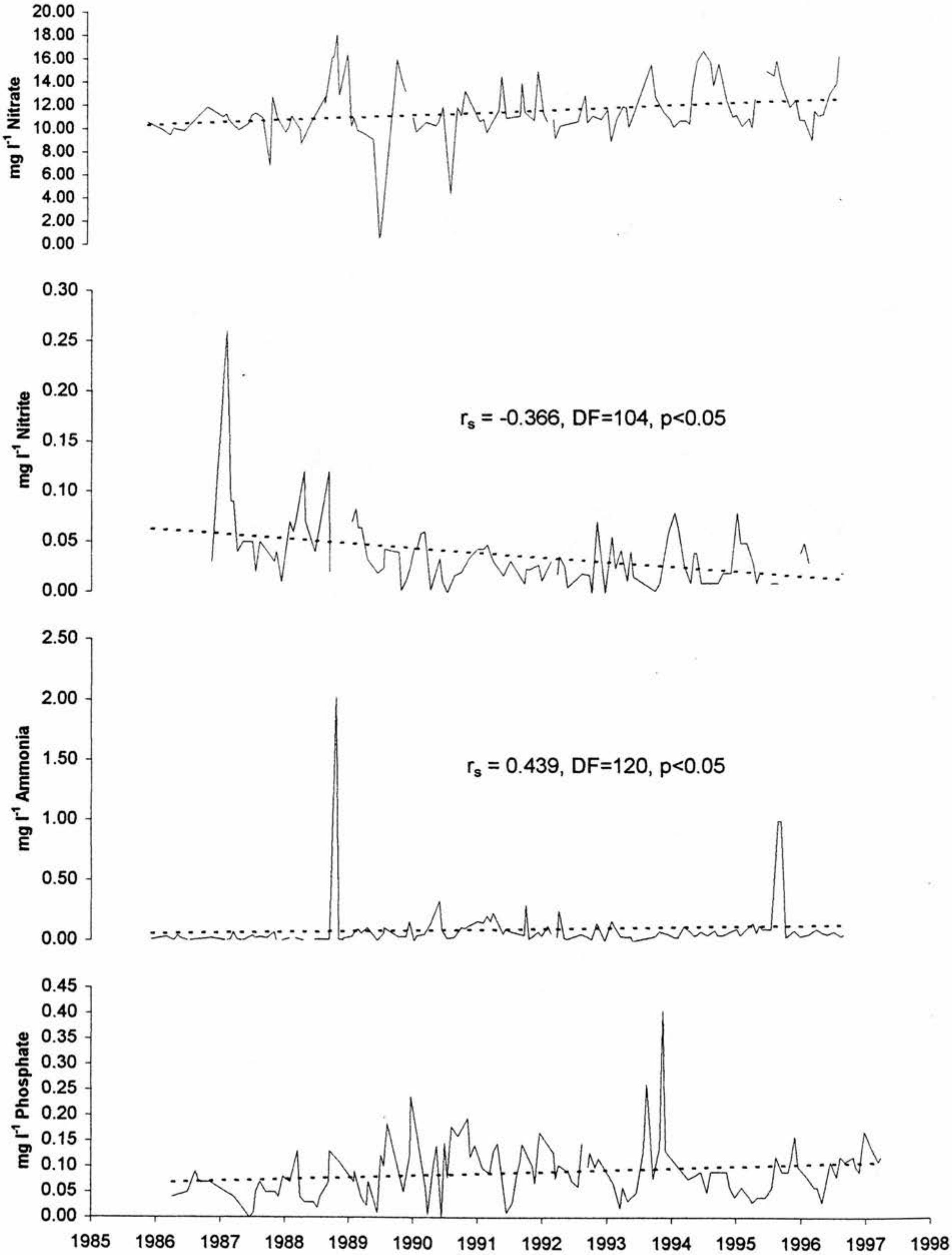


Figure 31. Nutrient levels over time for Motray Water



3.3 NUTRIENTS AND MACROALGAL GROWTH

In estuaries where extensive data sets of algal biomass and nutrient status are available, highly significant correlations between nutrient increase and macroalgal blooms have been seen (Raffaelli et al. 1989). Using an aerial photograph of summer macroalgal blooms (Caudwell et al. 1994) and field observations it was possible to map out the main areas of growth and match this to the levels of nutrients available.

