Hydrobiologia (2007) 588:97–108
DOI 10.1007/s10750-007-0655-0

ECSA38

An assessment of the potential impact of dredging activity on the Tamar Estuary over the last century: II. Ecological changes and potential drivers

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Abstract The Tamar estuary is a Special Area of Conservation (SAC) under the EU Habitats and Species Directive and a Special Protection Area under the Wild Birds Directive (1979). The lower Tamar is also the site of the Devonport naval dockyard which requires annual maintenance dredging, as well as occasional capital dredging for new installations. The main objective of this study was to investigate whether there is any evidence of significant temporal changes in key species (intertidal macrofauna, fishes, birds) and habitats (intertidal mudflats and saltmarsh) that could be related to dredging activities in the lower Tamar. Other physical variables, such as Tamar river flow and the North Atlantic Oscillation (NAO) index, representing potential drivers of changes in the abundance of biota, were also examined. Spatial and temporal changes in the abundance of intertidal macrofauna (between 1939 and 2000) were analysed but there was insufficient comparable data to enable us to draw any conclusions about long-term changes in the Tamar estuary. Commercially and ecologically important fish species (salmon and sea trout) showed a steady decline in numbers caught in the Tamar since the 1970's. There was a significant correlation between the number of salmon caught by rod and the Tamar river flow. The sea trout abundance was significantly negatively correlated with the NAO index, suggesting that sea trout may be adversely affected by mild winters, which have been a feature of the late 1980's and 1990's. There were also significant correlations between the number of salmon caught in the Tamar and other rivers of the SW of England. Ten species of wildfowl and wader birds were analysed. There were no significant correlations between over-wintering numbers and dredging activity, but there were significant declines in teal and wigeon over 30 years. These species also showed a negative correlation with the NAO index suggesting the declines were related to the milder winters; possibly reducing their need to migrate south as far as SW England. Aerial photographs of the Tamar showed that the Egypt salt marsh, creeks and mudflat maintained a remarkably consistent structure over a period of >50 years. However, there was evidence of gradual erosion (0.23 m y^{-1}) of the saltmarsh's front cliff edge that may be related to sea level rise (~1.5 mm y^{-1} in SW England). The study concluded that there

Guest editors: R. Lafite, J. Garnier & V. De Jonge
Consequences of estuarine management on hydrodynamics and ecological functioning

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was no evidence of ecological changes related to the dredging activity in the Tamar. However, there were significant changes in salmon and sea trout catches, and the number of over-wintering teal and wigeon, over many decades and these changes appear to be related to large scale climatic events rather than anthropogenic factors within the Tamar estuary.

Keywords Tamar estuary · Dredging · NAO index · River flow · Ecological status · Birds · Fish · Salt marsh

Introduction

The majority of estuaries around the world have been physically disturbed by human activities, including reclamation of salt marshes, dredging for ports and harbours, and construction of coastal defences. Many of the larger European estuaries, namely the Seine, Westerschelde, Rhine, Ems, Ria de Aveiro, Ribble and Mersey, have been extensively modified in the early to mid 20th century by channel dredging, embankment construction and the building of outer training walls. The changes to the hydrodynamics, sediment transport and morphology have generally been thoroughly investigated (Avoine et al. 1981; da Silva and Duck, 2001; Thomas et al. 2002; van der Wal et al. 2002; Lane, 2004; Bale et al. 2007), whereas the ecological effects have received less attention (Lewis et al. 2001; de Jonge, 2000; de Jonge & de Jonge, 2002; Cox et al. 2003).

The lower Tamar estuary is the site of the Devonport naval dockyard which requires annual maintenance dredging, as well as occasion capital dredging for new installations. The Tamar is also a Special Area of Conservation (SAC) under the Council of the European Union 'Habitats and Species Directive and a Special Protection Area under the Wild Birds Directive' (1979).

The main objective of this desk-top study was to investigate whether there is any evidence of significant temporal changes in key species (intertidal macrofauna, fishes, birds) and habitats (intertidal mudflats and saltmarsh) that could be related to dredging activities or other possible physical drivers in the Tamar estuary. This study did not examine the impact of the dredged material at the disposal site which is located outside the Tamar estuary.

Materials and methods

The Tamar estuary is located in the southwest of England (Long. 4°11′ W Lat. 50°23′ N). It is a macro-tidal, drowned river (Ria) system with a tidal range of 4.7 m and extensive areas (c. 60%) of intertidal mudflats. The ecological status of the Tamar estuary was assessed by data mining and examining long time-series for key biota, which included macrofaunal abundance, fish catch data, bird counts and saltmarsh area. Data used in this desktop study were not specifically collected with the aim of assessing the impact of natural disturbance or human activity on the Tamar estuary. Hence the spatial and temporal coverage is not ideal. The abundance of biota in the Tamar estuary could be influenced by a number of potential physical drivers. Those considered were: the amount of sediment dredged from the lower Tamar, the river flow into the Tamar, and climate changes reflected in the North Atlantic Oscillation (NAO) index.

Sediment dredging

Data for the total tonnes of sediment dredged from the lower Tamar between 1976 and 2001 were obtained from the Centre for Environment, Fisheries and Aquaculture Science (CEFAS), the government agency responsible for issuing the licence to dredge and dispose of material in UK estuaries and coasts.

Tamar River flows

River flow data for the Tamar system were provided by the Environment Agency (EA) which has a gauging station on the River Tamar at Gunnislake. This accounts for 73% of the freshwater input into the Tamar estuary, with 27% entering via the River Lynher and River Tavy.

North Atlantic oscillation index

The North Atlantic oscillation (NAO) index is based on the difference in normalised sea level air pressures between Portugal (Lisbon) and Iceland (Reykjavik) (Hurrell, 1995 and updated on Hurrell's website). The winter index (December to March) reflects the winter weather conditions experienced in northwest Europe.

