

## NOT TO BE CITED WITHOUT PRIOR REFERENCE TO THE AUTHORS

International Council for  
the Exploration of the Sea

Theme Session N: Ecology of  
Diadromous Fishes During the early  
Marine Phase. CM 1998/N:16

### THE RIVERINE, ESTUARINE AND COASTAL MIGRATORY BEHAVIOUR OF WILD ATLANTIC SALMON (*SALMO SALAR* L.) SMOLTS.

A. Moore\*, I.C. Russell\*, M. Ives\*, S. Ives\*, E.C.E. Potter\* and C.P. Waring\*\*,

\*Centre for Environment, Fisheries and Aquaculture Sciences,  
Lowestoft Laboratory, Pakefield Road, Lowestoft, Suffolk, NR33 0HT, UK  
Phone: 01502 524212 Fax: 01502 513865 E-mail: a.moore@cefas.co.uk

\*\* School of Biological Sciences, University of Portsmouth, Portsmouth, Hampshire,  
P2DY, UK

#### ABSTRACT

The migratory behaviour of wild Atlantic salmon *Salmo salar* (L.) smolts during their emigration from fresh water to the marine environment has been studied in 4 river systems in England and Wales using acoustic telemetry. Smolts trapped in freshwater and implanted with miniature acoustic transmitters were monitored during their subsequent migrations through the river estuaries and into coastal waters. Migration in freshwater was predominantly nocturnal, although there was a seasonal change in this pattern with later run fish moving during both the day and night. Smolts tagged earlier in the studies spent significantly longer in the rivers before migrating into coastal waters than fish tagged later in the studies. The movement of smolts through the estuaries was indicative of a nocturnal selective ebb tide transport pattern of migration. All the smolts migrated seawards on an ebb tide close to the surface and within the fastest moving section of the water column. Smolt migration in the lower portion of the estuaries was indicative of active directed swimming and there was no apparent period of acclimation required when moving from fresh to saltwater. Migration within coastal waters was again rapid within the upper water column and movement occurred during both day and night. There was a strong tidal component to the speed and direction of movement.

The impact of estuarine barrages and the exposure to sublethal levels of pesticides on the migratory behaviour and subsequent survival of salmon smolts in the marine environment is also described and discussed.

## INTRODUCTION

The spring emigration of Atlantic salmon smolts from freshwater to the marine environment is a period of rapid transition during which time the fish encounter a range of novel environmental and biological conditions. Adaptation to the marine environment is considered to occur whilst the fish are in freshwater (Boeuf 1993) and it has been suggested that the cues initiating smolt migration are related to a physiological requirement to move to saline conditions (Moore *et al.*, 1995). The emigration of smolts is regarded as a period of high mortality and the timing of the movement into coastal waters has been suggested to be important to their survival and subsequent return as adult fish (Hansen & Jonsson, 1989). Recent studies have suggested that this timing is the result of a seasonal change in the migratory behaviour of the smolts which enables the fish to enter the marine environment during a brief window of opportunity (Moore *et al.* 1995). However, the environmental mechanisms operating within the marine environment that may make this timing so critical have so far not been elucidated. An understanding of the factors affecting the timing of emigration and the orientation of salmon smolts through estuaries and into the marine environment is therefore important for the successful management of salmonid stocks.

This paper reviews a number of recent telemetry studies in river systems in England and Wales on the migratory behaviour of wild salmon smolts and their initial movements in coastal waters. The investigations suggest a seasonal change in the nocturnal pattern of movement and a selective ebb tide transport component to the migration within the estuary. The behaviour patterns of wild salmon smolts appear to have evolved to permit rapid, energetically favourable migration through the estuary at the optimum time whilst minimising the risk of predation. There also appears to be a strong tidal component to the speed and direction of movement of the smolts within the marine environment that results in the smolts migrating rapidly through the coastal zone.

