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The Movements of Atlantic Salmon (*Salmo salar* L.) and Sea Trout (*Salmo trutta* L.) Smolts in the Impounded Estuary of the R.Tawe, South Wales

MAFF, Directorate of Fisheries Research

R&D Technical Report W81

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The Movements of Atlantic Salmon (*Salmo salar* L.) and Sea Trout (*Salmo trutta* L.) Smolts in the Impounded Estuary of the R.Tawe, South Wales

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Statement of Use
This Technical Report fully describes the third phase of a collaborative study with MAFF on the behaviour of salmon and sea trout smolts in estuaries. The first two phases dealt with movements in unmodified estuaries and this third phase looked at the movements through an impounded estuary. The report is intended for use by scientists and operational staff who may require background information in order to deal with environmental impacts on estuarine smolt passage.

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R&D Technical Report W81

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1. EXECUTIVE SUMMARY

This report describes the results of a two year study on the migratory behaviour of Atlantic salmon and sea trout smolts in the lower river and impounded estuary of the River Tawe, South Wales. The study forms part of a larger DFR/NRA collaborative programme on estuarine smolt behaviour in both natural and modified estuaries.

During the seasonal smolt migrations in 1994 and 1995, 31 salmon and 21 sea trout smolts were trapped in fresh water, tagged with the DFR developed miniature acoustic smolt transmitter and released. Subsequent movements through the lower river and modified estuary were monitored using fixed acoustic sonar buoys, together with intermittent position fixing using hand-held hydrophones. Detailed movements of the smolts in relation to the Tawe Barrage were monitored using the DFR High Resolution Tracking System deployed within the impoundment immediately upstream of the construction. An important aspect of the project was to determine the potential impact of the Tawe Barrage on the migratory behaviour of salmonid smolts. Smolts negotiating the barrage were tracked manually in the lower estuary and coastal waters using a small research vessel.

Environmental factors measured during the study and related to the behaviour of the smolts included, diurnal changes, freshwater flows, temperature and flow velocities within the impounded estuary.

Salmon and sea trout smolts moved predominantly at night in the fresh water.
In the impounded estuary, salmon smolts emigrated during night and day, and sea trout during early dawn. Smolts moved passively with the current, but nevertheless oriented to remain in the areas of maximum flow. Smolts did not emigrate continuously through the impounded estuary and into the lower estuary. Smolts of both species held position within the impoundment immediately upstream of the barrage. Salmon smolts spent significantly longer periods above the barrage than sea trout smolts.

Smolts moved randomly in the impoundment immediately above the Tawe Barrage. Smolts were detected migrating past the barrage through the lock and over the weir during an overtopping tide.

Residency of both species in the River Tawe was related to the date of tagging and release. Smolts tagged earlier in the season spent significantly longer in the fresh water and impounded sections of the estuary before migrating into coastal waters than fish tagged later in the study.

No relationships were found between migration and water quality, although there was an apparent relationship between smolt movement and river flow. Smolts were trapped in freshwater when water levels were rising, and there was also a strong correlation between the speed of movement over the ground of the migrating smolts and river flow.

The behaviour patterns observed are compared with previous studies in unmodified river estuaries such as the Avon and Conwy, and discussed in relation to the possible impact of the Tawe Barrage on smolt migration.

Recommendations for further work are made, including the impact of contaminants in impounded estuaries on smolt survival, extension of the coastal tracking studies, impact of avian predators on salmonids and investigations of lock operation on smolt emigration.

KEY WORDS

Atlantic salmon, sea trout, smolt, migration, estuary, impoundment, radio tracking.

2. INTRODUCTION

In recent years there has been increasing concern about the potential impact of estuarine developments such as barrages on the behaviour and survival of migratory salmonids. Of particular concern are the effects on the seaward migration of Atlantic salmon (*Salmo salar* L.) and sea trout (*Salmo trutta* L.) smolts. The migration of smolts from fresh water to the marine environment is considered to be a critical period for the survival of salmon (Doubleday *et al.* 1979; Browne *et al.* 1982). The timing of this movement has been suggested to be particularly important, and factors delaying emigration may result in increase mortalities of post-smolts (Larsson 1977; Cross & Piggins 1982; Hansen & Jonsson 1989).

Between 1991 and 1993, two tracking studies were carried out by the Directorate of Fisheries Research (DFR), Lowestoft in collaboration with the National Rivers Authority (NRA) to obtain baseline data on the migratory behaviour of wild salmon and sea trout smolts through unmodified river estuaries. Migrating wild smolts were trapped in the fresh water sections of the Rivers Avon and Conwy, and tagged with miniature acoustic transmitters. Subsequently, the seaward movements of the smolts were monitored within the fresh water and estuarine sections of the rivers using an acoustic sonar buoy tracking system.

The study of salmon and sea trout smolts in the estuary of the River Avon, Southern England, indicated a nocturnal pattern of migration, with movement through the estuary occurring predominantly during an ebbing tide (Moore *et al.* 1992; and Moore & Potter 1994). The more extensive study in the River Conwy demonstrated that migration of salmon and sea trout smolts in fresh water was again predominantly nocturnal. However, in the case of salmon, there was a seasonal change in this pattern, with later run fish moving during both the day and night (Moore 1995; Moore *et al.* 1995). Smolts tagged earlier in the study spent significantly longer in the river before migrating into coastal waters than fish tagged later in the study. The movement of salmon smolts through the estuary was indicative of a nocturnal, selective ebb tide transport pattern of migration. All the salmonid smolts migrated seawards on an ebb tide, close to the surface and within the fastest moving section of the water column. The nocturnal pattern of migration would appear to be the result of an endogenous rhythm of swimming activity which results in the smolts moving up into the water column after dusk and migrating seawards. Smolt migration in the lower portion of the estuary was indicative of active directed swimming and there was no apparent period of acclimation required when moving from fresh to saltwater (Moore 1995; Moore *et al.* 1995).

To provide more information on smolt emigration, and to study the movements of smolts through an impounded estuary, the collaboration between DFR and NRA was continued on the River Tawe, South Wales. In 1992, the Tawe estuary was significantly changed by the construction of a barrage 1 km from the river mouth. This resulted in the formation of a large expanse of water approximately 22 ha in surface area. As a result of the barrage there is now only limited saltwater intrusion into the impoundment during approximately 71% of tides, and the tidal cycle has been significantly modified. The present study, carried out in the springs of both 1994 and

1995, examined the movements of wild salmon and sea trout smolts as they migrated from fresh water and through the impounded estuary. The localised movements of the smolts in relation to the Tawe Barrage were further examined using the DFR High Resolution Tracking System.

This report describes the findings of the study.

3. MATERIALS AND METHODS

3.1 Study Site

The River Tawe rises in the Black Mountains above Llyn-y-Fan Fawr, some 590 m above sea level, and drains a heavily urbanised catchment of 272 km^2. The river flows from the source in a south-westerly direction for 48 km to discharge into Swansea Bay at Swansea. All the major tributaries join the Tawe on its western bank, the Giedd at Ystradgnlais, the Twrch at Ystalyfera, the Upper Clydach at Pontardawe and the lower Clydach at Clydach.

In 1992, the lower Tawe estuary was significantly changed by the construction of a barrage which retains river water within an impoundment (Figure 1). The Tawe Barrage is located immediately downstream of a Marina complex, and consists of a primary and secondary weir, a lock and a fish pass. The crest of the primary weir is 8.05 m above Chart Datum and the secondary weir is 0.3 m higher at 8.35 m. The barrage is over-topped by approximately 71% of high tides and the water level on the seaward side of the barrage is higher than the primary barrage weir for approximately 16% of total time.

The barrage incorporates a HEP generator in the east abutment which has an outlet in the floor of the structure immediately downstream of the fish pass. The inlet and outlet are screened to prevent entrainment of adult and juvenile salmonids, although the generator was not operated during the study periods. An abstraction licence ensures that operation of the lock and generator does not reduce the flow through the fish pass to below 1 $m^3 s^{-1}$. In addition, during smolt migration in April and May a water level of 150 mm above the primary weir must be maintained.

The construction of the Tawe Barrage has significantly modified the upstream tidal regime of the estuary. As a result, there is a very restricted tidal cycle within the impounded sections of the estuary. During overtopping of the barrage, there is mixing of fresh water and salt water, and stratification occurs which may extend 5.5 km upstream of the barrage (Figure 1). Salinity profiles measured within the estuary indicated that the higher salinities (15-25 psu) occurred close to the river bed, whilst close to the surface (<1 m), the water was predominantly fresh.

Mean current speeds measured at a depth of 1.5 m within the impoundment immediately upstream of the barrage were 6.2 ± 0.56 cm s^{-1} (1994) and 7.1 ± 0.56 cm s^{-1} (1995). In the upstream tidal section of the impounded estuary mean current speeds were significantly higher, 87 ± 0.56 cm s^{-1} (1994) and 64 ± 0.56 cm s^{-1} (1995). In

1994, the minimum and maximum mean daily flows recorded at the river gauging station at Ynystanglws were 3.62 $m^3 s^{-1}$ and 20.53 $m^3 s^{-1}$ respectively. In 1995, the minimum and maximum mean daily flows recorded at Ynystanglws were 1.6 $m^3 s^{-1}$ and 5.58 $m^3 s^{-1}$ respectively. The Q95 river flows were 3.708 $m^3 s^{-1}$ (1994), and 0.693 $m^3 s^{-1}$ (1995).

3.2 Smolt trapping

The study was carried out over two years, between 8th April - 20th May 1994 and 13th April - 13th May 1995. During both years, migrating salmon and sea trout smolts were trapped in fresh water 2.6 km above the head of tide. Migrating smolts were trapped using fyke nets attached to a 50 cm x 50 cm x 50 cm keep box. In both years, the traps were operated during dusk and the hours of darkness starting at approximately 18 00 h, and operation was continued until sufficient smolts had been caught and released. This usually occurred by 02 00 h the following day. The traps were also operated during periods when the river was rising until the increased flow made trapping impossible. In addition, in 1994 the trap was operated for a period of 24 hours continuously to investigate the diurnal pattern of smolt behaviour. This trapping study was carried out between 2nd-3rd April.

3.3 Transmitter attachment

Salmon and sea trout smolts were tagged using miniature 300 kHz acoustic transmitters, developed at the DFR Fisheries Laboratory, Lowestoft (Moore *et al.* 1990a). The transmitter circuitry and battery were enclosed in a cylindrical polycarbonate case with hemispherical ends. They were 17 mm long x 8 mm in diameter, and weighed 1.30 g in air and 0.35 g in water. The transmitter had a maximum range in the estuarine environment of around 100 m and, transmitting at 60 pulses min^{-1}, a life of approximately 30 days.

The transmitters were surgically implanted into the peritoneal cavity of the smolts - Home Office Licence No. PPL 80/612. Fish were individually anaesthetised by immersion in 2-phenoxy ethanol (0.4 ml l^{-1} concentration). A level of surgical anaesthesia, judged by a total loss of reactivity and significant reduction in opercular beat rate, was reached in the fish within 2-3 minutes. Individual fish were measured, before being laid, with ventral side uppermost, on a prepared support of saline wetted tissue. During the tag implantation the gills were ventilated with an anaesthetic solution (0.2 ml concentration, flow rate 200 ml min^{-1}), via a tube in the mouth; this was sufficient to maintain an appropriate level of anaesthesia throughout surgery.