Intertidal macrofauna

Macrofauna data from eight different published sources were examined, but only three studies allowed some inter-comparison (Spooner & Moore, 1940; Warwick et al. 1991; Watson et al. 1995). The lack of intercomparable data arises from a number of interconnected facts: (1) Intertidal macrofauna are patchily distributed on a range of spatial and temporal scales. (2) Researchers have not set out to take intertidal macrofaunal samples in the same places, at similar times of year, over a period of time. Only four surveys have produced data with a reasonable spatial coverage of the Tamar mudflats. (3) Where samples have been collected, different sampling methods have been employed. These include sampling different areas of sediment, to different depths, sieving samples through different mesh sizes, extracting animals using different methods, and using different literature/expertise to identify them.

Analyses were conducted at the level of family, to try to compensate for taxonomic differences between surveys. Data were analysed using non-metric multidimensional scaling (MDS) using PRIMER (Clarke & Gorley, 2001).

Fish

Fish capture data (by rod and net) were obtained from the Environment Agency. Only two species, the Atlantic salmon (*Salmo salar*) and the sea trout (*Salmo trutta*), have been recorded in sufficient numbers and over several decades to provide data for a time-series in the Tamar and other estuaries in southwest England. The Tamar is one of the premier salmon rivers in the region and as a result of a gradual decline in fish numbers the EA produced a River Tamar Salmon Action Plan consultation document (Environment Agency, 1997). This aimed to identify (1) the factors causing a decline in the spring salmon run, and (2) the actions and finance necessary to maintain the salmon stock to the minimum biological acceptable level. The open season for rod fishing in the upper Tamar catchment is 1st March to 14th October for salmon and 3rd March to 30th September for migratory sea trout. The open season for the estuarine net fishery is 2nd March to 31st August. Due to the major decline in the combined rod and net catch figures for the Tamar, in 1961 bylaw changes were introduced restricting the Tamar to 15 net licences. The Net Limitation Order was renewed for a further 10 years in 1996. In 1996 voluntary measures were introduced with anglers requested to keep to a maximum limit of two salmon per person before June. The River Tamar Salmon Action Plan consultation document (Environment Agency, 1997) estimated the proportion of the total annual salmon that was exploited by rod (12.3%) and net (22%). This was based on declared data on rod and net catches and an estimate of the total numbers derived from the Gunnislake electronic fish counter between 1994 and 1996, with ~70% of salmon passing through the counter (estimated from radio tracking studies).

Birds

Bird count data for waders and wildfowl in the Tamar estuary were obtained from the WeBS database (Wetland Bird Survey) coordinated by the British Trust for Ornithology. The bird counts were based on monthly observations in three sectors in the lower Tamar (St. John's Lake–GR 430540; Lynher/Antony–GR 390560; Tavy–GR 460630) because these formed the largest intertidal areas, had the longest time-series, and were in the vicinity of the dredged section on the Tamar. We focused on ten birds, five wildfowl species (Canada goose—*Branta canadensis*; mallard—*Anas platyryhnchos*; shelduck—*Tadorna tadorna*; teal—*Anas crecca*; wigeon—*Anas penelope*) and five wader species (avocet—*Recurvirostra avosetta*; curlew—*Numenius arquata*; dunlin—*Calidris alpina*; oystercatcher—*Haematopus ostralegus*; redshank—*Tringa totanus*).

These were chosen on the basis that they were the most abundant species and because of the potential difficulties in interpreting temporal and spatial changes in species that are rare or have low abundance in the Tamar. The avocet (*Recurvirostra avosetta*) was an exception to this rule and was included due the importance of the Tamar system as an over-wintering site for this species.

Salt marsh

A large proportion of the Tamar estuary has been aerially photographed on several occasions since 1946. This provides a potential time-series of aerial surveys of the salt marshes in the Tamar estuary with the possibility of quantifying changes in the spatial coverage over >50 years. Aerial photographs taken in 1946 (Royal Air Force), 1988 (Geonex Ltd), 1992 (National Remote Sensing Centre) and 1999 (GetMapping) were obtained from the Devon and Cornwall County archives and Plymouth City Council. Egypt salt marsh (Grid Ref. SX440635) was selected for study because it is the most extensive marsh in the Tamar, approximately mid-way up the estuary on the eastern bank. Aerial photographs provided information on any gradual changes in mudflat and salt marsh morphology over the 53 years. Early aerial photographs were first geo-corrected to the digitally rectified 1999 aerial photographs thus enabling detailed comparisons to be achieved. The front edge of the Egypt salt marsh was ~0.8 m higher than the mudflat and formed a pronounced cliff face. The salt marsh was composed of *Halimione portulacoides*, *Plantago maritima*, with occasional *Spartina anglica*, *Spergularia marina* and *Cochlearia officinalis*.

Statistical analyses

Statistical analyses were performed using Minitab Statistical Software (Version 13) and PRIMER Version 5 (Clarke & Gorley, 2001).

Results

Physical variables

Maintenance dredging in the lower Tamar typically accounts for the annual removal of between 5,000 and 200,000 tonnes of dry sediment per year (Fig. 1). During the two periods of capital dredging in the Tamar, such as Weston Mill Lake in 1986 and Bull Point in 2001, the amount of sediment dredged increased significantly to between 500,000 and 700,000 tonnes per year.