## MATERIALS AND METHODS

Smolts were studied in the Rivers Avon and Test in southern England and Conwy and Tawe in Wales. The river systems have previously been described by Moore & Potter, (1994); Moore *et al.*, (1998); Moore *et al.*, (1995); Moore *et al.*, (1996). Smolts were trapped at night in freshwater as they migrated seawards and implanted with miniature 300 kHz acoustic transmitters (Moore *et al.*, 1990). The movement of the smolts within the river and estuary were monitored using an array of 300 kHz acoustic signal relay buoys (Moore *et al.*, 1995). Migration in the open sea was studied by actively tracking individual fish from a small research vessel immediately they left the estuary mouth (Moore *et al.*, 1998). The position of the boat was fixed at two-minute intervals using a Magellan GPS NAV 5000 PRO Satellite Receiver. Water depth was also continually monitored and recorded using the vessel's echo sounder.

## RESULTS AND DISCUSSION

### *Freshwater migration*

Migration in the freshwater sections of all four rivers was predominantly nocturnal although there was a seasonal change in this pattern of movement. Nocturnal migration early in the smolt run switched to movement during both day and night as the season progressed (Figure 1). This change in the migratory pattern of behaviour was reflected in a significant seasonal change in the residency time of the smolts, with fish tagged later in the season spending less time in freshwater before migrating into coastal waters (Figure 2). As a consequence, a significant proportion of the tagged smolts migrated out of the estuaries and into coastal waters over a brief 5-10 day period (Moore *et al.* 1995; Moore *et al.* 1998). This period may represent the optimal time or window of opportunity for smolts to migrate from the freshwater and into the marine environment. The nocturnal pattern of migration would appear to be the result of an endogenous rhythm of swimming activity, which results in fish moving into the upper water column after dusk and migrating downstream. This hypothesis is supported by a laboratory based behaviour study, which suggested that the light dark cycle might act as a *zeitgeber* (Moore *et al.* 1995). A number of fish were detected holding station in deep pools during the daytime, but subsequently moved downstream during the hours of darkness. Nocturnal migration of salmon smolts during the smolt run may reduce the chances of avian predation particularly by cormorants (*Phalacrocorax carbo*) and herons (*Ardea cinerea*) which are considered to prey on smolts. As the majority of these birds feed visually during the day (Kennedy & Greer, 1988), refuging of salmonid smolts close to the bed of the river during the day and migrating at night would reduce predation pressures on the fish. The nocturnal pattern of migration, which was not evident in later-running smolts, suggests a modification to the clock component controlling swimming behaviour. Departure from the predominantly nocturnal pattern of migration in later-run smolts may be related to ensuring that they reach coastal waters at the optimal time and enter the marine environment during the window of opportunity. The switch to day and night migration later in the season may subsequently make the smolts more vulnerable to predators. However, Fraser *et al.* (1993) have recently suggested that later in the season as the water temperature increases the smolts are better able to avoid endothermal predators.

### *Estuarine migration*

The initial movement of smolts through the estuaries was indicative of a nocturnal selective ebb tide transport pattern of migration (Figure 3). All the smolts migrated seawards on an ebb tide close to the surface and within the fastest moving section of the water column (Moore *et al.*, 1995; Moore *et al.* 1998). Energetically this is the most advantageous strategy for migration and would result in the rapid movement of smolts out into coastal waters. Where individual smolts emigrating through more extensive estuaries (e.g. River Test) did encounter a flooding tide, they moved away from the highest currents either closer to the bed of the estuary or to the estuary shores (Moore *et al.*, 1998). This either prevented the smolts being displaced large distances upstream or allowed the fish to continue to migrate seawards against the prevailing

current. Smolt migration in the lower portion of the estuaries was indicative of active directed swimming with the fish moving at speeds in excess of the current and often against the direction of flow (Moore *et al.* 1995). LaBar *et al.* (1978) have previously reported active swimming against the current by salmon smolts in the lower sections of the Penobscot River estuary. The significant change in the smolts behaviour from moving passively with the current to actively swimming seawards could have been initiated when the fish encountered a particular salinity threshold. There was no apparent period of acclimation required when moving from fresh to saltwater, and a physiological requirement to move to a saline environment may therefore be an important cue in initiating smolt migration (Moore *et al.*, 1995).