Following cleaning of the ventral surface of the fish with a surgical swab, an incision (15 mm in length) was made along the mid-ventral line, 5.0-7.0 mm anterior to the pelvic girdle. The transmitter, previously sterilised in surgical spirit, was inserted through the incision and positioned within the peritoneal cavity to lie directly below the incision. This positioning of the transmitter served to prevent adhesion between the intestinal viscera and the peritoneal surface of the incision. The incision was closed with two single stitches using coated Vicryl absorbable sutures (Ethicon Ltd.

Scotland). The incision was treated with a 3:1 mixture of Cicatrin antibiotic and Orahesive adhesive powder. The time of the surgical procedure was 2.5-4.5 minutes. This technique of transmitter attachment has been shown to have negligible physiological and behavioural effects on salmon smolts (Moore *et al.* 1990b), and has previously been used successfully to track both salmon and sea trout smolts within the Rivers Avon (Moore *et al.* 1990c; Moore *et al.* 1992; Moore & Potter 1994) and Conwy (Moore 1995). After transmitter attachment, the smolts were transferred to a tank of oxygenated water and allowed to recover fully from the effects of anaesthesia as described by Moore *et al.* (1990b) for salmon smolts. Recovery was usually within 5-10 minutes, and the fish were released after a period of 30 minutes together with a number of untagged smolts trapped at the same time.

3.4. Sonar buoy tracking system

The movement of the smolts within the riverine and estuarine sections of the River Tawe were monitored using an array of 300 kHz acoustic sonar buoys (Moore *et al.* 1992; Moore & Potter 1994). During both the 1994 and 1995 seasons, the sonar buoys were positioned at 10 locations between the limit of tidal influence at Beaufort Weir and immediately downstream of the barrage (Figure 1). Eight automatic listening stations (ALS) were deployed along the length of the river and estuary to record signals from the sonar buoys. At various intervals throughout the study, a hand-held 300 kHz acoustic hydrophone and a Lowe HF-150 communications receiver (Lowe Electronics Ltd, England) were used to record the positions of smolts holding position in the river during daylight hours.

3.5. High Resolution Tracking System

The DFR High Resolution Tracking System (HIRES) was deployed within the impoundment immediately above the Tawe Barrage to monitor the localised movements of the smolts as they approached the obstruction (Figure 2). The system is based upon the DFR sonar buoys and 300 kHz pinger tags, and fixes the position of a fish within a study area with a resolution of around 0.5 - 1 m. The system depends upon the detection of a signal from a pinger tag by at least three sonar buoys placed at known co-ordinates within the impoundment. The time delays between pairs of buoys receiving the tag signal are generated by a timer gate interface linked to a personal computer and the position is estimated using a common statistical technique, non-linear least squares. A full description of the system, positioning algorithm and data interpretation is given by Kell *et al.* (1994).

3.6. Data analysis

The River Tawe has been divided into 6 sections (Figure 1) based upon the physical, saline and tidal characteristics of the impounded and non-impounded sections of the river and estuary. These sections are:

1. Fresh water - trap site to tidal limit at Beaufort Weir (2.6 km).

2. Tidal - Beaufort Weir to the railway bridge adjacent to Morpha stadium - the extent of saline intrusion at the surface during spring tides (1.9 km).

3. Impoundment 1 - railway bridge to Social Club (1.2 km).

4. Impoundment 2 - Social Club to road bridge (1.5 km).

5. Impoundment 3 - road bridge to Swansea Barrage (0.9 km).

6. Lower estuary - downstream of Swansea Barrage.

Acoustic sonar buoys were deployed to monitor the movements of the smolts within each of these sections. The mean time of day at which the smolts were detected by the sonar buoy positioned closest to the middle of each section were calculated using vector analysis (see Batschelet 1981). The mean time in the tidal cycle that the smolts were detected by the sonar buoys immediately downstream of the barrage was also calculated. The length of the mean vectors were further used to test whether movement of the smolts within the relevant section was random with respect to time and state of tide using the Rayleigh test ('r' value) - see Batschelet (1981). High water at Swansea has been used as a reference point for tidal cycles.

The data from the 1994 and 1995 seasons have been analysed separately. Where it has been shown that there were no statistical differences between years, or where there was insufficient data during an individual year for statistical analyses, the data have been pooled.

3.6. Outer estuary and coastal tracking

A manual tracking study of wild smolts in coastal waters was carried out between the 26th April - 13th May 1994 and 20th April - 11th May 1995. The NRA Fisheries Enforcement vessel, *Fisher I* (Orkney Fishing Boats, England) was fitted with a DFR custom built 300 kHz acoustic hydrophone and Lowe HF-150 receiver. The hydrophone could be operated in both the vertical and horizontal modes, and the transducers extended 50 cm below the keel of the vessel to provide a 360^{o} horizontal field of view within the water. Operation of the hydrophone in the vertical mode provided an indication of the depth of the smolts.

At the beginning of each ebb tide, the tracking vessel was moored adjacent to the acoustic sonar buoy immediately downstream of the Swansea Barrage in the lower estuary. Seaward movements of previously tagged smolts, within the impoundment, were then detected by monitoring the radio signals from the appropriate acoustic sonar buoys using a Yaesu FT-290R Transceiver. When a smolt moved past the barrage and was detected moving within range of the sonar buoy adjacent to the vessel, the vessel-board acoustic hydrophone was operated and used to locate the signal from the transmitter inside the fish. The vessel was then manoeuvred to remain constantly within range of the fish and monitor its subsequent movements as it passed through the outer estuary and into coastal waters. The position of the boat was fixed at two minute intervals using a Magellan GPS NAV 5000 PRO Satellite Receiver. During movement through the lower and outer estuary a number of oranges were released to compare the speed of the fish with that of an inert neutrally buoyant object moving with the tide. Oranges were chosen as they are clearly visible, almost neutrally buoyant and have also been previously used in a similar context (Moore & Potter 1994; Moore 1995). Water depth was also continually monitored and recorded using the vessel's echo sounder.

3.7. Environmental data collection

Environmental monitoring equipment was placed at a number of sites within the tidal and impounded sections of the River Tawe. In both 1994 and 1995, a single RCM 7 Recording Current Meters (Aanderaa Instruments, Bergen, Norway), collected data on water velocity, temperature and salinity at fixed sites within each of the estuary sections. In addition, vertical salinity profiles of the estuary were obtained at a number of sites using a Mini STD SD202 probe (Sensordata, Bergen, Norway). Additional environmental data was routinely collected by the NRA on a weekly basis at sites in each of the tidal and impounded sections of the estuary.

In 1994, the times taken for passively drifting objects (oranges) to travel the length of the tidal and impounded sections of the estuary were also calculated. Batches were released at the top of the tidal section. Where individual oranges drifted out of the main flow or washed ashore, additional oranges were released within the main flow. This provided a time for the passage of an inert object, remaining within the main flow, to traverse the length of the impounded estuary. These data were compared to the times taken by the smolts to migrate the same distance through each section of the estuary during comparable flows using an unpaired t-test. The comparison was based on the assumption that the smolts were migrating in the upper water column which has previously been demonstrated in the River Conwy (Moore 1995: Moore *et al.* 1995).

4. RESULTS

4.1. Smolt trapping and release

In 1994, a total of 18 smolts (11 salmon and 7 sea trout) were tagged and released in the fresh water section of the River Tawe (Table 1). Subsequently, a total of 4 smolts (2 salmon and 2 sea trout) were tracked the length of the freshwater and impounded sections of the River Tawe and were last detected by the sonar buoys located downstream of the barrage within the lower estuary. A further 8 smolts (7 salmon 1 sea trout) were tracked from the trap site to the Tawe Barrage, but were not subsequently detected by the sonar buoys located downstream of the barrage during the study period. The remaining tagged fish were either not detected during the study period; detected moving downstream only as far as the fresh water and tidal sections; or predated by a brown trout.

In 1995, a further 34 smolts (20 salmon and 14 sea trout) were trapped and released in the River Tawe (Table 2). Of the tagged smolts, 12 (9 salmon and 3 sea trout) were tracked the length of the impounded estuary and last detected by the sonar buoys located downstream of the barrage in the lower estuary. A single sea trout smolt was detected below the barrage, but was subsequently tracked through the lock and back into the impounded estuary (see section 4.7). Nine smolts were tracked as far downstream as the impounded section immediately above the Tawe barrage, but were not detected by the sonar buoys located downstream of the barrage. Of the remaining 12 smolts, 8 were not detected at all after tagging and release, and the other smolts were detected in the fresh water and upper impounded sections of the estuary.

In 1994 and 1995, all tagged salmon and sea trout smolts were trapped during the hours of darkness. The first smolts to appear during each trapping session were recorded between 5 minutes and 4 hours 20 minutes after Nautical Twilight. Nautical Twilight is considered to be when the level of illumination is such that the horizon is in general not visible, and it is too dark for observation with a marine sextant (The Nautical Almanac 1991). Smolts then continued to be caught throughout the hours of darkness until cessation of the trapping operation. A number of smolts (4), that were not tagged due to poor physical condition, were captured during early dusk whilst the trap was being deployed. These fish were trapped during a spate when the river was rising and the mean daily flow measured at the gauging weir was 11.47 $m^3 s^{-1}$. No smolts were trapped during the daylight hours of the 24 hour continuous trapping sessions.

In 1994 and 1995, the capture of smolts coincided with river water temperatures of 10.5 °C and above (Tables 1 and 2). In 1995, both salmon and sea trout smolts were trapped when water temperatures had risen to between 18.9 and 19.2 °C.

4.2. Residency within the River Tawe

Mean residency times for salmon and sea trout smolts within each section of the River Tawe during the 1994 and 1995 seasons are shown in Table 3. In 1994, there was insufficient data to obtain the residency times for sea trout smolts in any section of the estuary. There were a number of significant spatial and temporal differences in the data. In 1994, salmon smolts spent a significantly longer period in fresh water than in 1995 ($p<0.01$; two tailed t-test assuming unequal variances). The reason for the difference in fresh water residency between the years is unclear, particularly as the mean river flow during the study period in 1994 was 8.49 $m^3 s^{-1}$, but only 2.55 $m^3 s^{-1}$ in 1995.

In 1994, the mean time that salmon smolts resided in each of the impounded sections of the estuary increased as the fish moved downstream (Table 3). For instance, the mean resident time of salmon was 2.28 hours in Impoundment 1; 9.82 hours in Impoundment 2; and 77.53 hours in Impoundment 3. In 1995, both salmon and sea trout smolts demonstrated a similar trend in their mean residence times in the impounded sections of the estuary (Table 3). The increasing time spent by the smolts in each subsequent section of the impounded estuary cannot be explained by differences in length of the sections. For instance, in 1995, the mean residence time of salmon smolts in Impoundment 1 (1.2 km in length) was 3.52 hours, whilst in Impoundment 3 (0.9 km in length) the mean residence time was 51.97 hours.

In 1995, there was a relationship between the day of release of the tagged smolts that were detected downstream of the Tawe Barrage and their total residency time within the River Tawe downstream of the trap site (Figure 3). The relationship was analysed using regression and the line fitted using the least squares method. As the smolt season progressed the released smolts spent less time within the River Tawe before migrating into the lower estuary (1995: least square regression: $r^2 = 0.531$; $p<0.01$), (Microsoft Excel 1992). In 1994, there were insufficient data to carry out a similar comparison.