The average daily mean river flow for the Tamar has been plotted separately for the winter

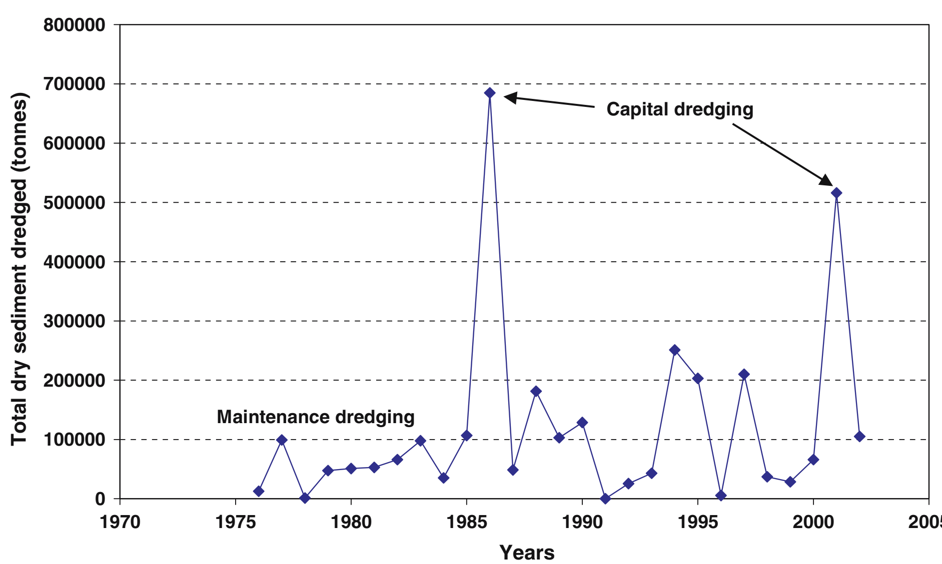


Fig. 1 The annual amount of sediment dredged from the Tamar estuary

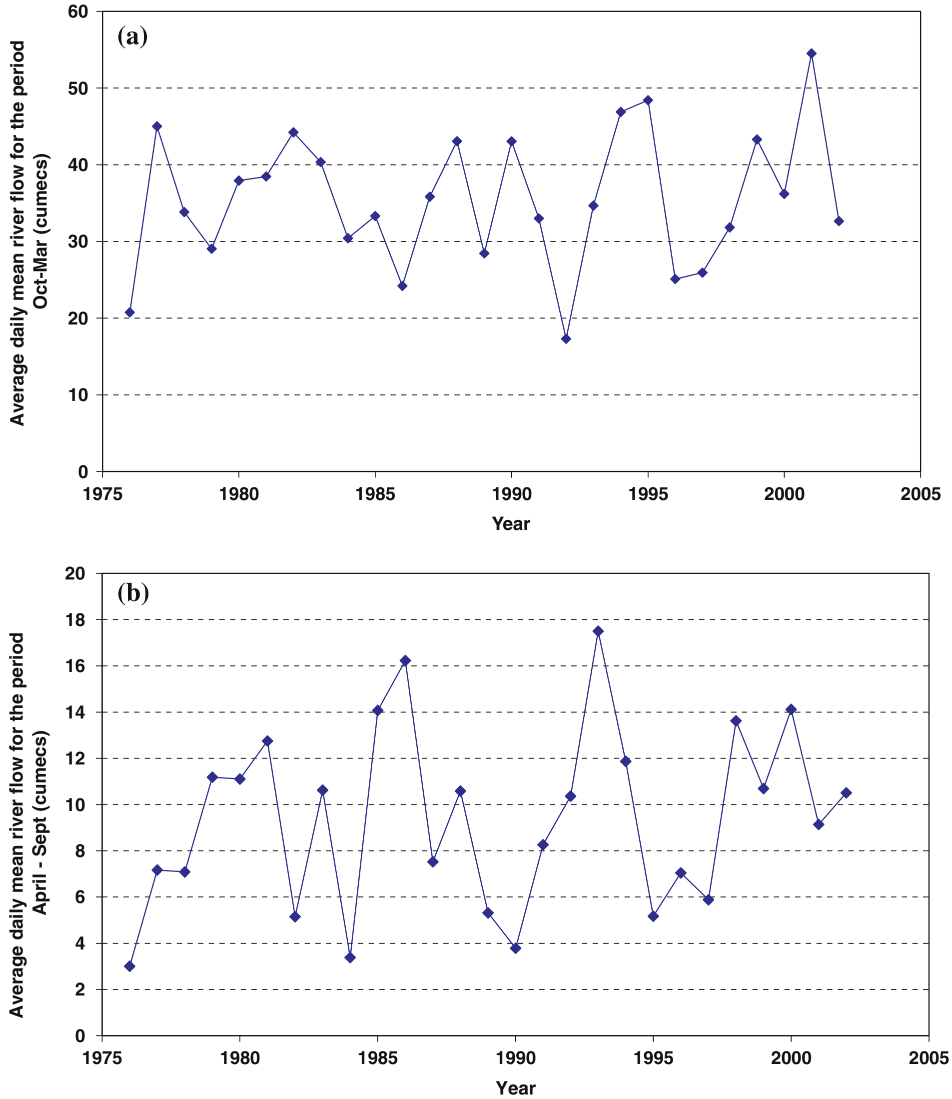


Fig. 2 Annual values for the average daily mean Tamar river flows (cumecs; m^{-3} s^{-1}) for A: Winter period (October–March) and B: Summer period (April–September)

(Fig. 2A; October–March) and the summer (Fig. 2B; April–September) seasons. This is because the high winter rainfall and river flows may influence the abundance of macrofauna and over-wintering birds, whereas the low summer flows may influence the migration and abundance of salmon and sea trout. There were low river flows with average daily mean flows of <6 m^3 s^{-1} during the summers of years 1976, 1982, 1984, 1989, 1990, 1995 and 1997. There were low river flows with average daily mean flows of <25 m^3 s^{-1} during the winters of 1976, 1986, 1992, 1996 and 1997, whereas in 1977, 1982, 1994, 1995 and 2001 there were high river flows of >45 m^3 s^{-1} which could induce significant disturbance and erosion of intertidal mudflats.