### ***Marine migration***

Tracking wild salmon smolts in the coastal zone is time-consuming and labour intensive and as a result the amount of data so far obtained on the marine migration of wild salmon smolts is limited. However, the available data indicated that the movement of salmon smolts from the estuary and into the coastal zone was continuous and occurred predominantly during the ebbing tide. The late season pattern of movement as observed in estuaries was still evident and smolts continued to migrate within coastal waters during both day and night. Fish migrated close to the surface and there was a strong tidal component to the speed and direction of movement (Figure 4). Fish emigrating from the River Avon (Figure 5) migrated in an easterly, south-easterly or southerly directions, predominantly in the direction of the prevailing tidal stream. It was not possible to track these fish for periods greater than 6 hours and so nothing is known of the pattern of movement after the reversal of the tidal direction. Tagging data from salmon released in adjacent river systems suggest that smolts migrate rapidly during the initial stages of their marine life cycle (Russell pers. comm.).

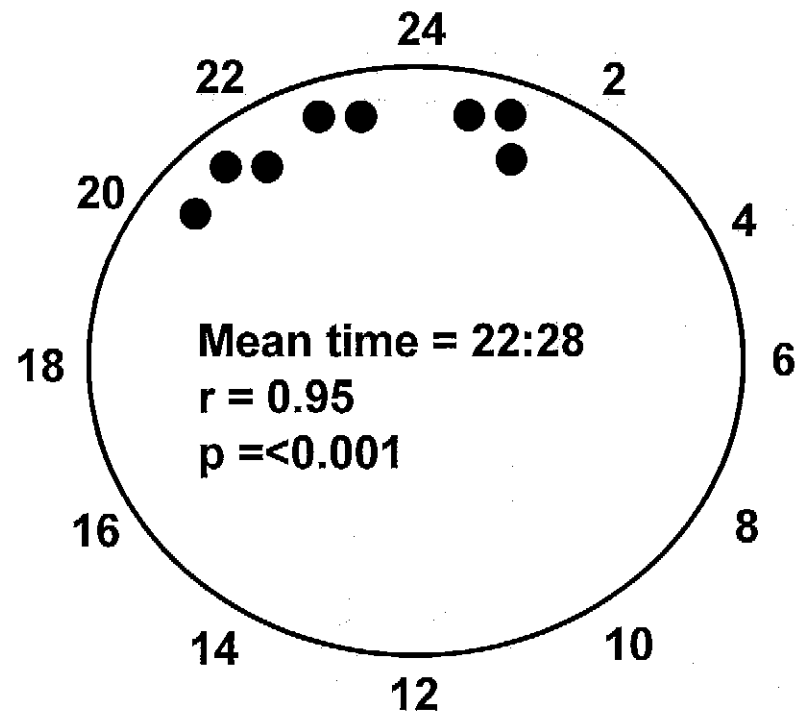
### ***Estuarine barrages***

Recently, there has been increasing concern about the potential impact of estuarine developments, such as barrages, on the emigration and survival of salmon smolts. A telemetry study on the impact of an estuarine barrage constructed across the River Tawe, South Wales, demonstrated that salmon smolts were significantly delayed within the impoundment prior to moving into the marine environment (Moore *et al.*, 1996). The construction of the barrage, which resulted in the formation of a largely freshwater lake, the length of the original estuary, modified the tidal cycle and removed the strong ebb tide currents that the smolts used to emigrate rapidly seawards. The significant reduction in the tidal cycle also resulted in poor water quality above the barrage and the concentration of contaminants within the impoundment. The exposure of salmon smolts to sub-lethal levels of pesticides (Waring & Moore 1996) and oestrogenic compounds (Madsen *et al.*, 1996) have been shown to significantly effect the hypo-osmoregulatory capabilities of the fish and result in high mortality once the fish migrate into the marine environment. In addition to the delay to migration caused by estuarine barrages, toxic mechanisms that interfere with smoltification and the adaptation of the smolts to the marine environment may also be a factor in the decline of some salmon stocks.

