ESTUARIAL MIGRATION OF ATLANTIC SALMON IN THE RIVER DEE (N. WALES)

ETSU T/04/00154/REP

Contractor

National Rivers Authority, Welsh Region

Prepared by

W K Purvis
C R Crundwell
D Harvey
B R Wilson

The work described in this report was carried out under contract as part of the New and Renewable Energy Programme, managed by the Energy Technology Support Unit (ETSU) on behalf of the Department of Trade and Industry. The views and judgements expressed in this report are those of the contractor and do not necessarily reflect those of ETSU or the Department of Trade and Industry.

First published 1994

ESTUARIAL MIGRATION OF ATLANTIC SALMON

IN THE RIVER DEE (N. WALES).

Project Number E/5A/4116/2840).

Prepared by:

National Rivers Authority, Welsh Region.
Dee Radio-Tracking Project.
Flood Defence Depot,
Chester Road,
Buckley,
CLWYD.
CH7 3AJ.

Authors; W.K. Purvis, C.R. Crundwell, D. Harvey and B.R. Wilson.

Client:

Energy Technology Support Unit,
Harwell,
OXFORDSHIRE.
OX11 0RA

TABLE OF CONTENTS.

	Page No.
EXECUTIVE SUMMARY	*Summary* 1-4
1.0 INTRODUCTION	1
1.1 Background	1
1.2 Tidal Barrages	1
1.3 Scope of Study	2
2.0 TERMS OF REFERENCE	3
2.1 Overall Objective	3
2.1.1 Estuarine Objectives	3
2.1.2 Chester Weir Objectives	3
3.0 DESCRIPTION OF STUDY AREA.	4
3.1 Dee System	4
3.1.1 Catchment to Chester Weir	4
3.1.2 The Estuary	4
3.1.2.1 Uses of the Estuary	4
3.1.3 Chester Weir	5
4.0 MATERIALS AND METHODS	6
4.1 Fish Capture	6
4.2 Tagging	6
4.2.1 Tags	6
4.2.1.1 Floy Tags	6
4.2.1.2 Internal Transmitting Tags	6
4.3 Tracking	7
4.3.1 Passive Tracking	7
4.3.1.1 Automatic Listening Stations	7
4.3.1.2 Acoustic Buoys	7
4.3.2 Active Tracking	8
4.3.2.1 Continuous Boat Tracking	8
4.3.2.2 Air Tracking	8
4.3.2.3 Other Active Tracking Methods	8
4.4 Environmental Data	9
4.4.1 Residual Flow	9
4.4.2 Water Quality Data	9
4.4.3 Ancillary Data	9
4.5 Data Analysis	9
4.5.1 Classification of Reaches	9
4.5.2 Classification of Behaviour	10
4.5.3 Approaches to Analysis	10
5.0 RESULTS	11
5.1 Tagged Population	11
5.1.1 Background	11
5.1.2 Differences Between Years	11
5.1.3 Differences Between Months	11
5.1.4 Relocation Experiment	11
5.1.5 Bias in Tagged Population	12
5.1.5.1 Release Times	12
5.1.5.2 Reach 3 Entry Times	12
5.2 Straying	12

5.3 Outer Estuary Behaviour 13
5.4 Environmental Results 14
5.4.1 Differences in FW Flow between Years 14
5.4.2 Differences in WQ between Years 14
5.4.3 Differences in Tidal Asymmetry 14
5.4.4 Differences in Reach Depth 15
5.4.5 Differences in WQ between Reaches 15
5.5 Behaviour in Middle and Inner Estuaries 15
5.5.1 Upstream Movements 15
5.5.1.1 Water Quality 15
5.5.1.2 Residual FW Flow 16
5.5.1.3 Day of Week 16
5.5.1.4 Time of Day 16
5.5.1.5 State of Tide 16
5.5.1.6 Passage Upstream of Chester STW 17
5.5.2 Reach Residence Time (T_r) 17
5.5.3 Net Reach Velocity (V_r) 17
5.5.3.1 The Impact of Reach Depth 18
5.5.3.2 The Impact of Tidal Regime 18
5.5.3.3 Impact of changes in WQ and Flow 19
5.5.4 Downstream Displacement 19
5.5.4.1 Estuarine Reach 19
5.5.4.2 Time of Year 19
5.5.4.3 State of Tide 20
5.5.4.4 Time of Day 20
5.5.4.5 Water Quality and FW Flow 20
5.5.5. Probability of Middle Estuary Passage 20
5.5.5.1 Temperature 20
5.5.5.2 Dissolved Oxygen 21
5.5.5.3 Residual FW Flow 21
5.5.6 Kelt Emigration Behaviour 22
5.6 Behaviour at Chester Weir 22
5.6.1 Fates of Tagged Sample 22
5.6.1.1 Differences between Years 22
5.6.1.2 Differences between Months 23
5.6.2 Weir Pool Arrivals 23
5.6.2.1 Time of Day 23
5.6.2.2 State of Tide 23
5.6.2.3 Height of Tide 23
5.6.2.4 Residual FW Flow 23
5.6.2.5 Trap Status 23
5.6.3 Trap Channel Arrivals 24
5.6.3.1 Time of Day 24
5.6.3.2 State of Tide 24
5.6.3.3 Trap Status 24
5.6.4 Weir Crossing Behaviour 24
5.6.4.1 Time of Day 24
5.6.4.2 State of Tide 24
5.6.4.3 Size of Tide 25
5.6.4.4 Residual FW Flow 25
5.6.4.5 Combination of Tidal State and Flow 26
5.6.5 Post Weir Crossing Behaviour 26
5.6.6 Weir Residence Time (T_w) 26
5.6.6.1 Residual FW Flow 26
5.6.6.2 Temperature 27
5.6.6.3 Size and State of Tide 27
5.6.6.4 Trap Status 27
5.6.7 Displacement from the Weir 27