The NAO winter index (December–March) is illustrated in Fig. 3 (from Hurrell, 1995 and updated on Hurrell's website). A low NAO index tends to occur when the weather is influenced by more north-easterly winds which results in colder winters. A high NAO index tends to occur when more westerly winds dominate the winter weather with warmer waters

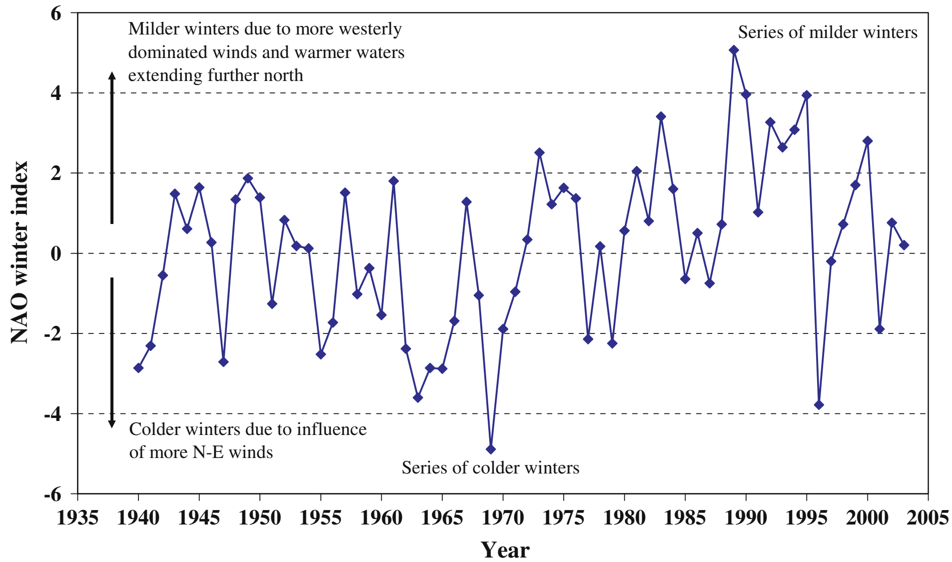


Fig. 3 Changes in the North Atlantic Oscillation Winter Index (December–March) since 1940

extending further north, and thus resulting in milder winters. The NAO index during the period 1940–2002 shows the gradual increase in the index during the 1970s, 1980s and the early 1990s, reflecting the milder winters over this period. A low NAO index, such as in 1962, 1963, 1964, 1965, 1969, 1977, 1979 and 1996, is usually associated with colder winters.

Ecological changes in the Tamar

The macrofaunal analysis showed there was a clear salinity driven gradient in benthic community structure along the estuary. However, there were clear differences between surveys, which were to be expected given that no effort was made to standardise sampling, and surveys were carried out at widely differing times by different researchers. The data that were suitable for this work were too sparse and disparate for us to draw any conclusions about changes through time in the estuary. The Tamar estuary is not atypical with respect to the quantity and quality of macrofaunal data. This problem is likely to be common to all estuaries and makes it difficult to use macrofauna community analysis as a sensitive measure for detecting long-term changes induced by anthropogenic and natural environmental factors.

Table 1 Statistical correlations between yearly fish catches in the Tamar, Exe and Taw rivers and the physical variables (river flow and North Atlantic Oscillation index)

Comparison	*r*	*P* value
Tamar salmon (rod & net) vs time (1954–2001)	–0.69	<0.001
Tamar salmon (rod & net) vs time (1961–1995)	–0.48	<0.005
Tamar sea trout (rod & net) vs time (1954–2001)	–0.64	<0.001
Tamar sea trout (rod & net) vs time (1965–1995)	–0.77	<0.001
Tamar total salmon vs total sea trout (1954–2001)	0.50	<0.001
Tamar salmon (net) vs Exe (net) (1954–2001)	0.65	<0.001
Tamar salmon (net) vs Taw (net) (1954–2001)	0.75	<0.001
Tamar salmon (rod) vs river flow (Apr–Sep) (1976–1995)	0.66	<0.001
Tamar salmon (rod & net) vs NAO index (1954–2001)	–0.21	n.s.
Tamar sea trout (rod & net) vs NAO index (1954–2001)	–0.39	0.006
Tamar salmon (net) vs NAO index (1954–2001)	–0.21	n.s.
Exe salmon (net) vs NAO index (1954–2001)	–0.10	n.s.
Taw salmon (net) vs NAO index (1995–2001)	–0.20	n.s.

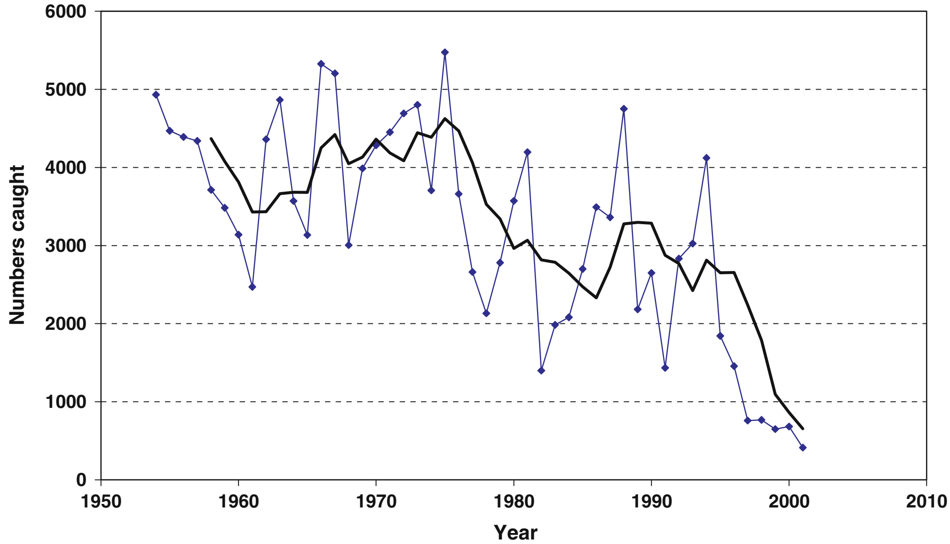


Fig. 4 Number of salmon (*Salmo salar*) caught by net and rod fishing in the Tamar estuary. Annual values (diamonds) and five year running means (thick line)