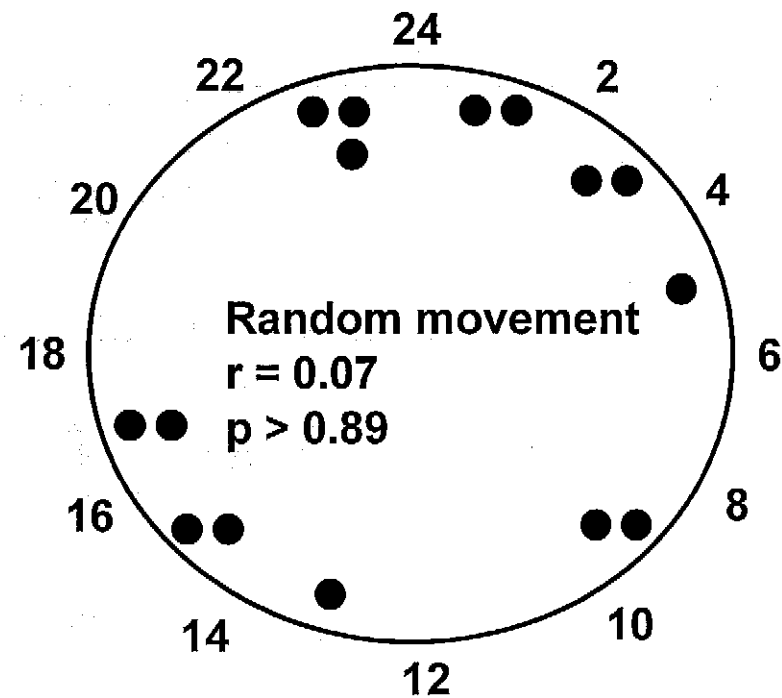
## REFERENCES

- Batschelet, E. 1981. *Circular Statistics in Biology*. London: Academic Press. 371 pp.
- Boeuf, G. 1993. Salmonid smolting: a pre-adaptation to the oceanic environment. In: *Fish Ecophysiology*. Edited by J.C. Rankin and F.B. Jensen Chapman and Hall, London. 105-135.
- Fraser, N.H.C., Metcalfe, N.B. & Thorpe, J.E. 1993. Temperature dependent switch between diurnal and nocturnal foraging in salmon. *Proceedings of the Royal Society of London B* **252**, 135-139.
- Hansen, L. P. & Jonsson, B. 1989. Salmon ranching experiments in the River Imsa; Effect of timing of Atlantic (*Salmo salar*) smolt migration on the survival to adults. *Aquaculture* 82: 367-373.
- Kennedy, G.J.A. & Greer J.E. 1988. Predation by cormorants, *Phalacrocorax carbo* (L.), on the salmonid populations of an Irish river. *Aquaculture and Fisheries Management* **19**, 159-170
- LaBar, G. W., J.D. McCleave, & Fried, S.M. 1980. Seaward migration of hatchery-reared Atlantic salmon, *Salmo salar*, smolts in the Penobscot River estuary, Maine: open water movements. *Journal du Conseil International pour l'Exploration de la Mer* **38**, 257-269.
- Madsen, S.S., Mathiesen, A.B. & Korsgaard, B. 1997. Effects of 17 $\beta$ -estradiol and 4-nonylphenol on smoltification and vitellogenesis in Atlantic salmon (*Salmo salar*). *Fish Physiology and Biochemistry* **17**, 303-312.
- Moore, A. & Potter, E.C.E. 1994. The movements of sea trout (*Salmo trutta* L.) smolts through the estuary of the River Avon, Southern England. *Fisheries Management and Ecology* **1**, 1-14.
- Moore, A., Russell, I.C., & Potter, E.C.E. 1990. The effects of intraperitoneally implanted dummy acoustic transmitters on the behaviour and physiology of juvenile Atlantic salmon, *Salmo salar* L. *Journal of Fish Biology* **37**, 713-721.
- Moore, A., Potter, E.C.E., Milner, N.J. & Bamber, S. 1995. The migratory behaviour of wild Atlantic salmon (*Salmo salar* L.) smolts in the estuary of the River Conwy, North Wales. *Canadian Journal of Fisheries and Aquatic Sciences* **52(9)**, 1923-1935
- Moore, A., R. Stonehewer, L.T. Kell, M.J. Challiss, M. Ives, I.C. Russell, W.D. Riley & D.M. Mee, 1996. The movements of emigrating salmonid smolts in relation to the Tawe barrage, Swansea. In: *Barrages: Engineering Design & Environmental Impacts*. Edited by N. Burt & J. Watts. HR Wallingford Ltd. John Wiley & Sons Ltd. 409-417.

Moore, A., Ives, S., Mead, T.A. & Talks, L. (1998) The migratory behaviour of wild Atlantic salmon smolts in the River Test and Southampton Water, southern England. *Hydrobiologie* (In press).