The downstream movements of smolts were detected by all of the acoustic sonar buoys in fresh water, and by the majority of the buoys in the tidal and impounded sections of the estuary. This indicated that the fish must have passed within 50-75 m (the detection range) of the sonar buoys, and thus probably remained within the main flow of the river. However, a number of smolts which were detected moving past the sonar buoy at the top of Impoundment 3 section, were detected only intermittently by the HIRES sonar buoys. This suggests that the smolts moved outside the range of these buoys and were positioned a distance away from the barrage. In 1994 and 1995, manual tracking with a hand-held hydrophone during daylight hours, located a number of these smolts below the moorings adjacent to the Swansea Yacht Club.

Only 28% of the tagged smolts were detected by the sonar buoys located downstream of the Tawe Barrage in the lower estuary. The reasons are not clear, but there are a number of possibilities:

- smolts may have not migrated past the Tawe Barrage during the study, but remained within the impoundment;
- smolts may have been predated prior to moving into the lower estuary;
- tags may not have been detected in the more turbulent water below the barrage;
- smolts moving downstream through the lock may have not been detected due to accompanying boat noise;
- tag failure.

4.3. Diurnal patterns of migration.

4.3.1. Atlantic salmon

During 1994, the movement of tagged salmon within the fresh water section of the River Tawe was predominantly nocturnal (Table 4). The mean times of day that the salmon smolts passed the tidal limit of the river was 20 16h, and the movement was non-random with respect to time with an 'r' value of 0.74 ($p<0.05$). This nocturnal pattern of movement continued within the tidal section of the River Tawe with a mean time of passage of 20 48h ('r' = 0.915; $p<0.001$). Movement within Impoundment 1 was also nocturnal (mean time 22 04h; 'r' = 0.733; $p<0.05$), however movement through the remaining two impounded estuary sections was random with respect to time of day, and continued during both the day and night.

In 1995, the mean time of day that salmon smolts passed the tidal limit of the river was 18 52h (Table 5), and the movement was again non-random with respect to time with an 'r' value of 0.625 ($p<0.01$). Once again this nocturnal pattern of movement continued within the tidal section of the River Tawe with a mean time of passage of 19 36h ('r' = 0.741; $p<0.001$). Movement within Impoundment 1 was also nocturnal (mean time 20 48h; 'r' = 0.687; $p<0.001$), however movement through the remaining two impounded estuary sections was random with respect to time and continued during both the day and night. Movement of smolts within the lower estuary immediately downstream of the Tawe Barrage was random with respect to time, and continued during both the day and night.

4.3.2. Sea trout

In 1994, the movement of tagged sea trout smolts within the fresh water section of the River Tawe was also predominantly nocturnal (Table 4). The mean time of day that the sea trout smolts passed the tidal limit of the river was 21 36h, and the movement was non-random with respect to time with an 'r' value of 0.852 ($p<0.05$). There was insufficient data to analyse the movements of sea trout in either the tidal, impounded sections, or lower estuary.

In 1995, the movement of tagged sea trout smolts within the fresh water section of the River Tawe was also predominantly nocturnal (Table 5). The mean time of day that the sea trout smolts passed the tidal limit of the river was 23 04h, and the movement was non-random with respect to time with an 'r' value of 0.581 ($p<0.05$). However, the movement of the sea trout smolts through the tidal section was random with respect to time of day, with smolts moving downstream during both the day and night (Table 5). This random movement was discontinued in the impounded sections of the estuary and subsequent sea trout movement downstream to the barrage was non-random with respect to time. Mean times for downstream movement of sea trout smolts within Impoundment 1, 2 and 3 sections, were 23 48h ('r' = 0.8; $p<0.05$), 06 28h ('r' =0.971; $p<0.001$) and 05 48h ('r' = 0.862; $p<0.05$) respectively (Table 5). Movement in the lower sections of the impounded estuary occurred during early morning.

4.4. Tidal patterns of migration

The construction of the Tawe Barrage significantly modified the upstream tidal regime of the estuary, and now there is a very restricted tidal cycle within the impounded sections of the estuary. The saline intrusion is limited because although the barrage is over-topped during approximately 71% of tides, this only occurs close to high tide and accounts for approximately 16% of total time. Thus, there is little change in the pattern of flows in the impoundment throughout the tidal cycle. As a result, no attempt has been made to analyse the movements of salmon and sea trout smolts upstream of the Tawe Barrage with respect to the tidal cycle. However, in 1995 the combined movements of both species immediately downstream of the barrage with respect to the tidal cycle has been analysed. The movement of salmonid smolts past the sonar buoys located immediately downstream of the barrage in the lower estuary was random with respect to the tidal cycle, and occurred during both ebbing and flooding tides. In 1994, there was insufficient data to carry out a similar analysis.

In 1994, the mean time of movement over the ground of smolts through the tidal and impounded sections of the River Tawe was not significantly different to that of an inert object travelling during comparable flows within the main current (Table 6). In the tidal section there was a significant relationship between the movement over the ground of smolts and the mean daily river flow recorded at Ynystanglws (least square regression: $r^2 = 0.496$; $p<0.01$), (Figure 4). These results suggest that the smolts moved passively through the estuary with the flow, but with some degree of orientation that maintained them in the main current. In 1995, there was insufficient data to carry out a similar comparison.

4.5 Movements in relation to Tawe Barrage - HIRES

The HIRES system was operated during both years of the study. However, in 1995, the system was disrupted by severe interference which was not apparent until after the study. As a consequence no detailed tracks were produced by the HIRES system during the second year of the study. However, data from an ALS monitoring the HIRES buoys has been used to obtain information on the residence times of fish within the study area.

The residence times of salmon and sea trout smolts within the detection range of the HIRES sonar buoys in 1994, was not significantly different to the residence times in 1995 ($df = 21$; $t = 0.348$; $p>0.7$ - two tailed t-test, unequal variances). In 1994, the residence time was 54.76 ± 23.1 hours and in 1995, 42.93 ± 22.52 hours (mean ± S.E.M.). In 1994, the time spent by individual smolts immediately above the barrage ranged from 0.2 to 389.53 hours. This represented between 3.5 and 99.0% of the total time spent by the smolts within the tidal and impounded sections of the estuary. Similarly, in 1995, the time spent by individual smolts immediately above the barrage ranged from 0.3 to 110.24 hours. This represented between 0.28 and 91.95% of the total time spent by the smolts within the tidal and impounded sections of the estuary.

However, there were species differences in the time spent within the study area. In 1994, salmon smolts spent significantly longer in the HIRES study area than sea trout smolts (Table 7). However, in 1995, this pattern changed, and there was no significant difference in the time spent immediately upstream of the barrage between the two species (Table 7).

In 1994, there was no consistent pattern of movement of salmon and sea trout smolts immediately upstream of the Tawe Barrage. A detailed HIRES track of a salmon smolt between 11 15h and 13 30h on 9th May, is shown in Figure 5. The smolt was last detected by the sonar buoy located downstream of the barrage in the lower estuary at 13 59h. During this period the lock was closed, and it is assumed that the smolt negotiated the barrage by passing over the weir or through the fish pass.

A number of smolts (6), demonstrated exploratory movements within the study area. Individuals were monitored moving back and forth along the length of the barrage, and in a circular pattern between the sonar buoys. It was also observed that in a number of instances smolts within the study area moved in the direction of the lock during its filling. This suggests that the localised increase in flow within the impoundment as a result of filling the lock basin acted as a stimulus to the smolts to again move downstream.

There appeared to be no diurnal or seasonal differences in the pattern of movements of smolts immediately upstream of the barrage. Exploratory movements were observed during both day and night, and in the early and later parts of the smolt run.

4.6 Movement past the Tawe Barrage

Salmonid smolts may have used one of four routes in negotiating the Tawe Barrage to move downstream into the lower estuary. These were the primary weir; the secondary weir during overtopping tides; the fish pass; and the lock during "free-flow" or the "locking in and out" of boats. The last recorded movements of smolts immediately upstream and downstream of the Tawe Barrage in relation to the tidal cycle and lock activity in 1994 and 1995, are shown in Tables 8 and 9 respectively. In 1994, the movements of the smolts past the Tawe Barrage are unknown. Four smolts, (2 salmon and 2 sea trout), were detected by the sonar buoys located downstream of the barrage in the lower estuary. Three of these fish were detected when the lock was open, and it is assumed that they moved sea ward via this route. One of these smolts was detected downstream during "free-flow", and it is likely, given the increase in flow within the impoundment during this period, that the fish moved into the lower estuary through the lock. The fourth fish was detected when the lock was closed, which suggests that the smolts negotiated the barrage by either moving over the primary weir, or through the fish pass.

In 1995, two smolts, (1 salmon and 1 sea trout), negotiated the barrage by moving through the lock. This was verified by manual tracking (see section 4.7). The movements of the remaining smolts were not known. However, 5 smolts were detected by the sonar buoys downstream of the primary weir when the lock was closed. This suggests that the fish passed either through the fish pass or over the weirs. In two instances this movement downstream occurred during overtopping tides.

4.7. Outer estuary and coastal tracking

On the 7th May 1995 a single salmon smolt was actively tracked as it migrated past the Tawe Barrage and out into Swansea Bay (Figure 6).

The salmon smolt, (145 mm in length), was released in the River Tawe on the 5th May 1995. The smolt was subsequently detected by the HIRES buoys immediately upstream of the barrage at 0615h on 7th May. Its movements within HIRES were followed from 1150h onwards by monitoring the radio signals from the appropriate acoustic sonar buoys. During this period the smolt repeatedly moved along the length of the barrage towards the lock during lock activity. On four occasions, having moved adjacent to the lock, the smolt appeared to be disturbed by boat traffic and moved rapidly upstream. The smolt was last detected by the HIRES buoys at 1314h during "locking out" of a small vessel. It was subsequently detected by the hydrophone on the tracking vessel at 1317h as the lower lock gates were opened and the smolt moved into the lower estuary. The fish was then actively tracked seaward on an ebbing tide (HW + 1h 21min). It was evident from the operation of the hydrophone in the vertical mode that the smolt was moving in the upper water column close to the surface. As the fish was tracked, a number of inert objects (oranges) were released. However, to remain in contact with the smolt the tracking vessel had to move significantly faster that the objects, indicating that the fish was probably actively swimming with the flow.

The smolt followed the direction of the maintained channel within Swansea Bay as far as the SW Inner Green Grounds Bell (51° 34.00N 3° 56.95 W), adjacent to Mumbles Head. It then moved in a SW direction on a bearing of 245° south of the Mixon Shoal. The smolt was tracked until 1729h, to a position 3.5 km south of Brandy Bay (51° 32.01N 4° 02.66 W). The track was abandoned whilst the vessel was still in contact with the fish, due to low fuel levels on the tracking vessel. The smolt had been continuously tracked for 6h 08min over a distance of 12.6 km. The speed over the ground of the smolt during the track was 57 cm s^{-1}.