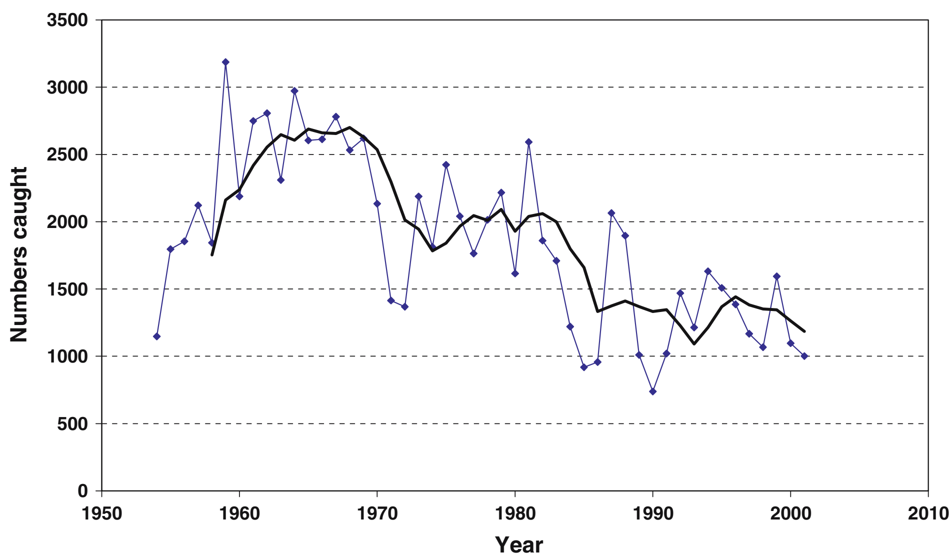


Fig. 5 Number of sea trout (*Salmo trutta*) caught by net and rod fishing in the Tamar estuary. Annual values (diamonds) and five year running means (thick line)

The numbers of salmon and sea trout caught in the Tamar have shown a steady and significant decline over several decades ($P < 0.001$; Table 1), regardless of the time-period (1954–2001, but also for 1961–1995 after the net licence restrictions and before catch limits). There was also a significant correlation between the two species ($P < 0.001$; Table 1). Net and rod catches of salmon showed a marked decline in 1975, and again in 1996, but this latter decline was in part due to the fishing restrictions introduced at this time. The overall decline was >4-fold over 30 years (Fig. 4). The number of sea trout caught also declined, but by only 50% between 1970 and 2000 (Fig. 5).

The recording of wildfowl numbers in the Tamar began in 1961, whereas the wader numbers did not start until 1971 and then only in one

Table 2 Statistical correlations for yearly bird peak numbers in the lower Tamar versus time and North Atlantic Oscillation (NAO) index

Relationship	Range of peak numbers	*r*	*P*-value
Canada goose vs time (1961–2002)	0 to 356	0.78	<0.001
Mallard vs time (1961–2002)	14 to 526		n.s.
Shelduck vs time (1961–2002)	92 to 728	0.36	0.02
Teal vs time (1961–2002)	54 to 518	–0.42	0.006
Wigeon vs time (1961–2001)	311 to 9084	–0.62	<0.001
Avocet vs time (1972–2001)	3 to 99		n.s.
Curlew vs time (1994–2001)	263 to 758	–0.74	0.037
Dunlin vs time (1994–2001)	2113 to 7011	–0.81	0.015
Oystercatcher vs time (1994–2002)	114 to 308		n.s.
Redshank vs time (1994–2002)	76 to 388	–0.86	0.006
Canada goose vs NAO (1961–2002)		0.37	0.017
Mallard vs NAO (1961–2002)		0.36	0.022
Teal vs NAO (1961–2002)		–0.35	0.025
Wigeon vs NAO (1961–2001)		–0.35	0.025

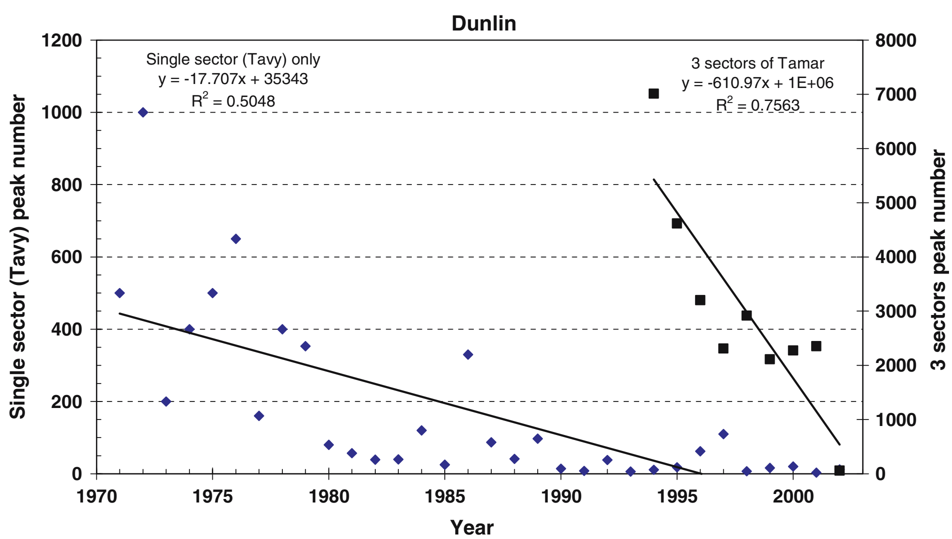


Fig. 6 Number of over-wintering dunlin recorded in the lower Tamar, showing a significant decline over time, regardless of whether recording in a single sector (Tavy) over a long time-scale (1971–2002), or a short time-scale but in all three lower Tamar sectors (1994–2002)

sector (the Tavy branch of the estuary). The recording of waders in all three sectors did not occur until 1994, thus providing a more limited time-series. Temporal changes in the peak numbers of over-wintering wildfowl and waders in the Tamar estuary were variable. Table 2 presents the significant correlations between bird peak numbers against time. Some species showed little change (mallard, avocet, oystercatcher) while others increased significantly (Canada goose, shelduck) and some declined markedly (wigeon, teal, curlew, dunlin and redshank). The increase in Canada goose numbers in the Tamar since the early 1980s probably reflects its general increase since its introduction from North America. The decline in the numbers of curlew, dunlin (Fig. 6) and redshank was significant, regardless of whether recording in a single sector (Tavy) over a longer time-scale ($P < 0.002$; 1971–2002) or a shorter time-scale but in all three Tamar sectors (Table 2; 1994–2002).