The dominant area of macroalgal growth was on the western side of Kincaple Flats with a smaller patch appearing on the northern shore below Shelley Spit. This correlates reasonably well with the availability of ammonia and nitrate from the sediment and from the water outlets.

3.4 GENERAL DISCUSSION

The levels of nutrients measured in this study and in past surveys show that there is sufficient nutrient load to cause eutrophication in the estuary. Nutrient concentrations are highly variable through time, fluctuating daily, weekly and by season. The most important inorganic nutrient in saline systems is nitrogen (as nitrate) as opposed to phosphorus (as phosphate) in freshwaters. As a major ingredient in agricultural fertilisers and as the dominant form of nitrogen, nitrate levels are thought to be important in the evaluation of enrichment and eutrophication in saline water systems (Mathieson et al. 1995). Approximately 76% of the Eden catchment is graded as prime agricultural land (Clelland 1994), 54% of which is devoted to arable crops (mainly spring barley and wheat). It is estimated that the fertiliser input contributes 4490 tonnes per annum of nitrogen into the catchment, resulting in approximately 1200 tonnes nitrogen (or 5300 tonnes nitrate) leaching into the river. This would be expected to result in concentrations of 44 mg l^{-1}, higher than the mean of 33 mg l^{-1} for 1994.

The EC Nitrate Directive recommends a limit of 50 mg l^{-1} NO_3 for drinking water which equates to approximately 11.3 mg l^{-1} total oxidised nitrogen (TON : nitrate load + nitrite load). Although the directive does not specify a level for eutrophication, the Highland River Purification Board commonly uses a level of 0.3 mg l^{-1} TON as an indicator of potential eutrophication (Mathieson et al. 1995). Mathieson et al. calculated that the Eden estuary has the highest total nitrogen concentration of all Scottish estuaries, with a winter mean of 8.57 mg l^{-1} and a summer mean of 6.92 mg l^{-1}. The second highest concentrations were found in the Ythan Estuary where the eutrophication problems are well documented and shelduck numbers are declining significantly. However while the Ythan has been recognised as having a eutrophication problem, the Eden has not.

Better management of nitrogenous waste such as slurries, a more conservative approach to the use of fertilisers and specific management of the river valley to reduce nitrogen loads to the river water are needed combined with more comprehensive and continuous surveys of water quality and the growth and spread of macroalgal species.

CHAPTER 6

GENERAL DISCUSSION

1 SHELDUCK DECLINE AND BREEDING SUCCESS

This study has confirmed that there is a decline in shelduck abundance on the Eden Estuary and has investigated various possible interactions which may be causing the decline. Due to the limited time available and the absence of long term data for many variables, it has not been possible to gather conclusive evidence for eutrophication or for a shift in the abundance and distribution of the shelducks' prey species.

It was hoped that an objective measure of breeding success could be made, but because of the difficulty of finding nest sites this was not possible. Several broods were seen on the estuary during June. However, they disappeared very quickly and I saw only 3 recently fledged juveniles at the beginning of August. It is likely that more ducklings were raised than those seen, but it is also likely that the number is lower than would be expected. From the daily counts I estimated a breeding population of up to 100 pairs. Patterson (1982) estimates that between c.35% and 50% of the territorial birds in his studies successfully produced broods. One might therefore expect approximately 30 to 40 broods. Patterson (1982) also calculates between 0.2 and 2 chicks fledged per breeding pair. This gives a figure of between 20 and 50 juveniles for the Eden which is far more than the estimated figure for this year. Patterson's calculated breeding output per pair is variable between years (mean = 0.99 ± 0.2 SD). The breeding success of the Eden population is likely to be similarly variable and this year was particularly poor for breeding. If the birds are already in an environment which is becoming detrimental to them, poor breeding output is an additional cause for concern. Unfortunately there is no past data on breeding success available.