## Early Season



## Late Season

Figure 1. The seasonal migration of Atlantic salmon smolts in the River Avon (1998) in relation to the time of day. The mean times that fish were recorded passing a sonar buoy situated at the top of the estuary have been calculated from the mean vectors (Batschelet 1981). The 'r' values provide a measure of randomness on movement with respect to time calculated using the Rayleigh test.

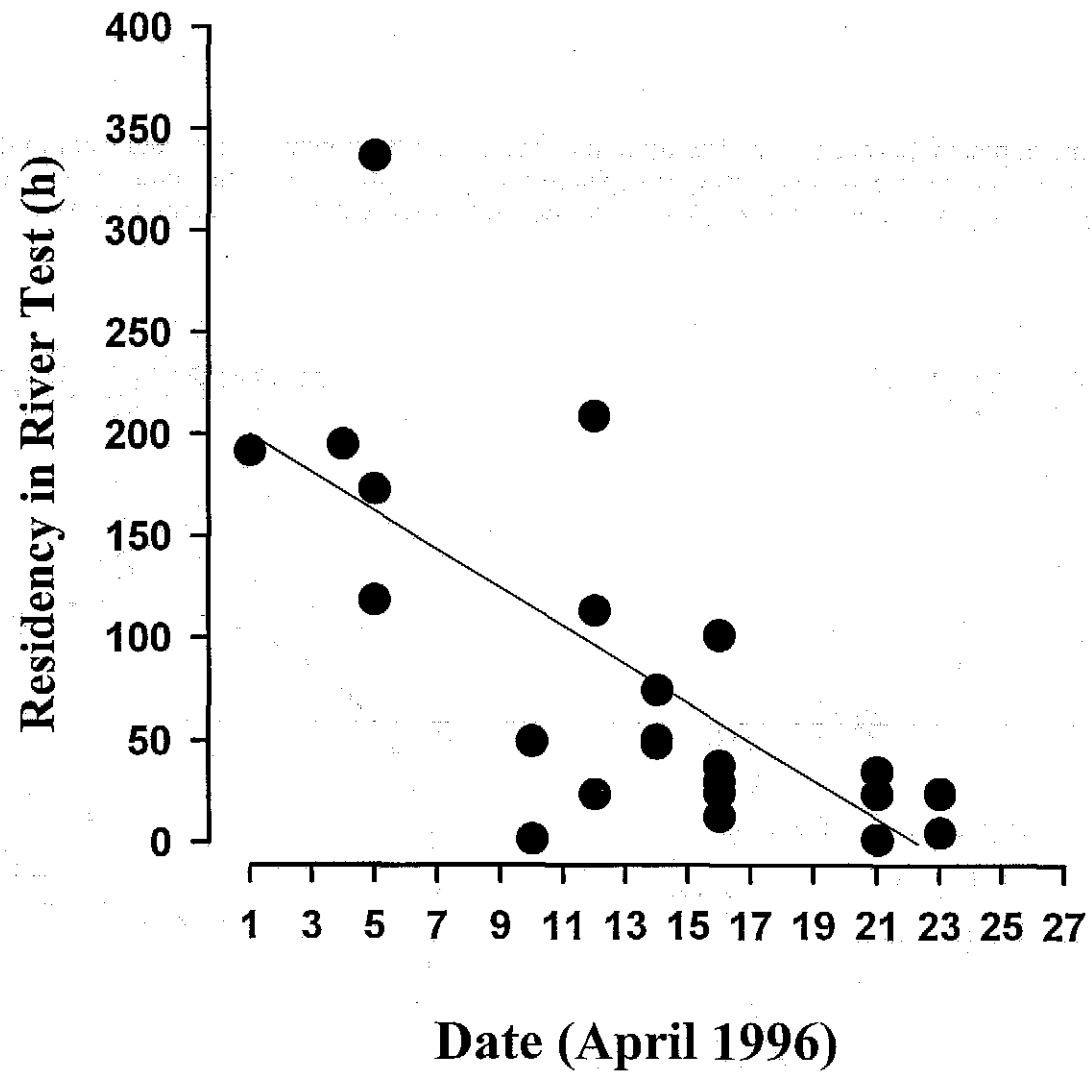


Figure 2. The relationship between transit time within the River Test after tagging and day of release of salmon smolts (least squares regression:  $r^2 = 0.539$ ;  $p < 0.01$ ).