A sea trout smolt, was also actively tracked for a short period within the lower estuary. The smolt (201 mm in length), was released on 17th April 1995 and was detected by the HIRES buoys at 1258 h on the 4th May. It was last detected by the HIRES buoys during "locking out" of a small vessel. The smolt was subsequently detected by the hydrophone on the tracking vessel at 1309 h, as the lower lock gates were opened, and the smolt moved into the lower estuary. The fish was also detected by the downstream sonar buoy, but further contact with the smolt was lost. However, at 1519 h on the 8th May the fish was again detected below the barrage by the tracking vessel. The smolt was then continually monitored until it moved into the lock during "locking in" of a fishing vessel. The fish was subsequently detected by the HIRES sonar buoys above the barrage at 1546 h. This was the last time the smolt was detected during the study.

4.8 Environmental data

Environmental data from each section of the impounded estuary in relation to the movements of salmon and sea trout smolts are shown in Table 10. The minimum and maximum values that were recorded within 24 hours of the smolts passing a sampling point are shown. The greatest range in pH (7.05-9.24), salinity (0.2-23.2 psu) and dissolved oxygen (2.75 - 10.18 mg/l), was experienced in the tidal section of the impounded estuary. The highest pH measurement occurred at a depth of 0.15 m. In the section immediately above the barrage, movement of smolts coincided with water temperatures of between 9.6 and 16.6 ° C. There were fluctuations in the measured levels of dissolved oxygen and B.O.D. in all sections of the impounded estuary. In 1995, during routine NRA water quality measurements in the impounded estuary, dissolved oxygen levels at two sites in the tidal and Impoundment 1 sections were found to be below the minimum requirement. This resulted in Swansea City Council sluicing the impounded estuary.

In 1994 and 1995, there was no apparent relationship between the residency time of each fish and mean river flow calculated for the period the fish were within the river (Figure 7). The relationship was analysed using regression and the line fitted using the least squares method (1994: least square regression: $r^2 = 0.001$; $p>0.87$ - 1995: least square regression: $r^2 = 0.001$; $p>0.9$), (Microsoft Excel 1992). However, in 1994, smolts were trapped during a spate when the river was rising and the mean daily flow measured at the Ynystanglws gauging weir was 11.47 $m^3 s^{-1}$. In addition, there was a significant relationship between the movement over the ground of smolts and the mean daily river flow recorded at the gauging weir(least square regression: $r^2 = 0.496$; $p<0.01$), (Figure 4). The times that salmon and sea trout smolts were recorded passing each of the sonar buoys in the fresh water sections of the River Tawe in relation to the river flow are shown in Figure 8. Movement in fresh water occurred during flows ranging from 4.51 - 20.53 $m^3 s^{-1}$ (1994), and 1.59 - 5.58 $m^3 s^{-1}$ (1995).

5. DISCUSSION

The present study was the first to be carried out to monitor the movements of wild salmon and sea trout smolts through an impounded estuary in the UK. A total of 52, (31 salmon 21 sea trout), were tagged and released over the two years. Although this represented only a small percentage of the total smolt run, the consistency in both the temporal and spatial patterns of behaviour suggests that the results were representative of the behaviour of salmonid smolts in the modified River Tawe. It should be noted that no prior baseline studies on smolt behaviour were undertaken before barrage construction and modification of the Tawe estuary. Therefore, interpretation of the results of the present study in relation to the impact of the barrage construction on smolt behaviour is difficult. However, the present study provides a suitable comparison with previous studies on the movements of salmon and sea trout smolts through the unmodified estuaries of the Rivers Avon (Moore *et al.* 1992; Moore & Potter 1994) and Conwy (Moore 1995; Moore *et al.* 1995).

5.1 Fresh water migration

The migration of salmon and sea trout smolts in the fresh water section of the River Tawe was predominantly nocturnal as previously reported in the studies on the Rivers Avon and Conwy (Moore *et al.* 1992; Moore & Potter 1994; Moore 1995; Moore *et al.* 1995), and other river systems (Thorpe & Morgan 1978; Thorpe *et al.* 1981; Lundqvist & Eriksson 1985; Hansen & Jonsson 1985; Greenstreet 1992). There was no indication in the present study of a seasonal change in diurnal migration of salmon smolts demonstrated in the River Conwy (Moore 1995). However, there was a significant seasonal change in the residency time of all smolts, with fish tagged later in the season spending less time in the River Tawe before migrating downstream of the barrage and into the lower estuary.

The nocturnal pattern of migration of the salmon and sea trout in the River Tawe may have been the result of an endogenous rhythm of swimming activity which resulted in fish moving into the upper water column after dusk and migrating downstream (Moore 1995). A number of fish were detected holding station in deep pools during the daytime, but subsequently moved downstream during the hours of darkness.
The nocturnal pattern of migration of salmon and sea trout smolts indicated that light level was the most important environmental stimulus controlling migration in fresh

water. Previous studies have suggested that a number of other environmental factors may also initiate and modify salmon and sea trout smolt migration in fresh water. Migration may occur when a certain temperature threshold has been exceeded (Osterdahl 1969; McCleave 1978), or by variations in the patterns of temperature over a prolonged period (Jonsson & Ruud-Hansen 1985). During this study smolt migration in the main river coincided with temperatures of above 10° C, the threshold reported in previous studies (Osterdahl 1969; Solomon 1978).

Nocturnal migration by both salmon and sea trout smolts would have reduced the chances of avian predation particularly by cormorants (*Phalacrocorax carbo*), which prey on smolts in the River Tawe. Predation by birds on salmon smolts may be as high as 70% in some areas (Larsson 1985; Kennedy & Greer 1988), and 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.

A previous study by Solomon (1978), has suggested that a sudden increase in river flow rate is an important environmental factor initiatiating smolt migration. In the River Tawe, although there was no observable correlation between river flow and smolt residency, smolts were trapped in freshwater when water levels were rising, and there was also a strong correlation between the movement over the ground of the migrating smolts and the river flow. Thorpe & Morgan (1978) and Thorpe *et al.* (1988) have argued that during smolt migration in freshwater, the fish become less willing to hold station against the current, and as a result any increase in river flow will result in the downstream displacement of the smolts. Although it is apparent that other factors such as temperature and diurnal patterns of swimming behaviour are implicated in the control of downstream migration in freshwater, increasing river flow may be important in permitting the smolts in the River Tawe to migrate rapidly seawards.

5.2. Migration within the impounded estuary

5.2.1. Atlantic salmon

There were significant differences in the spatial and temporal patterns of migration of salmon smolts in the modified estuary of the River Tawe. Movement through the tidal and upper impounded sections of the estuary was predominantly nocturnal, but subsequent movement through the remaining sections of the estuary and past the barrage occurred during both day and night. It appears likely that the reduced tidal and flow regime within the impoundment increased the migration time of the smolts through the Tawe estuary. This increase resulted in some smolts, which initiated their migration through the tidal section of the estuary under the cover of darkness, moving through the lower impoundment above the barrage during daylight hours. Tidal currents within an estuary are important cues for initiating smolt migration and in enabling smolts to move rapidly out into coastal waters. Previous studies in the unmodified Rivers Avon and Conwy, (Moore *et al.* 1992; Moore & Potter 1994; Moore 1995; Moore *et al.* 1995), have indicated the presence of a selective nocturnal ebb tide transport component to estuarine Atlantic salmon smolt migration. Similar patterns of smolt behaviour have been described by Fried *et al.* (1978) and Holm *et al.* (1982).

The Tawe Barrage appears to have acted as a barrier to the movement of the smolts, delaying the migration of fish into the lower estuary and subsequently into coastal waters. Smolt migration through the impounded estuary and past the barrage was not continuous. On reaching the barrage, the majority of smolts resided immediately above the constructions for periods up to 16 days, and individual smolts were monitored moving continuously along the length of the barrage during daylight hours prior to moving downstream. Significantly longer periods were spent holding position just above the barrier than migrating through the upstream impounded estuary sections. It is not known where the fish holding position in the impoundment were located in the water column. If fish had refuged close to the bottom of the estuary during daylight hours as demonstrated in freshwater, then they would have been exposed to the areas with the poorest water quality.

Smolt movement downstream of the Tawe Barrage and into the lower estuary occurred during all states of the tide and during night and day. Except during overtopping tides, no information was available to the smolts within the impoundment on the tidal cycle below the barrage. Smolts which moved past the barrage during a flooding tide within the lower estuary, were likely to be retained within this section until the subsequent ebb tide. It is likely, that under these conditions smolt movement into coastal waters was further delayed and rendered the fish vulnerable to avian predation.

5.2.2. Sea trout

Sea trout smolts did not demonstrate the same pattern of migration in the impounded estuary that was evident in the salmon smolts. Migration was predominantly nocturnal in the upper impoundment, but occurred during early morning in the lower impounded sections of the estuary. Movement through the impoundment also appeared to be passive, but with some degree of orientation with respect to the main flow (Moore & Potter 1994). This pattern of movement was indicative of a reduced mean seaward current speed increasing the time of migration through the impounded estuary.

Sea trout smolt migration through the impounded estuary and into the lower estuary, downstream of the barrage, was also not continuous. Once again, the majority of smolts held position immediately above the construction prior to moving into the lower estuary. However, sea trout smolts spent significantly shorter periods above the barrage (> 2.5 days) than salmon smolts.

5.3 Migration past the Tawe Barrage

The movement of the majority of salmon and sea trout smolts past the Tawe Barrage and into the lower estuary is a matter of conjecture. However, it is known that two smolts moved into the lock during the filling of the lock basin, and subsequently emigrated into the lower estuary. A number of other smolts were last recorded above the barrage shortly before the lock was opened. It is possible that the resultant localised increase in the flow within the impoundment due to the lock activity, was a sufficient stimulus for the smolts close to the barrage to move downstream. In addition, to enter the lock smolts would have needed to have orientated to remain within the maximum flow. The movement of smolts in response to flow has been described in previous studies (Moore *et al.* 1992; Moore & Potter 1994; Moore 1995; Moore *et al.* 1995). A number of other smolts were detected downstream of the barrage during periods when the lock was closed, suggesting that the fish moved seaward over the weirs or through the fish pass.

5.4 Impact of Tawe Barrage

The impact of the Tawe Barrage upon stocks and populations of salmonids in the Tawe catchment is difficult to assess from the present study. However, although no data is available on the movements of smolts prior to barrage construction, it is likely that the barrage has modified smolt behaviour. The patterns of movement of smolts in the Tawe estuary differed from unmodified estuaries such as the Rivers Avon and Conwy (Moore *et al.* 1992; Moore & Potter 1994; Moore 1995; Moore *et al.* 1995). The barrage formed a partial barrier to the movement of the smolts, and may have delayed their subsequent migration into coastal waters. Previous studies have suggested that the timing of the movement from fresh to salt water is critical to the survival of salmon smolts, and their return as adults (Larsson 1977; Cross & Piggins 1982; Hansen & Jonsson 1989). The study on the River Conwy, indicated that salmon smolts emigrated out into coastal waters during a limited period, and it was suggested that this may represent the optimal time or window of opportunity for the smolts to migrate into the marine environment (Moore 1995). The delay caused by barrage, may have resulted in smolts not moving out of the River Tawe at the optimal time. However, it is not evident what environmental mechanisms are operating during this initial marine phase that make this timing so crucial.