2 COMPARISON WITH THE YTHAN ESTUARY

The Eden estuary has the highest concentrations of total oxidised nitrogen in Scotland, followed by the Ythan estuary. The Ythan has a long history of data collection for shelduck, invertebrate populations and macroalgal biomass. It is also the only estuary in Scotland which is recognised by the Paris Commission as being eutrophic (Mathieson et al. 1995). Some work has been done on the Ythan on the possible consequences of eutrophication on the bird populations (Raffaelli et al. 1989; Raffaelli et al. 1998).

Raffaelli et al. (in press) have shown:

- There has been a significant increase in the macroalgal mat cover over the past 40 years.

- *Corophium volutator* abundance is lowest in areas which have high macroalgal biomass and highest in areas where macroalgae is absent.

- Shorebird counts on the estuary, after an initial increase between 1960 and 1980, are now significantly declining with the spread of macroalgae.

- The shelduck population has redistributed across the Ythan estuary over the last 20 to 30 years.

Raffaelli et al. suggest that the shelduck is particularly vulnerable to increases in macroalgal cover because of their preferred feeding method. Even small amounts of macroalgae can prevent the birds from using their characteristic sieving technique to feed. In a previous study, Raffaelli et al. (1989) showed that nitrogen loadings on the estuary have been increasing over time while the shelduck and wigeon (*Anas penelope*) populations have declined significantly.

Both of these studies suggest a strong association between an increase in nutrients, an increase in macroalgal biomass and a decrease in the abundance of shorebirds, specifically the shelduck.

Comparing the characteristics of the Ythan estuary to the Eden reveals both similarities and discrepancies. Both systems have high nitrogen loadings and both have populations of shelduck that are in decline. Only the Ythan has provable increases in macroalgal mat coverage, the Eden having only a perceived increase, as noted in previous chapters.

The geography of the two estuaries is very different. Although the Ythan is probably a higher energy system than the Eden, because of its elongated shape flushing times are likely to be longer than the Eden. Therefore there is more potential for accumulation of nutrients in the sediment. The Eden, despite being a lower energy system, flushes very rapidly due to its shallow profile and as a result, nutrient levels do not persist spatially. This may be the reason why, despite having higher levels of nutrients than the Ythan, the Eden does not seem to have the same degree of macroalgal growth.

However, the results of this study and the effects seen on the Ythan estuary, strongly suggest that the Eden is affected by eutrophication. This is problematic for the shelduck population, given the Eden's nationally important status as a breeding and overwintering site for the species.

3 PREVENTATIVE MEASURES

It is very important that further work is done both on the chemistry and biology of the Eden estuary. A current report of the water chemistry of the catchment (as performed by Clelland 1994) and measures of the macroalgal biomass present would be extremely helpful in further analysis and monitoring of the estuary.

Nitrogen loadings on the catchment are already far higher than the national mean (1.84 mg l^{-1} national winter mean, 1.35 mg l^{-1} national summer mean (calculated from Mathieson and Atkinson 1995)) at 8.57 mg l^{-1} in winter and 6.92 mg l^{-1} in summer. Changes in the management of the catchment could generate a significant reduction in nitrogenous wastes leaching into the ground water.

Mathieson and Atkinson (1995) suggested the following guidelines, published by the Scottish Office, should be applied to the Ythan:

1./ Improvements in the storage of slurry.

2./ Restrictions on the timing of slurry and fertiliser application to the driest periods of the year to reduce leaching.

3./ Changes in ploughing regimes to ensure that soil disruption is minimised in times of high rainfall.