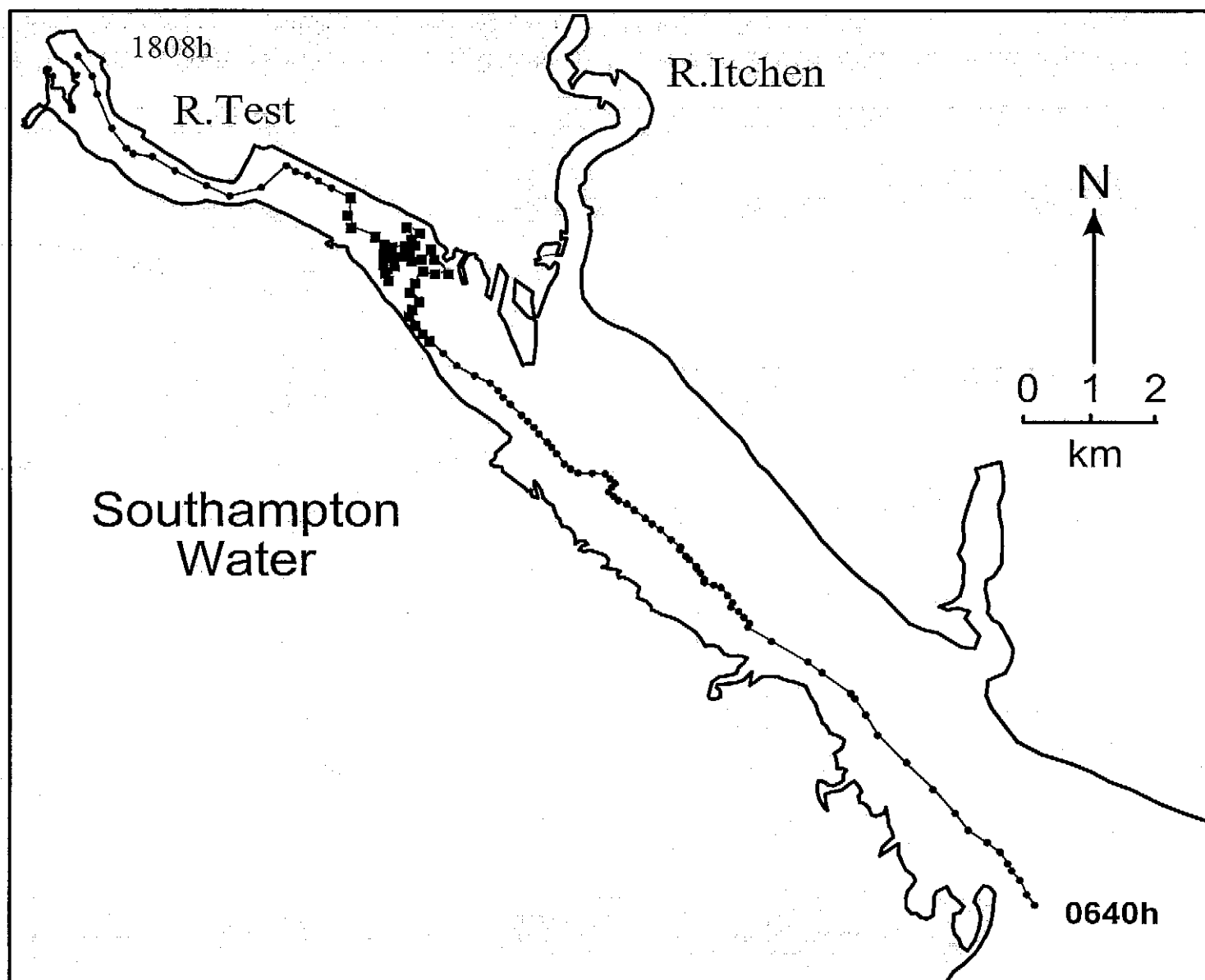


Figure 3. Movement of a wild salmon smolt as it migrated through the estuary of the River Test and Southampton Water in 1996. ●—● denotes the position of the tracking vessel relative to the salmon every 5 minutes during an ebb tide; ■—■ denotes the position of the tracking vessel relative to the salmon every 5 minutes during a flood tide.