Smolts which resided for extended periods within the impoundment were vulnerable to predation, particularly by cormorants. The numbers of cormorants observed feeding in the impoundment during the study often exceeded ten at any one time. Similarly, fish which moved past the barrage and were delayed by a flooding tide would also have been rendered vulnerable to predation.

The reduced tidal and river flows within the impoundment did not enable smolts to move rapidly through the estuary and into coastal waters under the cover of darkness. Nocturnal ebb tide movement was observed in unmodified estuaries such as the Avon and Conwy (Moore *et al.* 1992; Moore & Potter 1994; Moore 1995; Moore *et al.* 1995). Operation of the Tawe Barrage lock during critical periods may be necessary to increase the flows within the impoundment. This would involve operating the lock during the hours of darkness, and allowing "free flow" during every high tide. In addition, the impoundment could be partially drained at regular intervals throughout April and May to ensure that smolts were not retained above the barrage.

Little is known of the effects on smolts of exposure to contaminants within the impoundment. Although the movement of salmon and sea trout smolts through the impounded sections of the estuary appeared to be unaffected by changes in water quality, exposure for extended periods to sublethal levels of contaminants and low oxygen levels may have significant effects on the subsequent survival of smolts in the marine environment.

5.5. *Outer estuary and coastal movements*

The present study has again demonstrated that wild salmon smolts, that have migrated naturally from the riverine to estuarine environments can be successfully tracked out into coastal waters. The track of the salmon was indicative of active directed swimming, with movement in excess of the tidal currents. These studies are labour intensive and susceptible to sea and weather conditions, but provide the best opportunity to study the early marine phase of the smolt migration. The use of an Acoustic Doppler Current Profiler (ADCP) in conjunction with coastal studies may also provide much needed further information on the possible rate of movement of fish in the sea. A larger more directed study is required during this phase of the life cycle of the salmon together with a comparative study of the patterns of movement and behaviour of the sea trout smolts.

6. SUMMARY

1. This report describes the results of a two year telemetry study on the migratory behaviour of salmon and sea trout smolts in the impounded estuary of the River Tawe, South Wales. The study forms part of a wider DFR/NRA collaborative programme on estuarine smolt behaviour which began with a study of sea trout on the Hampshire Avon and continued on the River Conwy.

2. Smolts were tagged and released in the fresh water section of the River Tawe with DFR developed miniature acoustic transmitters. Subsequent movements of smolts were monitored using strategically positioned DFR acoustic sonar buoys located in the fresh water and impounded sections of the River Tawe estuary. The localised movements of smolts in relation to the Tawe Barrage were studied using the DFR High Resolution Tracking System. Smolt movements were related to a number of environmental parameters including diurnal changes, tidal state, water velocity, river discharge, temperature, dissolved oxygen and pH.

3. Movement of both salmon and sea trout smolts through the fresh water section of the River Tawe was predominantly nocturnal.

4. The subsequent movement of salmon smolts through the lower impounded sections of the estuary occurred during both day and night. Movement of sea trout smolts was predominantly in the early morning around dawn.

5. Residency of both species in the River Tawe was related to the date of tagging and release. Smolts tagged earlier in the season spent significantly longer in the fresh water and impounded sections of the estuary before migrating into coastal waters than fish tagged later in the study.

6. The movement of salmon and sea trout smolts within the impoundment was indicative of passive movement with the flow, but with some degree of orientation that maintained them in the main current

7. The movement of salmon and sea trout smolts through the impounded estuary and into the lower estuary, downstream of the barrage, was not continuous. Smolts of both species held position within the impoundment immediately upstream of the barrage. Salmon smolts spent significantly longer above the barrage than sea trout smolts.

8. Movement of smolts above the Tawe Barrage appeared to be predominantly random. Smolts were detected migrating past the Tawe Barrage by passing through the lock or over the weir during an overtopping flood tide.

9. The tracking of wild salmonid smolts in the lower estuary and coastal waters was successful, further indicating that the technique may be more widely applicable. A 12 km track of a salmon smolt in Swansea Bay indicated that the fish was close to the surface and moved actively along the course of the maintained channel as far as The Mumbles, before moving in a SW direction.

10. The behaviour patterns observed are compared with previous studies in unmodified river estuaries such as the Avon and Conwy, and discussed in relation to the possible impact of the Tawe Barrage on smolt migration.

7. RECOMMENDATIONS

1. Changes in the operation of the Tawe Barrage lock may be necessary to increase the flow regime in the impounded estuary during the smolt run. This would provide a localised stimulus to smolts for downstream migration and reduce the residence time of fish above the barrage.

2. A further dedicated study on the movements of smolts in coastal waters is required to investigate the speed with which fish move out into the open sea. This and previous studies have shown that wild smolts, moving naturally from fresh water through estuaries, may be tracked further out in coastal waters.

3. The effects of contaminants and reduced water quality in impounded estuaries on the sea water adaptability and survival of smolts entering sea water should be investigated.

4. The levels of predation by cormorants and their effects on populations of salmonids in modified and unmodified estuaries should be investigated.

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Table 1. Summary of information relating to Atlantic salmon and sea trout smolts tagged in the River Tawe in 1994.

Smolt	Tag No.	Length mm	Date	Capture Time	Release Time	River Temperature ° C	Residency in River Tawe hours	Last Recorded Position
salmon	37	174	22/04/95	23 30	23 48	11.6	342.87	Impoundment 3
salmon	47	172	23/04/94	00 50	01 11	11.6	487	Impoundment 3
sea trout	31	184	23/04/94	23 15	23 30	12.1	316.83	Lower estuary
sea trout	#	176	24/04/94	22 35	22 45	10.5	29.45	Impoundment 3
salmon	12	172	24/04/94	22 15	22 32	10.5	204.5	Impoundment 3
sea trout	18	214	25/04/94	00 01	00 35	10.5	-	Predated by trout
sea trout	17	204	25/04/94	00 01	00 35	10.5	-	Tidal
salmon	26	168	25/04/94	00 01	00 35	10.5	23	Impoundment 3
salmon	35	174	28/04/94	22 30	22 55	11.4	272.5	Lower estuary
sea trout	49	189	30/04/94	00 05	00 15	14.7	-	Not detected
salmon	10	164	30/04/94	21 40	21 59	14.9	107.83	Impoundment 3
salmon	8	174	30/04/94	23 10	23 44	14.9	87.82	Impoundment 3
salmon	43	162	30/04/94	23 10	23 44	14.9	78.25	Impoundment 3
salmon	2	147	02/05/94	23 50	00 10 - 03/05	14.7	-	Not detected
salmon	15	177	02/05/94	23 50	00 10 - 03/05	14.7	57.95	Lower estuary
sea trout	14	204	14/05/94	21 30	22 20	13.2	11.33	Lower estuary
sea trout	45	165	14/05/94	21 30	02 30	13.2	-	Freshwater
salmon	7	162	17/05/95	22 30	22 40	11.5	-	Not detected

Table 2. Summary of information relating to Atlantic salmon and sea trout tagged in the River Tawe in 1995.

Smolt	Tag No.	Length mm	Date	Capture time	Release time	River Temperature ° C	Residency in River Tawe hours	Last Recorded Position
sea trout	10	167	17/04/95	22 05	22 15	10.8	-	Not detected
sea trout	4	172	17/04/95	23 30	23 45	10.8	140.95	Lower estuary
sea trout	14	201	17/04/95	23 30	23 45	10.8	496.02	Impoundment 3
sea trout	50	195	17/04/95	23 30	23 45	10.8	162.32	Impoundment 3
salmon	42	197	18/04/95	23 30	23 45	10.6	198.12	Lower estuary
salmon	43	198	19/04/95	00 00	00 25	10.6	162.1	Lower estuary
salmon	18	176	19/04/95	00 00	00 25	10.6	81.26	Lower estuary
salmon	26	159	19/04/95	00 00	00 25	10.6	229.77	Lower estuary
salmon	13	152	23/04/95	21 05	21 45	11.1	167.1	Lower estuary
salmon	45	142	23/04/95	21 05	21 45	11.1	142.23	Impoundment 3
sea trout	12	204	23/04/95	22 00	22 20	11.1	-	Not detected
salmon	3	174	23/04/95	22 00	22 20	11.1	56.3	Impoundment 3
sea trout	20	186	23/04/95	22 45	23 05	11.1	165.27	Lower estuary
salmon	44	173	24/04/95	00 00	00 15	11.1	347.58	Impoundment 2
salmon	8	149	28/04/95	21 15	21 40	12.9	201.6	Impoundment 2
salmon	17	154	28/04/95	21 30	21 40	12.9	135.48	Lower estuary
salmon	16	174	28/04/95	22 30	22 45	12.9	51.1	Impoundment 3
sea trout	7	171	28/04/95	23 00	23 25	12.9	118.02	Lower estuary
salmon	29	157	28/04/95	23 00	23 25	12.9	322.65	Impoundment 3
salmon	40	152	28/04/95	23 20	23 45	12.9	68.07	Impoundment 3
sea trout	38	210	29/04/95	00 15	00 35	12.9	344.7	Freshwater
sea trout	30	178	29/04/95	00 15	00 35	12.9	284.22	Impoundment 3
salmon	41	170	29/04/95	00 20	00 35	12.9	-	Not detected
salmon	5	150	03/05/95	21 45	23 00	17	-	Not detected
salmon	48	157	03/05/95	23 00	23 20	17	111.27	Lower estuary
sea trout	31	179	03/05/95	23 40	23 55	17	-	Not detected
salmon	15	145	05/05/95	23 10	13 25	18.9	37.81	Lower estuary
sea trout	39	202	05/05/95	23 30	23 44	18.9	43.62	Impoundment 3
sea trout	21	181	06/06/95	23 50	00 00	19.2	56.93	Impoundment 3
sea trout	35	164	07/05/95	23 30	23 45	18	103.7	Impoundment 1
salmon	46	205	08/05/95	00 15	00 30	18	32	Lower estuary
salmon	19	142	08/05/95	00 00	00 20	18	-	Not detected
sea trout	33	197	08/05/95	00 00	00 20	18	-	Not detected
salmon	1	142	08/05/95	00 15	00 30	18	-	Not detected

Table 3. The mean residency times (hours) of Atlantic salmon and sea trout smolts in each of the sections of the River Tawe in 1994 and 1995

		Fresh water	Tidal	Impoundment 1	Impoundment 2	Impoundment 3	Lower Estuary	Total Estuary
1994								
Total smolts	mean ± s.e.m.	115.54 ± 45.28	1.02 ± 0.18	2.14 ± 0.77	8.45 ± 3.70	60.2 ± 32.32	Insufficient data	71.81 ± 32.3
	n	12	12	12	12	12	-	12
salmon	mean ± s.e.m.	119.40 ± 55.12	1.20 ± 0.21	2.28 ± 1.00	9.82 ± 4.88	77.53 ± 41.99	Insufficient data	90.83 ± 41.59
	n	9	9	9	9	9	-	9
sea trout	mean ± s.e.m.	Insufficient data	Insufficient data	Insufficient data	Insufficient data	Insufficient data	Insufficient data	Insufficient data
1995		**Fresh water**	**Tidal**	**Impoundment 1**	**Impoundment 2**	**Impoundment 3**	**Lower Estuary**	**Total Estuary**
Total smolts	mean ± s.e.m.	67.82 ± 13.33	2.12 ± 0.57	5.23 ± 0.91	8.77 ± 1.91	62.99 ± 19.24	Insufficient data	79.11 ± 22.84
	n	26	25	25	25	23		23
salmon	mean ± s.e.m.	59.76 ± 9.20	1.50 ± 0.09	3.52 ± 0.84	6.60 ± 1.89	51.97 ± 11.67	Insufficient data	63.59 ± 22.56
	n	16	16	16	16	14		14
sea trout	mean ± s.e.m.	78.29 ± 30.39	3.01 ± 1 50	7.72 ± 1.71	11.89 ± 3.87	80.11 ± 46.87	Insufficient data	102.73 ± 30.80
	n	10	9	9	9	9		9

Table 4. The downstream movements of Atlantic salmon and sea trout smolts through each of the sections of the River Tawe in relation to the time of day in 1994. The mean times at which fish were recorded passing the sonar buoy positioned closest to the middle of each section have been calculated from the mean vectors (Batschelet 1981). The ' r ' values provide a measure of randomness of movement with respect to time calculated using the Rayleigh test. The value **n** is the total number of fish movements past the respective sonar buoy in each section.