4./ Cover crops in autumn and winter to lock some of the nitrogen loadings into the system's biomass.

5./ Enhanced use of rotations to include cover crops.

These measures may also be useful in the Eden catchment as such a large proportion of it is used for arable farming (76%). A more thorough understanding of drainage patterns around the estuary and restrictions on the effluent discharges from, for example, the pig farm on the southern shore and the golf links would significantly reduce the levels of available nutrients entering the water table.

It is necessary to analyse and treat problems of enrichment from the most fundamental level. The shelduck seems to be a good indicator species, given its feeding specificity, for changes at lower trophic levels. However, its sensitivity to eutrophication may lead to the species eventually abandoning the estuary altogether.

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APPENDIX A

AMMONIA ANALYSIS

REAGENTS

Phenol solution (20ml phenol in 200ml 95% v/v ethyl alcohol)
Sodium nitroprusside solution (1g sodium nitroprusside in 200ml de-ionized water)
Alkaline reagent (100g sodium citrate with 5g sodium hydroxide in 500ml de-ionized water)
Oxidising solution (100ml alkaline reagent with 25ml sodium hypochlorite)

METHOD

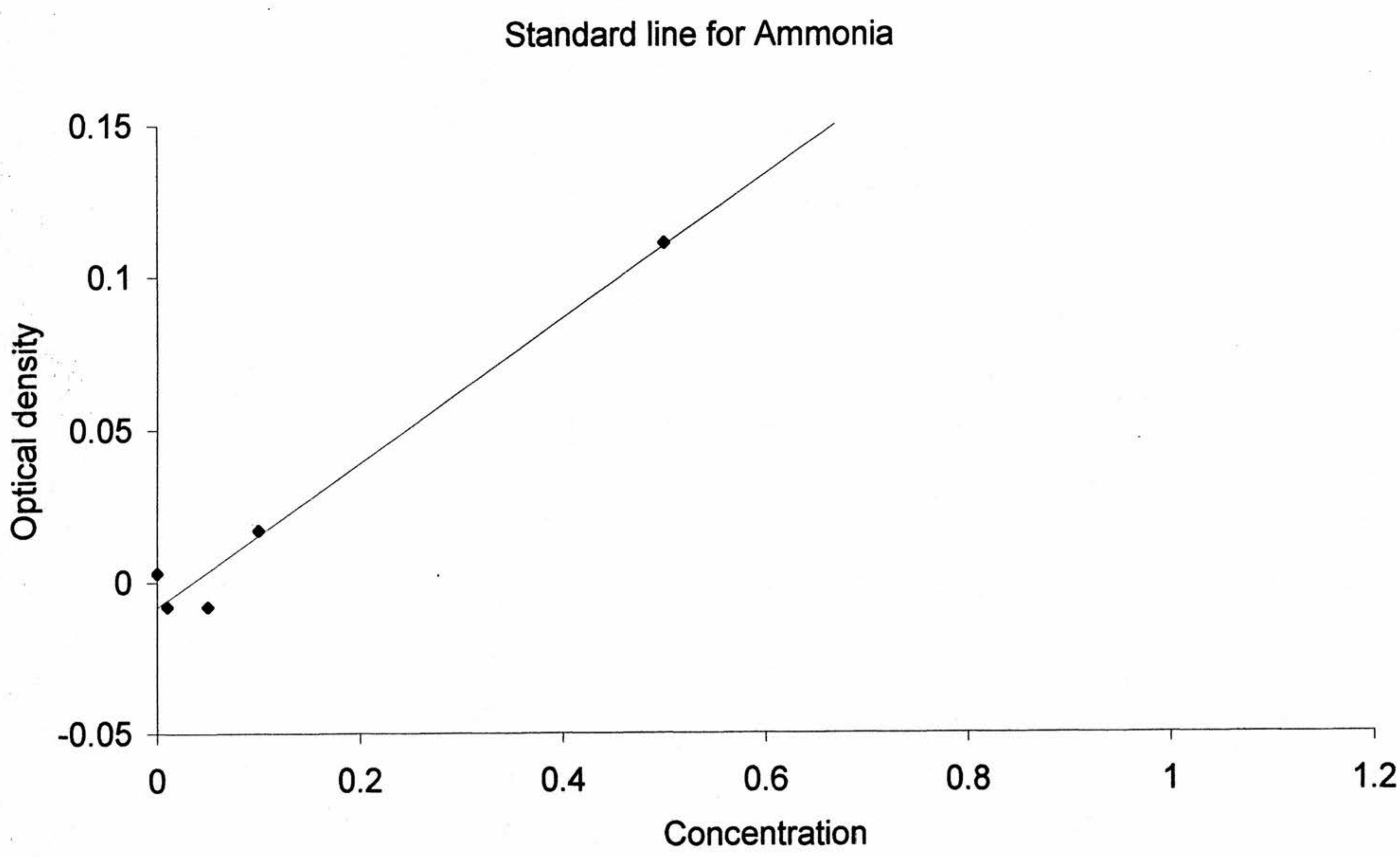
1). Prepare blanks of 250 µl M-Q water, with 10 µl phenol solution, 10 µl sodium nitroprusside solution and 30µl oxidising solution.