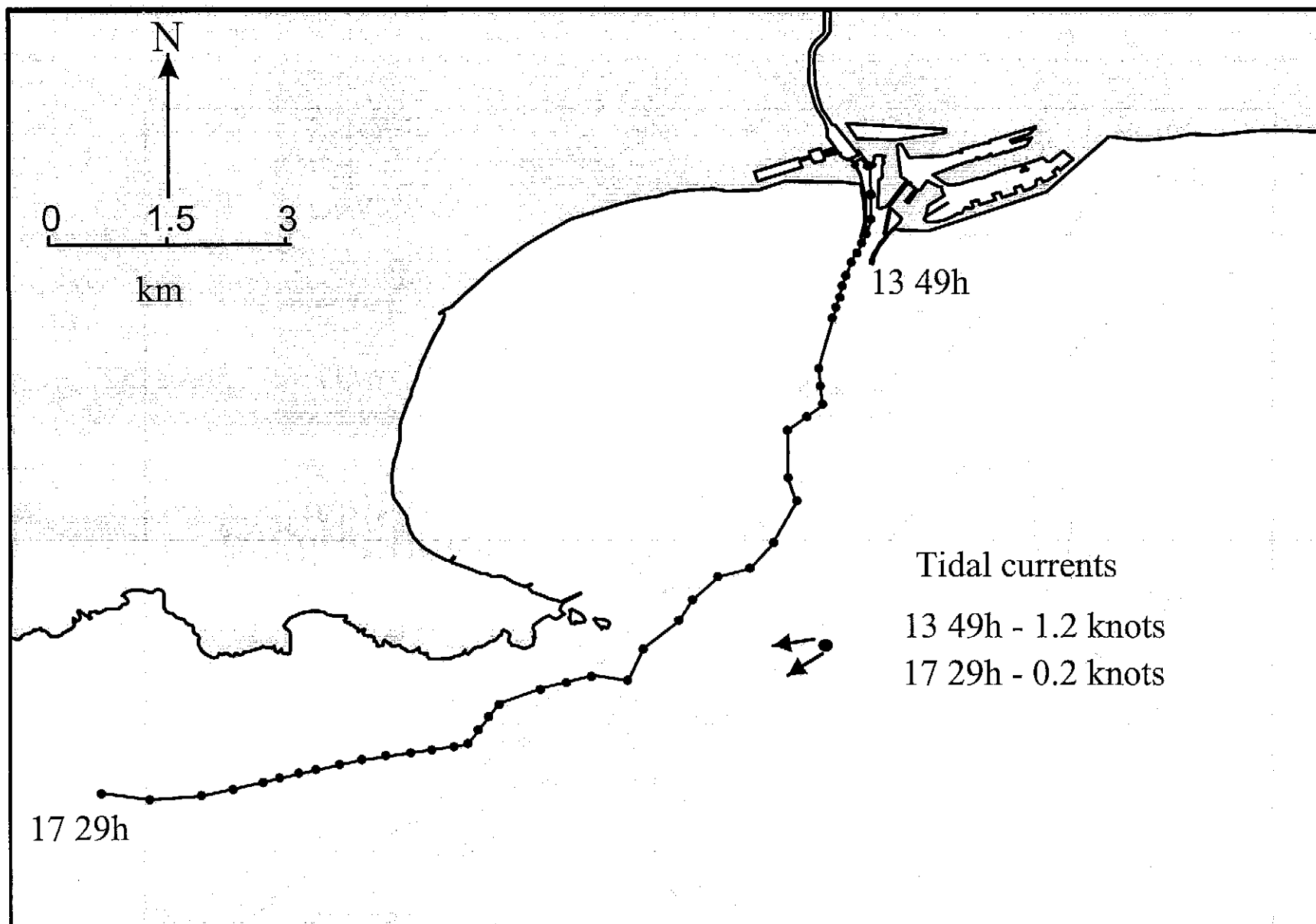


Figure 4. Track of a salmon smolt previously trapped and tagged in the freshwater section of the River Tawe as it migrated within the coastal zone.  
 ●—● denotes the position of the tracking vessel relative to the salmon every 5 minutes.