The aerial photographs of the Egypt salt marsh in 1946 (Fig. 8a) and 1999 (Fig. 8b) clearly

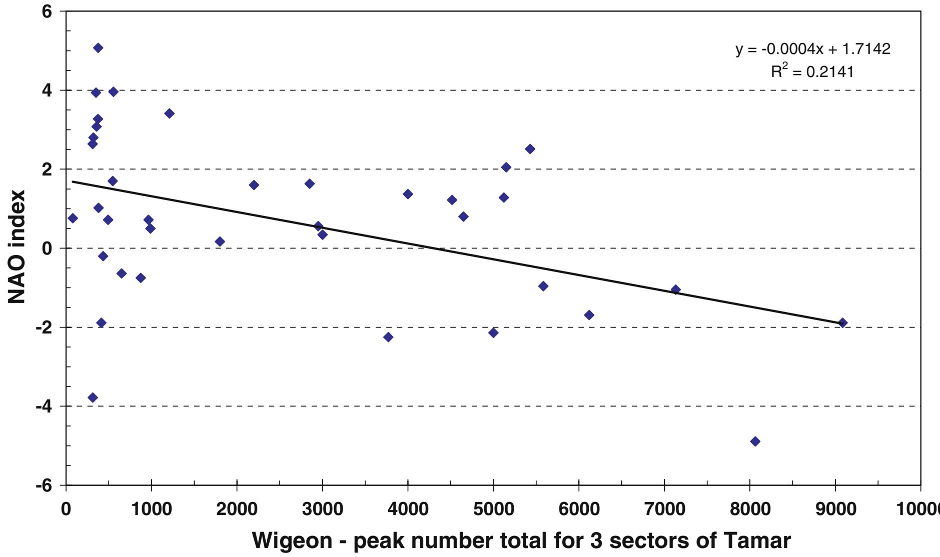
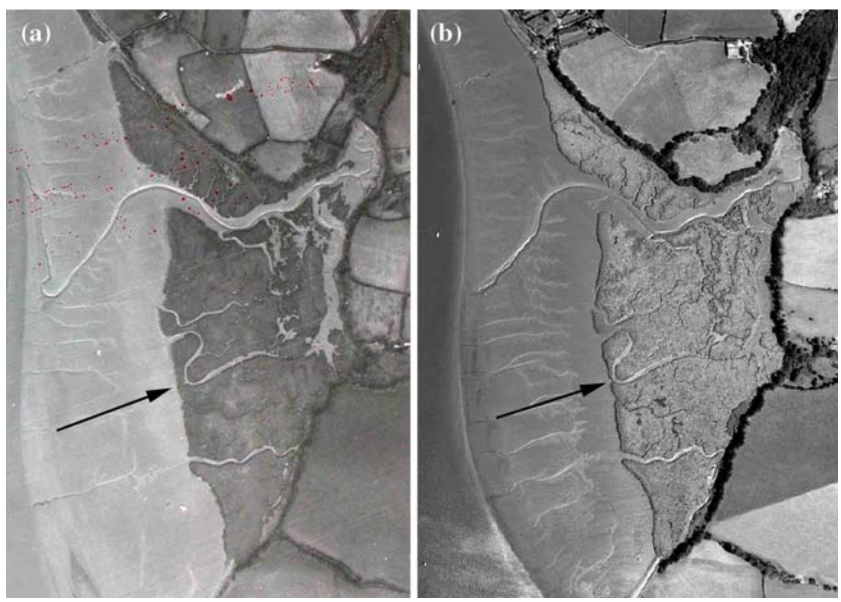


Fig. 7 Relationship between North Atlantic Oscillation (NAO) index (December–March) and peak numbers for over-wintering wigeon in the lower Tamar for the years 1961–2001

Fig. 8 (**A**) Aerial photograph of Egypt salt marsh and mudflat on the eastern bank of the Tamar, taken in 1946 (reproduced with kind permission of the RAF). (**B**) Aerial photograph of Egypt salt marsh and mudflat taken in 1999 (reproduced with kind permission of Getmapping.com). Arrow denotes salt marsh cliff where there is clear evidence of gradual erosion over 53 years



demonstrate that creeks, both within the salt marsh and the main drainage creek crossing the 300 m wide mudflat, have a very consistent structure over a period of >50 years. Even the strong physical processes in the Tamar estuary (i.e. tidal currents, waves, rainfall and fluvial flow) have failed to alter the course of the established creek that drains the salt marsh and runs down the mudflat. The only noticeable change was the gradual erosion of the salt marsh's front cliff edge (arrows in Fig. 7 and 8). It was estimated that ~12 m of the front edge of the salt marsh was eroded between 1946 and 1999, which is equivalent to an erosion rate of 0.23 m y^{-1}. This is consistent with recent observations in the field during the winter, when blocks between 0.15 and 0.3 m in depth are found on the mudflat in-front of the cliff.

Discussion

Both the Tamar river flow and the amount of sediment dredged from the Tamar were considerably lower than reported for other larger European estuaries, ranging from the Mersey (river flow 25–300 $m^3 s^{-1}$, 3×10^6 tonnes dry sediment dredged y^{-1}; Lane, 2004) to the Rhine (mean annual flow of 2,200 $m^3 s^{-1}$; 10.8×10^6 dry tonnes y^{-1}; de Jonge & de Jonge, 2002). However, the ratios between sediment dredged and river flow were similar. There was no evidence that changes in numbers of fish captured, or over-wintering birds, or salt marsh erosion were correlated with dredging activity in the Tamar estuary. However, there were significant correlations with indicators of large scale inter-annual changes in climate (e.g. NAO index and river flows).