1994		**Fresh water**	**Tidal**	**Impoundment 1**	**Impoundment 2**	**Impoundment 3**	**Lower Estuary**
Total smolts	**mean time**	20 52h	20 04h	22 32h	Random movement	Random movement	Insufficient data
	r value	0.892	0.784	0.774	0.508	0.351	
	p	< 0.001	< 0.01	< 0.001	> 0.05	> 0.25	
	n	12	6	12	9	12	
Salmon	**mean time**	20 16h	20 48h	22 04h	Random movement	Random movement	Insufficient data
	r value	0.74	0.915	0.733	0.406	0.204	
	p	< 0.05	< 0.001	< 0.05	> 0.287	> 0.659	
	n	7	6	9	8	9	
Sea trout	**mean time**	21 36h	Insufficient data	Insufficient data	Insufficient data	Insufficient data	Insufficient data
	r value	0.852					
	p	< 0.05					
	n	5					

Table 5. The downstream movements of Atlantic salmon and sea trout smolts through each of the sections of the River Tawe in relation to the time of day in 1995. The mean times at which fish were recorded passing the sonar buoy positioned closest to the middle of each section have been calculated from the mean vectors (Batschelet 1981). The ' r ' values provide a measure of randomness of movement with respect to time calculated using the Rayleigh test. The value **n** is the total number of fish movements past the respective sonar buoy in each section.

1995		**Fresh water**	**Tidal**	**Impoundment 1**	**Impoundment 2**	**Impoundment 3**	**Lower Estuary**
Total smolts	**mean time**	20 24h	20 32h	21 44h	Random movement	Random movement	Random movement
	r value	0.525	0.587	0.67	0.317	0.44	0.394
	p	< 0.01	< 0.01	< 0.001	> 0.20	> 0.05	> 0.15
	n	26	25	20	18	21	12
Salmon	**mean time**	18 52h	19 36h	20 48h	Random movement	Random movement	Random movement
	r value	0.625	0.741	0.687	0.192	0.271	0.375
	p	< 0.01	< 0.001	< 0.001	> 0.602	> 0.31	> 0.25
	n	16	16	14	13	15	9
Sea trout	**mean time**	23 04h	Random movement	23 48h	06 28h	05 48h	Insufficient data
	r value	0.581	0.471	0.8	0.971	0.862	
	p	< 0.05	> 0.15	< 0.05	< 0.001	< 0.05	
		10	9	6	5	6	

Table 6. The mean times (± s.e.m.) taken for drogues (oranges) and smolts to migrate through the tidal and impounded sections of the River Tawe estuary in 1994 during comparable river flows. Data between drogues and smolts have been compared using a t-test assuming unequal variances.

	Tidal	Impoundment 1	Impoundment 2	Impoundment 3
Drogues **n**	0.83 ± 0.07 hours 3	1.54 ± 1.3 hours 3	1.84 ± 0.16 hours 3	2.73 ± 2.8 hours 3
Smolts **n**	1.17 ± 0.21 hours 11	1.13 ± 0.28 hours 11	1.72 ± 0.37 hours 10	1.78 ± 0.39 hours 8
df **t** **significance**	12 1.22 ns	12 1.3 ns	11 0.275 ns	9 1.74 ns

Table 7. The mean residency times of Atlantic salmon and sea trout smolts within the HIRES study area in 1994 and 1995. Data between Atlantic salmon and sea trout have been compared using a t-test assuming unequal variance.

	1994	1995
Atlantic salmon **n**	72.67 9	23.66 14
Sea trout **n**	8.4 3	16.77 8
df **t** **significance**	8 1.5 $p < 0.05$	13 0.51 ns

Table 8. The last recorded movements of salmonid smolts upstream and downstream of the Tawe Barrage in relation to tidal cycle and lock activity in 1994.

Smolt	Tag No.	Date	Time (impoundment)	Time (downstream)	Tidal Height	Tidal Cycle Relative to Previous HW	River Flow (cumecs)	Lock Activity
Salmon	47	12-May	08 10	-	8.17	0h 57min	5.25	Open - 08 15, 09 05
Salmon	12	03-May	11 04	-	6.21	10h 52min	4.98	Open - 11 10, 12 30
Salmon	15	05-May	10 16	10 20	3.1	8h 8min	13.3	Open - 10 35
Salmon	26	25-Apr	23 48	-	2.12	5h 53min	12.97	Closed
Salmon	35	09-May	12 33	13 59	1.4	7h 10min	5.17	Open - 14 30
Salmon	10	05-May	21 41	-	2.12	6h 57min	13.3	Closed
Salmon	8	04-May	15 49	-	6.7	2h 18min	6.97	Open - 15 50
Salmon	43	04-May	06 00	-	2.2	5h 11min	6.97	Open - 08 45
Sea Trout	31	06-May	04 36	04 50	7.48	1h 22min	15.06	Closed
Sea Trout	#	26-Apr	04 12	-	4.1	8h 17min	20.54	Closed
Sea Trout	18	15-May	06 47	-	5.4	9h 17min	11.48	Open - 07 05, 07 15, 07 45
Sea Trout	14	15-May	09 49	09 57	8.3	1h 00min	11.48	Open - Free Flow 09 25 - 10 10

Table 9. The last recorded movements of salmonid smolts upstream and downstream of the Tawe Barrage in relation to tidal cycle and lock activity in 1995.

Smolt	Tag No.	Date	Time (upstream)	Time (downstream)	Tidal Height (metres)	Tidal Cycle Relative to Previous HW	River Flow (cumecs)	Lock Activity
salmon	26	26-Apr	19 08	14 16 (28/4)	4.39	7h 35min	2.56	Open - 13 45, 14 00
salmon	43	25-Apr	-	18 31	5.2	2h 09min	3.03	Open - 17 50, 18 10
salmon	42	27-Apr	04 32	05 36	8.53	11h 58min	2.43	Closed
salmon	46	09-May	07 34	08 05	3.38	5h 58min	1.61	Closed
salmon	18	22-Apr	21 55	22 04	6.35	9h 59min	4.07	Closed
salmon	3	26-Apr	06 38	-	5.9	1 h 51min	2.65	Open - 09 35
salmon	45	29-Apr	19 59	-	7.99	0h 43min	2.23	Open - 21 10
salmon	13	30-Apr	19 40	20 48	8.1	1h 01min	2.23	Open - 19 40, 20 05, 20 20, 20 25, 20 45
salmon	29	11-May	09 54	-	2.48	6h 01min	1.59	Open - 11 30
salmon	17	04-May	12 58	13 09	3	3h 31min	1.81	Open - 13 00
salmon	40	02-May	19 49	-	9.05	11h 00min	2.12	Open - Free Flow 19 40 - 20 40
salmon	48	08-May	13 38	14 30	5.61	1h 25min	1.64	Open - 14 00, 14 30
salmon	15	05-May	13 14	13 20	3.91	3h 25min	1.81	Open-13 20
sea trout	7	03-May	20 57	21 06	8.69	0h 14min	1.97	Closed
sea trout	21	09-May	09 01	-	4.14	6h 44min	1.6	Open - 09 20, 09 50
sea trout	14	04-May	12 58	-	4.85	3h 31min	4.22	Open - 13 00
sea trout	4	23-Apr	17 35	20 31	3.39	7h 12min	5.65	Open - 17 35, 18 25, 18 45, 19 40
sea trout	30	09-May	20 48	-	3.48	7h 08min	1.59	Closed
sea trout	50	24-Apr	18 04	-	4.47	2h 48 min	3.51	Open - 18 10, 18 25, 19 00
sea trout	20	30-Apr	20 13	20 15	8.44	0h 28min	2.27	Closed

Table 10. Environmental data in relation to the movement of Atlantic salmon and sea trout smolts through each section of the River Tawe. The minimum and maximum values of each parameter recorded as smolts passed the relevant environmental monitoring stations are presented. The data from 1994 and 1995 have been combined.

Environmental Parameter	Fresh water	Tidal	Impoundment 1	Impoundment 2	Impoundment 3
Temperature (° C)	11.8 - 16	9.3 - 16	9.5 - 16.4	11.7 - 16.9	9.6 - 16.6
pH	7.9 - 8.8	7.05 - 9.24	7.12 - 8.22	7.51 - 8.72	8 - 8.49
Salinity (psu)	n/a	0.2 - 23.2	0.3 - 23.2	1.0 - 29.1	1.0 - 29.5
Dissolved oxygen (mg/l)	11.9 - 14.5	2.75 - 10.18	7.61 - 13.6	9.55 - 16.47	8.04 - 13.3
B.O.D. (mg/l)	1.1 - 2.3	-	1.4 - 6.9	2.2 - 6.7	-