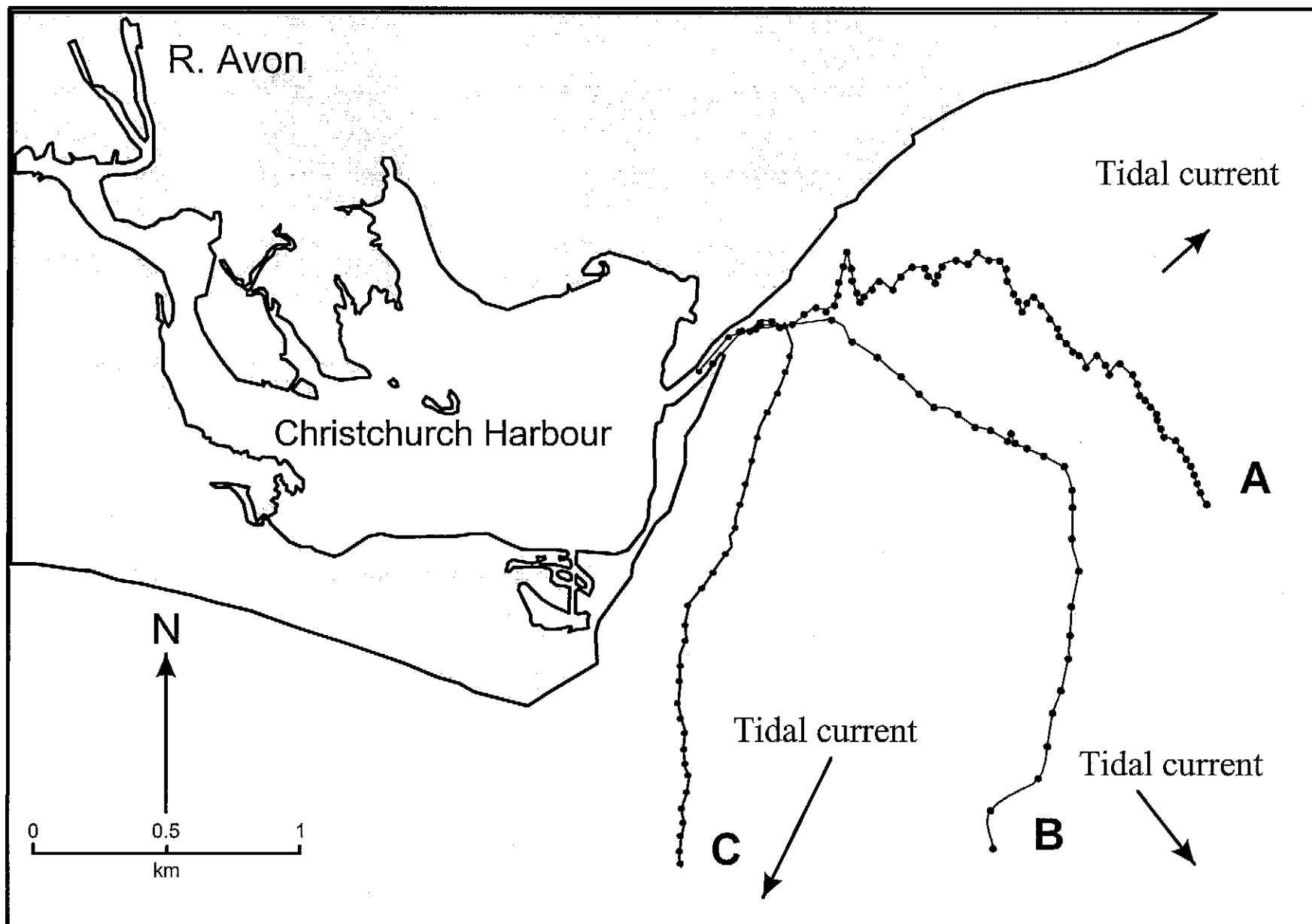


Figure 5. The movements of 3 wild salmon smolts in the coastal waters after emigrating from the River Avon in relation to the tidal cycle. Track A – HW + 20mins; Track B - HW + 2h 40mins; Track C – HW + 4h 18min. Tidal currents move in a south-westerly direction during an ebb tide. ●—● denotes the position of the tracking vessel relative to the salmon every 5 minutes. The length of the arrow denotes the relative speed of the tidal current.