2). Prepare standards of 250 µl of each standard with 10 µl phenol solution, 10 µl sodium nitroprusside solution and 30 µl oxidising solution.

3). Prepare samples 250 µl substrate with 10 µl phenol solution, 10 µl sodium nitroprusside solution and 30 µl oxidising solution.

4). Incubate all in the dark for 20 minutes.

5). Read at 630nm.



Standard line for Ammonia
0.15
0.1
0.05
0
-0.05
Optical density
0
0.2
0.4
0.6
0.8
1
1.2
Concentration

NITRATE ANALYSIS

Reagents

NAS Szechrome reagent (1:1 conc sulphuric acid and conc phosphoric acid with 0.5% NAS Szechrome [Park Scientific])

Method

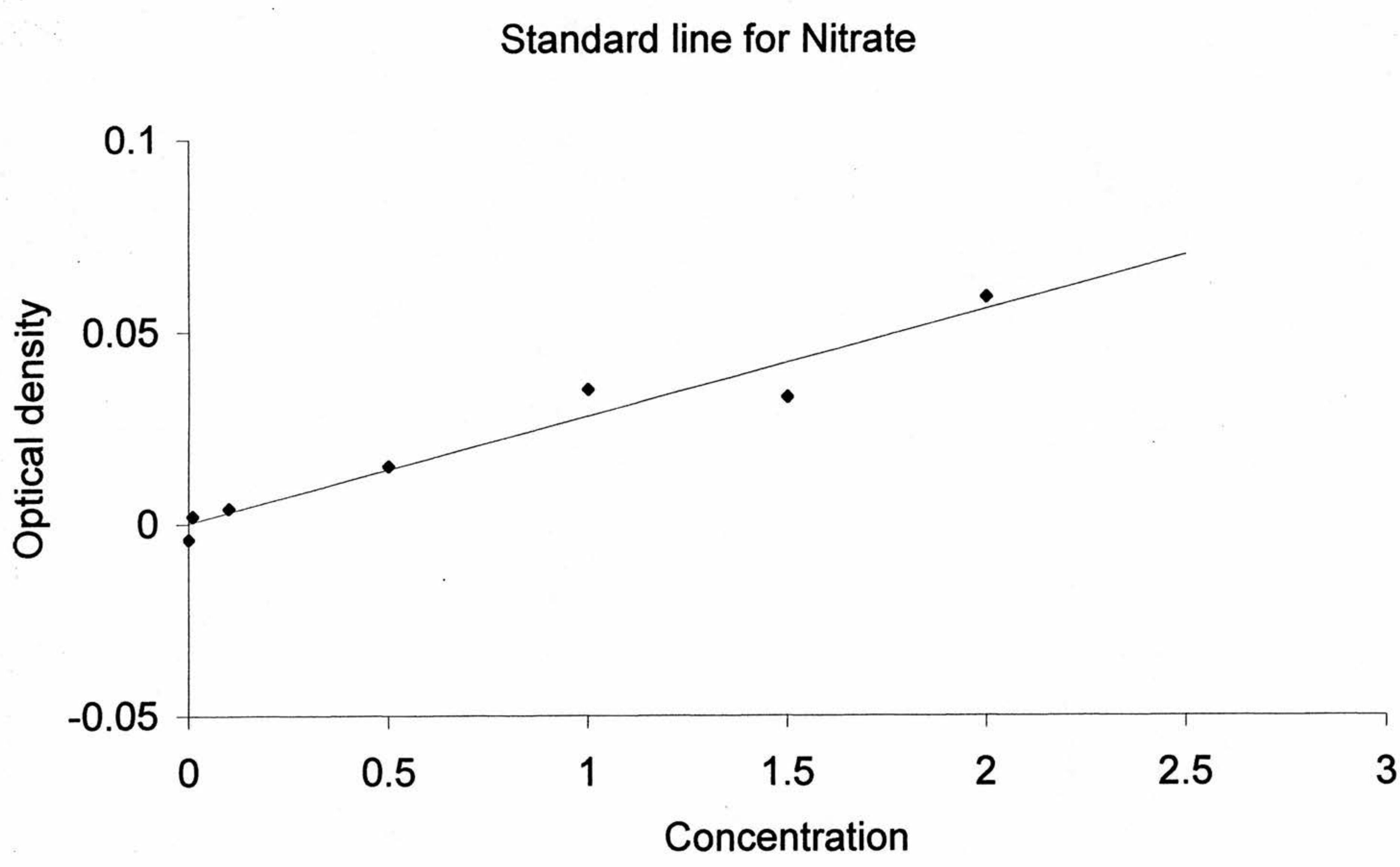
1). Prepare blanks of 14 µl M-Q water with 286 µl Szechrome.

2). Prepare standard of 14 µl substrate with 286 µl Szechrome.

3). Prepare samples of 14 µl substrate with 286 µl Szechrome.

4). Leave to stand for 10 minutes.

5). Read at 570nm.


Standard line for Nitrate
Optical density
0.1
0.05
0
-0.05
0
0.5
1
1.5
2
2.5
3
Concentration

Nitrite Analysis

Reagents

Sulfanilamide solution (5g sulfanilamide in 50 ml conc hydrochloric acid and 300 ml M-Q water, then dilute to 500 ml with M-Q water)
N-(1-naphthyl)-ethylenediamine dihydrochloride solution (0.5g dihydrochloride in 500 ml water)