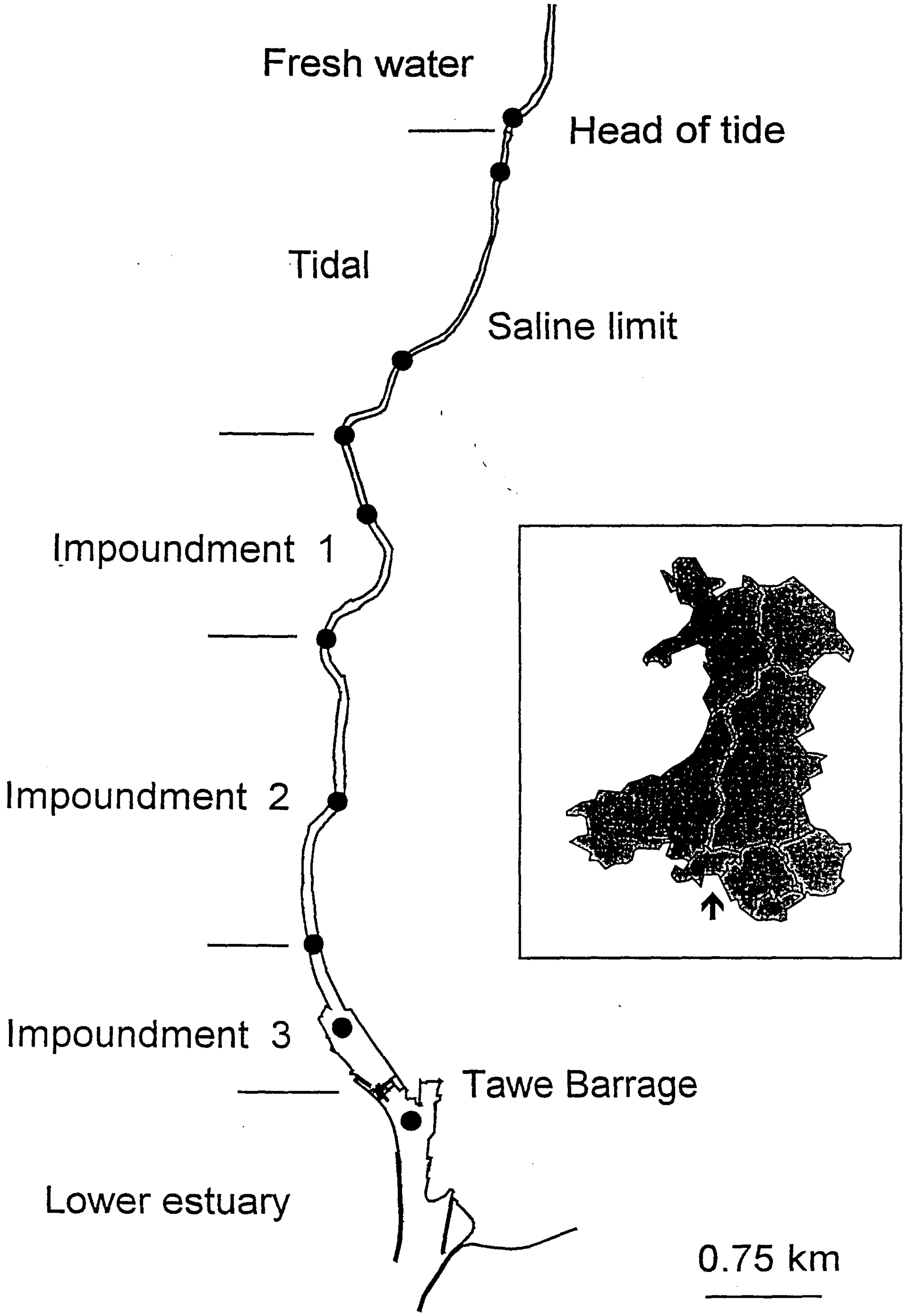


Figure 1. Map of the River Tawe showing the positions of the sonar buoys (●). The six sections of the river referred to in the text are also indicated.

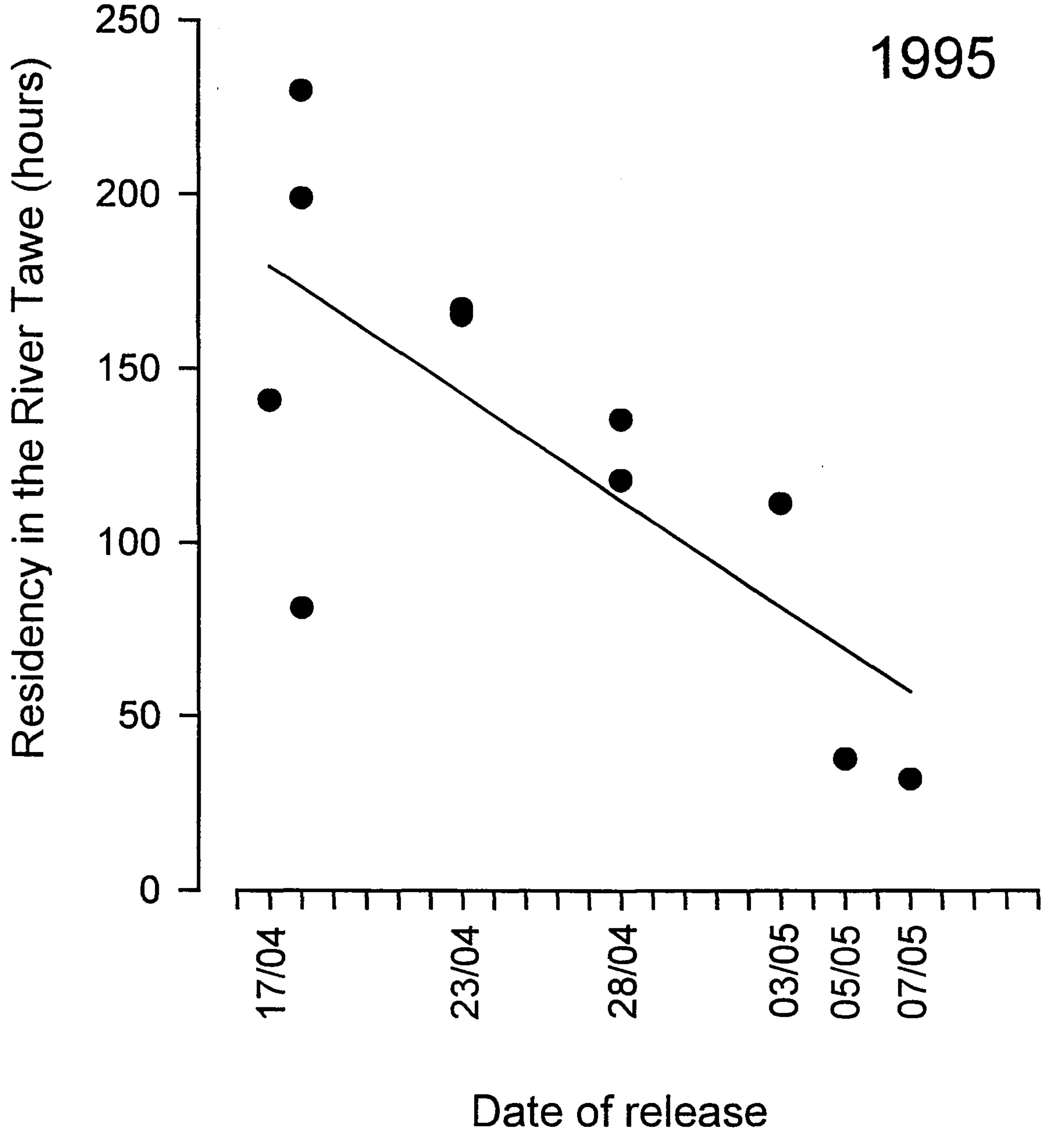


Figure 3. The relationship between residency time within the River Tawe and day of release of Atlantic salmon and sea trout in 1995. Details of the fitted regression line are given in the text.

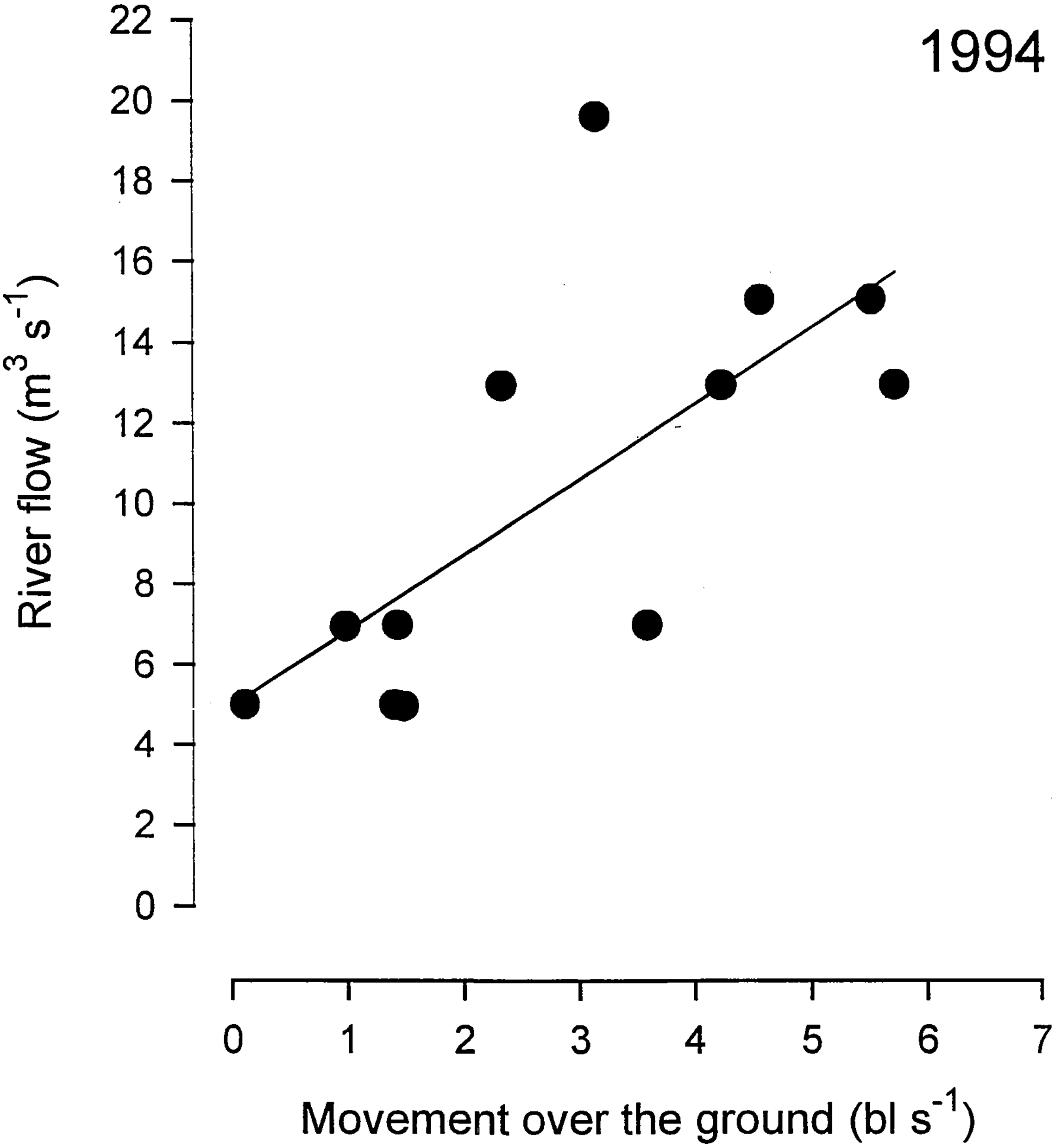


Figure 4. The relationship between the movement over the ground of Atlantic salmon and sea trout smolts and river flow in the tidal section of the River Tawe in 1994.