There was a significant correlation between salmon catches by rod and the Tamar river summer flow ($P < 0.001$; Table 1). This analysis was limited to the period 1976–1995 to avoid the period of catch limitation introduced for the Tamar in 1996, although there was also a similar correlation ($r = 0.56$, $P = 0.003$) for the whole period (1976–2001). A similar correlation between salmon rod catches and river flow was recorded in the Aberdeenshire Dee by Potts & Malloch (1991). Erkinaro et al. (1999) also observed a positive correlation, with low river flow reducing swimming activity and delaying salmon migration in Norway.

Comparison between salmon net catches in the Tamar and other Devon estuaries (Table 1) showed a similar inter-annual pattern with a major decline in numbers during the 1990s. The Tamar, Exe and Taw/Torridge estuaries all showed peaks in salmon netted in the mid-1950s, 1962, 1966, 1971–73, 1975, 1981, 1987–89, and there were significant correlations between the estuaries ($P < 0.001$; Table 1). This inter-annual variation in the number of salmon caught is indicative of factors acting over a large spatial scale rather than on a local scale in individual estuaries (e.g. pollution or dredging activity). Two important measures of annual changes in climate, namely river flow and the NAO index, were also correlated with the fish catch data (Table 1). The Tamar sea trout data was significantly negatively correlated with the NAO index for the period 1954–2001. This suggests that sea trout may be adversely affected by milder winters ($r = -0.39$; $P = 0.006$), rather than river flow during the spring-summer (no significant correlation). There were consistent negative correlations between the NAO index and salmon caught in the Tamar and other Devon estuaries, but these were not statistically significant ($P = 0.10$), despite the significant correlation between the catches of salmon and sea trout. The lack of a significant correlation between salmon caught and the NAO index may be due to the distortions to the salmon catch data caused by changes in catch efficiency, catch limitation and licensing regulations. The long-term ecological and economic implications of a negative correlation between fish abundance and the NAO index, is the continuing decline in the sea trout, and possibly salmon fisheries, with global warming (milder winters and earlier springs). Sims et al. (2004) has recorded a significant negative correlation between the NAO index and the timing of migration and the peak abundance of the flounder (*Platichthys flesus*) off south-west England. Flounder migrated onto their estuarine spawning grounds some 1–2 months earlier in years that were up to 2°C cooler, and over a shorter time period (2–6 days) compared to warmer years (12–15 days).

The results showed significant correlations between peak bird numbers and the NAO index (Table 2) for four of the five wildfowl species (Canada goose, mallard, teal and wigeon). The Canada goose and mallard were positively correlated with NAO, showing a tendency to increase in numbers with milder winters. These are resident species and the positive correlation could reflect a decline in numbers during colder winters, possibly due to a movement further southwards or locally away from the estuary, or mortality. In contrast, the teal and wigeon (Fig. 7) were negatively correlated with NAO showing a tendency to decline during the warmer winters. The wigeon breeds in Iceland and Scandinavia and the teal breeds in northern Britain but both over-winter in the south of England. Therefore the colder winters (i.e. lower NAO index) may result in the birds moving further south and increasing their over-wintering numbers in southwest England. We are not aware of literature showing similar correlations between the NAO index and the number of over-wintering wildfowl and waders. There are, however, correlations between the NAO index and the time of arrival of short-distance migrant birds returning to their breeding ground after over-wintering in western and southern Europe (Forchhammer et al. 2002; Jonzen et al. 2002). The milder winters associated with the higher NAO lead to improved foraging and weather conditions during their northward spring migration.

None of the wildfowl or wader species studied showed any correlation between bird numbers and dredging activity in the Tamar. There were no marked changes in numbers during the year of peak dredging activity or during the following winter (1986–2001).

There is no evidence to suggest that the salt marsh erosion is caused by the dredging of sediment from the lower Tamar estuary. Significant salt marsh erosion occurs in the Bristol Channel (Allen, 1993) and in southeast England (Hughes & Paramor, 2004), where it is associated with combined sea level rise and isostatic adjustment of the land after the last glacial period (i.e. uplift of the land in Scotland and downward movement of land in southern England). In southwest England there is an average sea level rise of ~1.5 mm y^{-1} and this may be a contributory factor to the erosion of Egypt salt marsh. Other important factors include the high fluvial flows in the winter months, combined with wave action coinciding with high water. Dredging in the Tamar is unlikely to be a contributory factor because there was no significant change in the tidal prism, due to the removal of relatively small amounts of sediment, and there appears to be a reasonably balanced sediment budget (Bale et al., 2007). This is in contrast to the Westerschelde estuary, where there has been extensive dredging and deepening of the shipping channels since the mid 1960s. Cox et al. (2003) examined aerial photographs and demonstrated alternating phases of extension and erosion of the salt marsh edge. The balance between extension and erosion appeared to be related to the increase in the tidal prism brought about by the dredging operations. The consequent increase in the inundation frequency of the marshes increased the erosion rate due to tidal currents and waves. Bakker et al. (1993) reported rates of erosion of salt marsh of up to 4 m $year^{-1}$ in the Westerschelde which were attributed to changes in the location of the channel caused by intensive dredging.

Conclusions

The numbers of salmon and sea trout caught, and the numbers of over-wintering wildfowl and wader birds (teal, wigeon, curlew, dunlin, redshank) in the Tamar estuary have declined over several decades. There was no evidence that these changes were related to dredging activity in the Tamar. Significant positive correlation between salmon and river flows, and negative correlation between sea trout and the NAO index, indicate that these declines were probably driven by reduced river flow and milder winters. Similarly, the significant negative correlations between teal, wigeon and the NAO index suggest that lower over-wintering numbers were associated with milder winters. However, it is not known whether this may be due to poorer breeding success in northern Europe or due to the winter migration of these species not extending as far south during milder winters. Aerial photographs demonstrated that the mudflats, creeks and salt marsh maintained a very consistent structure over a period of >50 years. However, there was a slow rate of erosion of the cliff at the front of the salt marsh, but this could not be related to any natural or anthropogenic disturbances due to the relatively infrequent records of aerial photography.