Method

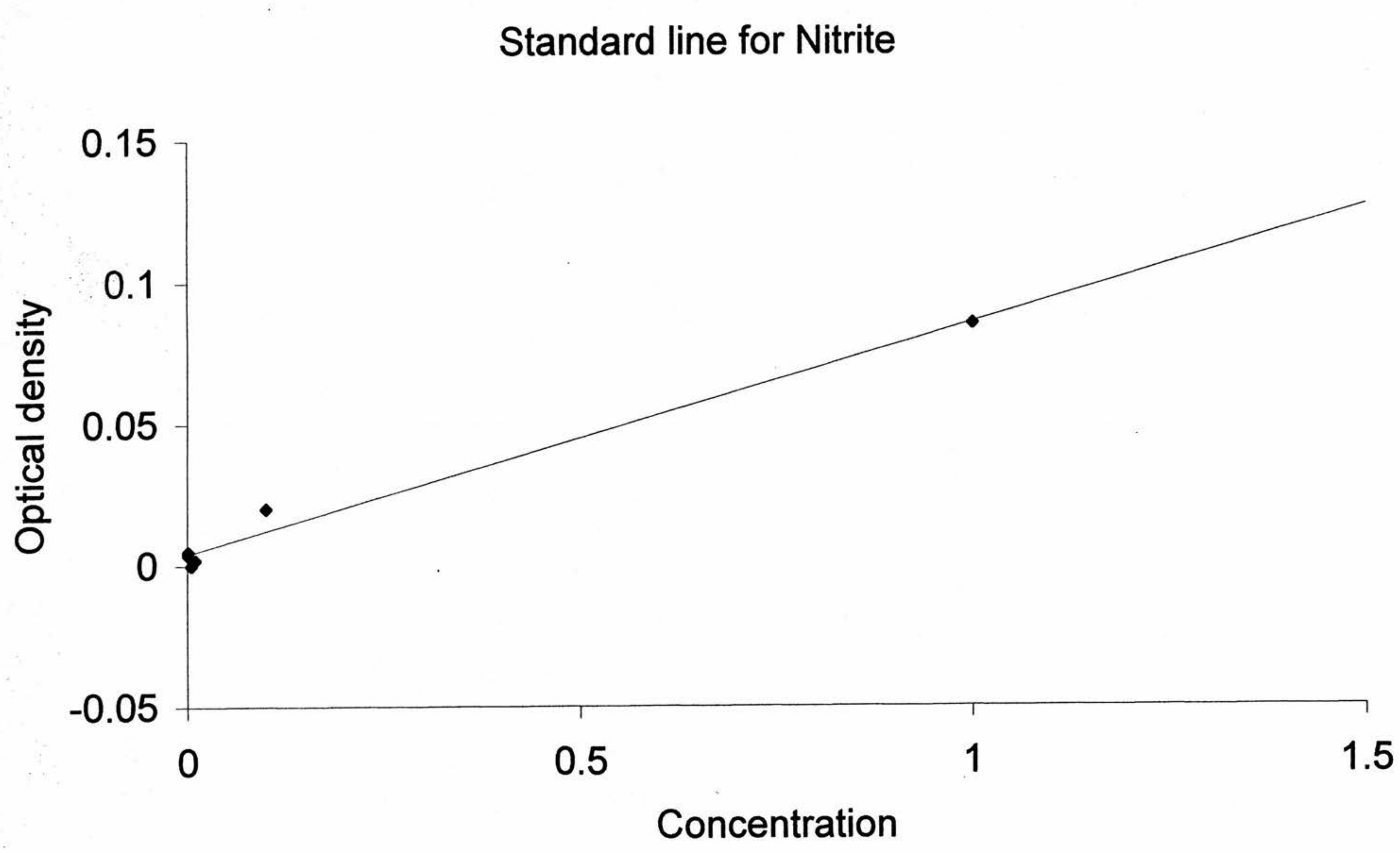
1). Prepare blanks, standards and substrates comprising 100 μl substrate with 25 μl sulfanilamide solution.

2). Allow to stand for 5 minutes (between 2 and 10 minutes)

3). Add 25 μl dihydrochloride.

4). Allow to stand for 10 minutes

5). Read at 543 nm.


Standard line for Nitrite
Optical density
0.15
0.1
0.05
0
-0.05
0
0.5
1
1.5
Concentration

PHOSPHATE ANALYSIS

REAGENTS

Ammonium molybdate (5.72% w/v) in 6M HCl
Malachite Green solution (0.0812% in distilled water)
Distilled water