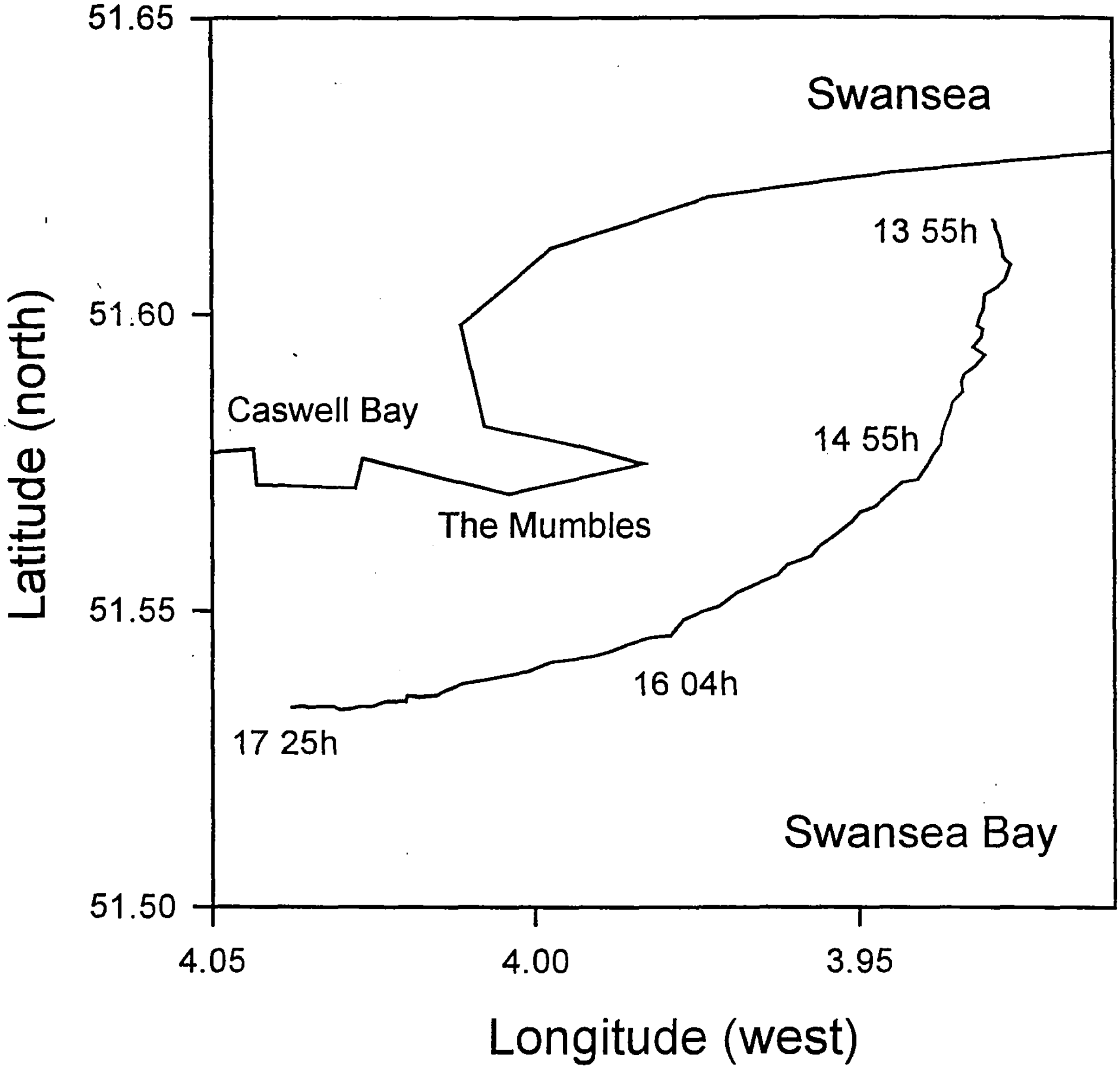
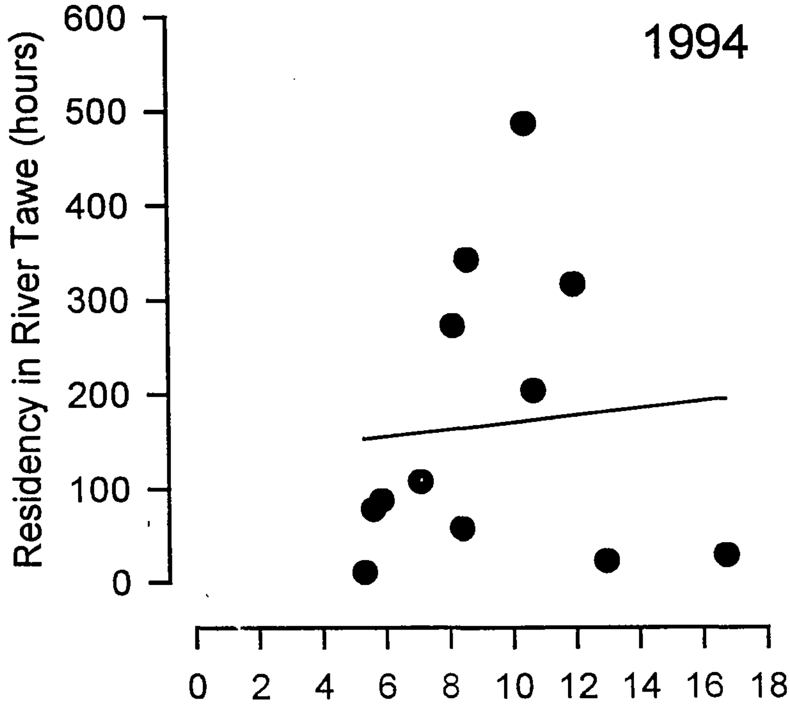


Figure 6. The track of an Atlantic salmon smolt in Swansea Bay, 7th May 1995.



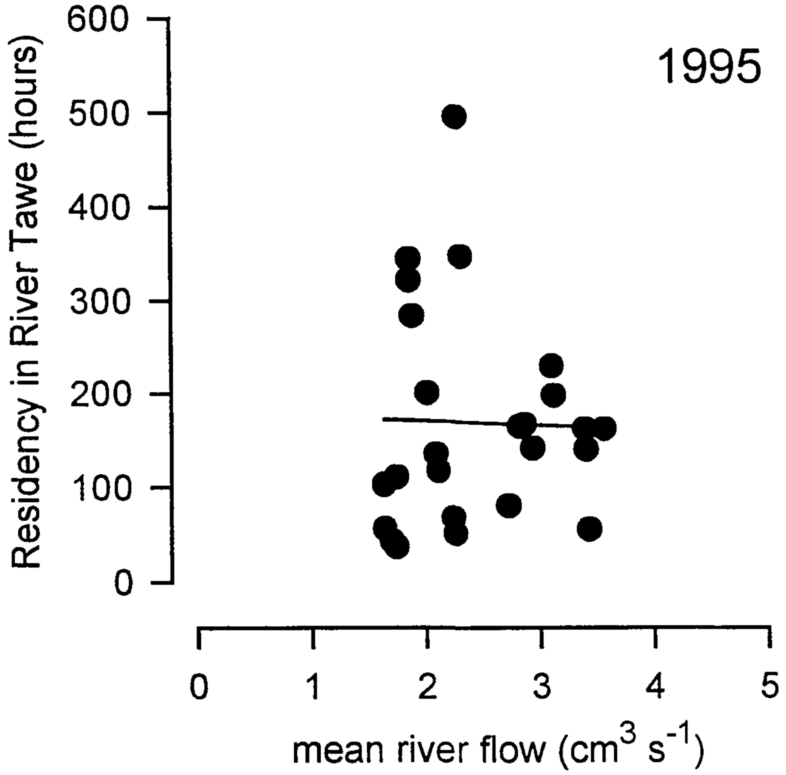


Figure 7. The relationship between the residency of Atlantic salmon and sea trout smolts in the River Tawe and the mean river flow during the period of residency in 1994 and 1995. Details of the fitted regression line are given in the text.

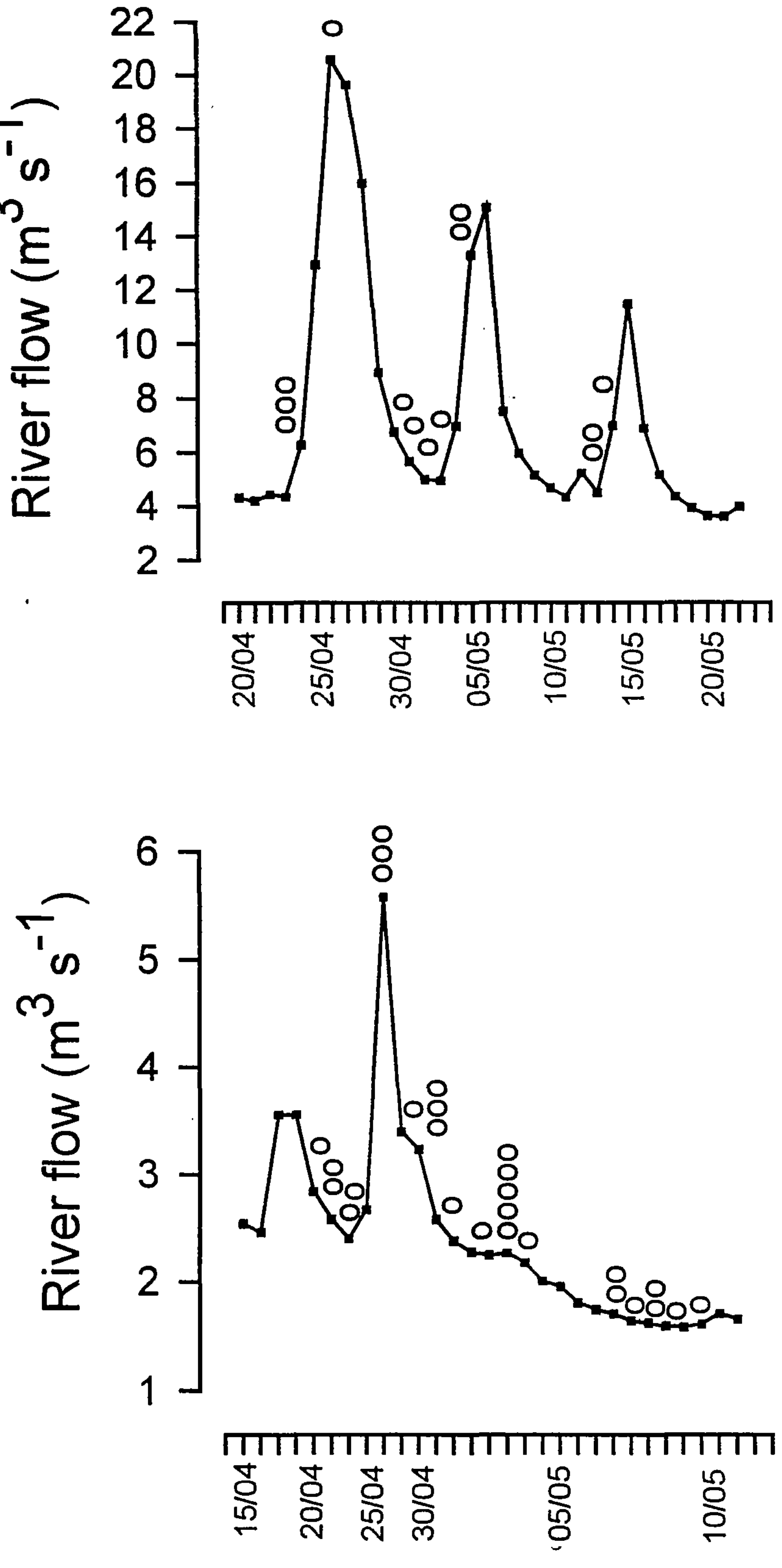


Figure 8. The timing of movement of Atlantic salmon and sea trout smolts through the freshwater section of the River Tawe in relation to the river flow in 1994 and 1995. O denotes the movement of a single smolt.