Acknowledgements This work was jointly funded by the Tamar Estuaries Consultative Forum and the NERC Estuaries and Coastal Function and Health programme of the PML. Fish count data was supplied by the Environment Agency. Bird count data were supplied by the Wetland Bird Survey (WeBS), a joint scheme of the Brtitish Trust for Ornithology, The Wildfowl & Wetlands Trust, Royal Society for the Protection of Birds and Joint Nature Conservation Committee.

References

Allen, J. R. L., 1993. Muddy alluvial coasts of Britain: field criteria for shoreline position and movement in the recent past. Proceedings of the Geologists' Association 104: 241–262.

Avoine, J., G. P. Allen, M. Nichols, J. C. Salomon & C. Larsonneur, 1981. Suspended-sediment transport in the Seine estuary, France: effect of man-made modifications on estuary-shelf sedimentology. Marine Geology 40: 119–137.

Bakker, J. P., J. Deleeuw, K. S. Dijkema, P. C. Leendertse, H. H. T. Prins & J. Rozema, 1993. Salt marshes along the coast of the Netherlands. Hydrobiologia 265: 73–95.

Bale, A. J., R. J. Uncles, A. Villena-Lincoln & J. Widdows, 2007. As assessment of the potential impact of dredging activity on the Tamar estuary over the last century: I. Bathymetric and hydrodynamic changes. Hydrobiologia 588: 83–95.

Clarke, K. R. & R. N. Gorley, 2001. PRIMER v5: User manual/tutorial. PRIMER-E Ltd, Plymouth UK. pp. 91.

Cox, R., R. A. Wadsworth & A. G. Thomson, 2003. Long-term changes in salt marsh extent affected by channel deepening in a modified estuary. Continental Shelf Research 23: 1833–1846.

da Silva, J. F. & R. W. Duck, 2001. Historical changes of bottom topography and tidal amplitude in the Ria de Aveiro, Portugal—trends for future evolution. Climate Research 18: 17–24.

Environment Agency, 1997. River Tamar Salmon Action Plan consultation document. Environment Agency, South West Region, Exeter, 50pp.

Erkinaro, J., F. Okland, K. Moen, E. Niemela & M. Rahaiala, 1999. Return migration of Atlantic salmon in the River Tana: role of environmental factors. Journal of Fish Biology 55: 506–516.

European Union, 1997. Council Directive 97/62/EC adapting Directive 92/43/EEC on the conservation of natural habitats and of wild fauna and flora. Council of the European Union.

Forchhammer, M. C., E. Post & N. C. Stenseth, 2002. North Atlantic Oscillation timing of long- and short-distance migration. Journal of Animal Ecology 71: 1002–1014.

Hughes, R. G. & O. A. L. Paramor, 2004. On the loss of saltmarshes in southeast England and methods for their restoration. Journal of Applied Ecology 41: 440–448.

Hurrell, J., 1995. Decadal trends in the North Atlantic Oscillation: regional temperatures and precipitation. Science 269: 676–679.

de Jonge, V. N., 2000. Importance of temporal and spatial scales in applying biological and physical process knowledge in coastal management, an example for the Ems Estuary. Continental Shelf Research 20: 1655–1686.

de Jonge, V. N. & D. J. de Jong, 2002. 'Global change' impact of inter-annual variation in water discharge as a driving factor to dredging and spoil disposal in the river Rhine system and of turbidity in the Wadden Sea. Estuarine Coastal and Shelf Science 55: 969–991.

Jonzen, N., A. Hedenstrom, C. Hjort, A. Lindstrom, P. Lundberg & A. Andersson, 2002. Climate patterns and the stochastic dynamics of migratory birds. Oikos 97: 329–336.

Lane, A., 2004. Bathymetric evolution of the Mersey Estuary, UK, 1906–1997: causes and effects. Estuarine Coastal and Shelf Science 59: 249–263.

Lewis, M. A., D. E. Weber, R. S. Stanley & J. C. Moore, 2001. Dredging impact on an urbanized Florida bayou: effects on benthos and algal-periphyton. Environmental Pollution 115: 161–171.

Potts, W. T. W. & A. J. C. Malloch, 1991. River flow, Atlantic salmon (Salmo salar L.) movement and rod catch in the Aberdeen Dee. Journal of Fish Biology 39: 755–764.

Sims, D. W., V. J. Wearmouth, M. J. Genner, A. J. Southward & S. J. Hawkins, 2004. Low-temperature-driven early spawning of a temperate marine fish. Journal of Animal Ecology 73: 333–341.

Spooner, G. M. & H. B. Moore, 1940. The ecology of the Tamar estuary. VI. An account of the macrofauna of the intertidal muds. Journal of the marine biological Association of the U.K. 24: 283–330.

Thomas, C. G., J. R. Spearman & M. J. Turnbull, 2002. Historical morphological change in the Mersey Estuary. Continental Shelf Research 22: 1775–1794.

van der Wal, D., K. Pye & A. Neal, 2002. Long-term morphological change in the Ribble Estuary, northwest England. Marine Geology 189: 249–266.

Warwick, R. M., J. D. Goss-Custard, R. Kirby, C. L. George, N. D. Pope & A. A. Rowden, 1991. Static and dynamic environmental factors determining the community structure of estuarine macrobenthos in SW Britain: Why is the Severn Estuary different? Journal of Applied Ecology 28: 329–345.

Watson, P. G., R. J. Clifton, J. T. Davey, P. E. Frickers & A. W. Morris, 1995. Sediment-water contaminant exchange. National Rivers Authority Report, Bristol, 185pp.