METHOD

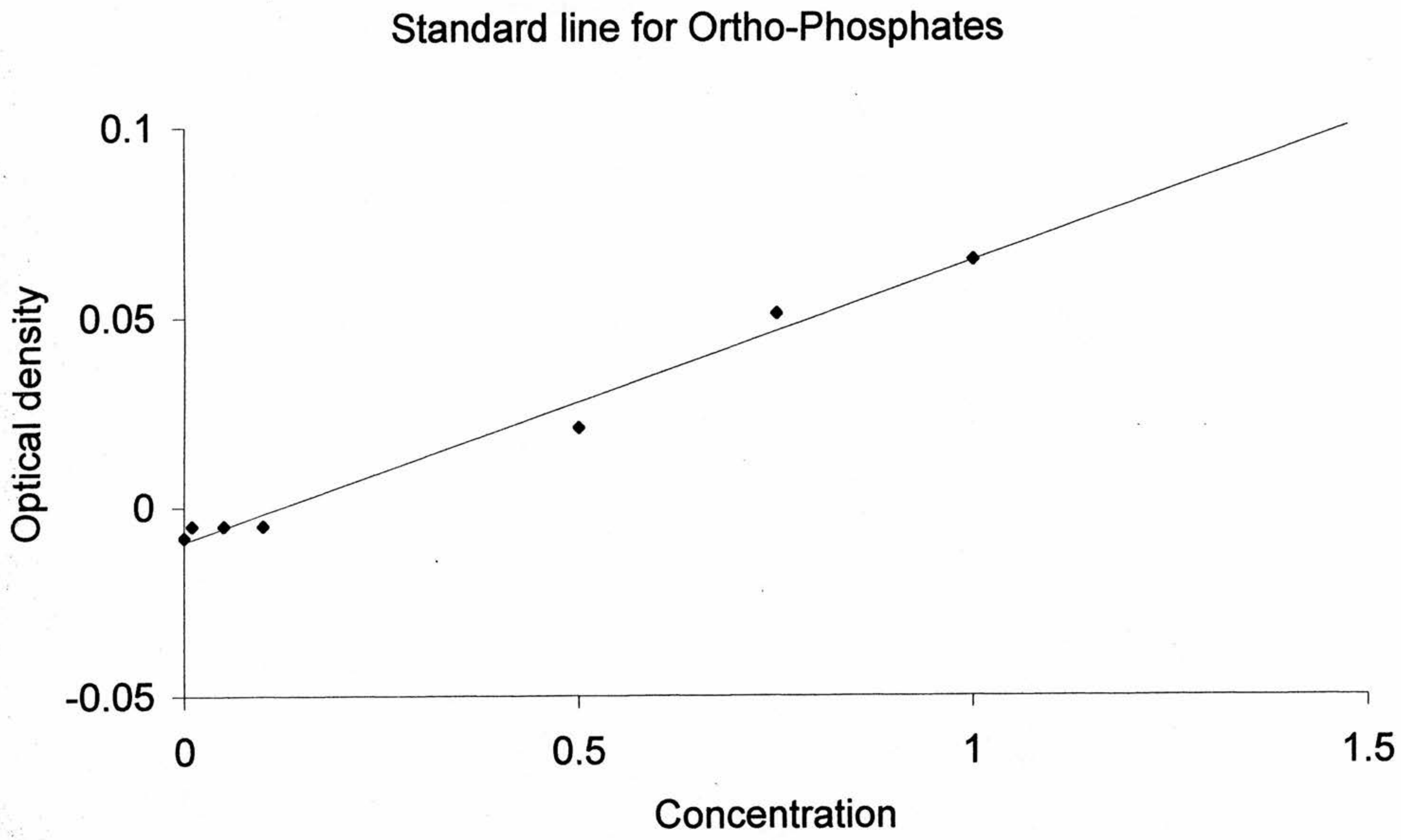
1). Mix 1 part ammonium molybdate solution with 1 part malachite green solution and 4 parts distilled water. Mix well. (= PR)

2). Add 100 µl of sample with 200 µl freshly prepared PR.

3). Prepare standard series comprising 100 µl standard and 200 µl PR.

4). Prepare a blank comprising 100 µl distilled water and 200 µl PR.

5). Mix well and read at 630 nm.


Standard line for Ortho-Phosphates
Optical density
0.1
0.05
0
-0.05
0
0.5
1
1.5
Concentration