5.6.7.1 Residual FW Flow 27
5.6.7.2 Time of Day 27
5.6.7.3 Trap Status 28
5.6.7.4 State of Tide 28
5.6.7.5 Time of Year 28
5.6.8 The Weir as a Total Barrier 28
5.6.9 Vacillatory Behaviour 28
5.6.9.1 Multiple Weir Crossing 29
5.6.9.2 Trap Channel Oscillatory Behaviour 29
5.6.10 Trap Efficiency 30
5.6.11 Trap Avoidance 30
5.6.12 Kelt Emigration 30
5.6.12.1 Behaviour in Impounded Reach 30
5.6.12.2 Weir Crossing Behaviour 30

6.0 DISCUSSION 32
6.1 Straying Amongst Estuary-Tagged salmon 32
6.2 Modelling of Estuarine Behaviour 33
6.3 Dee Estuary Behavioural Model 33
6.3.1 Bias in Tagged Population 33
6.3.2 Outer Estuary Behaviour 34
6.3.3 Salmon Absent for Long Periods 34
6.3.4 Middle Estuary Behaviour 34
6.3.4.1 Impact of FW Flow 34
6.3.4.2 Impact of Tide 35
6.3.4.3 Impact of Channel Depth 35
6.3.4.4 Impact of Water Quality 36
6.3.5 Inner Estuary Behaviour 37
6.3.5.1 Impact of Time of Day 37
6.3.5.2 Impact of Freshwater Flow 38
6.3.5.3 Impact of Water Quality 38
6.3.6 Variation in Behaviour at Different Times of Year 38
6.3.6.1 Early Running Salmon 38
6.3.6.2 Autumn Entrants 39
6.4 Behaviour at Chester Weir 39
6.4.1 General Weir Behavioural Model 40
6.4.1.1 Fish Ladder Arrival 40
6.4.1.2 Weir Crossing 40
6.4.1.3 Trap Avoidance 40
6.4.2 Factors Affecting Delays at the Weir 40
6.4.3 Displacement from the Weir 41
6.4.3.1 The Importance of Searching Behaviour 42
6.4.3.2 The Importance of Tidal Effects 43
6.4.3.3 The Time of Year 43
6.4.4 Post Weir Crossing Behaviour 43
6.4.4.1 General Behaviour Patterns 43
6.4.5 Kelt Emigration 44

7.0 CONCLUSIONS 46
7.1 Introduction 46
7.2 Outer Estuary Behaviour 46
7.3 Behaviour in Middle and Inner Estuaries 46
7.4 Straying 46
7.5 Kelt Behaviour 47
7.6 The Effectiveness of the Fish Pass 47
7.7 Interruption to Migration 47
7.8 Factors Affecting Weir Passage 47
7.9 Displacement of Salmon from the Weir 48

7.10 Multiple Crossing and Impoundment Passage 48

8.0 RECOMMENDATIONS 49

9.0 REFERENCES CITED 51

ACKNOWLEDGEMENTS 53

FIGURES

TABLES

EXECUTIVE SUMMARY.

1.0. Main Objectives.

I. To describe the migration of adult Atlantic Salmon (Salmo salar L.) through the Dee estuary and to relate behaviour to environmental factors; river flow, water quality and tidal regime.

III. To assess the impact of the tidally influenced weir at Chester on salmon migration.

2.0. Background.

There is concern that proposed barrages, whether for power generation (eg Severn Estuary) or amenity (eg Usk estuary) will impact upon populations of some fish species which utilise estuaries. Atlantic salmon are not tolerant of conditions of poor water quality and are therefore of considerable value as indicators of the health of estuaries. Furthermore, they make substantial contributions to many economically important recreational fisheries. Salmon migrate through estuaries at least twice during their life cycle which puts them at risk from developments within the estuarine environment. However, the behaviour of salmon in estuaries, their responses to estuarine obstructions and the effectiveness and efficiency of fish passes are all poorly understood. The main concerns relating to power generating schemes include the effects of physical obstruction to migration, altered tidal regimes, possible reductions in impoundment water quality and damage resulting from contact with the turbines.

Telemetric tracking is used routinely to describe fish behaviour and is currently the best available technique for investigating estuarine behaviour in salmon. Radio tracking is more widespread but the reduced transmission ranges for radio waves in brackish water necessitates the use of acoustic systems in estuarine habitats. Initial studies depended solely upon the active tracking of fish using hand-held or boat-mounted hydrophones and it was not until the development of an effective passive tracking system for use in estuaries that estuarine tracking was attempted more widely in the U.K. A number of studies were undertaken and data gathered enabled a simple model of estuarine behaviour to be derived. However, these studies were carried out principally to address site-specific objectives which restricted the applicability of any findings in more general terms.

The Dee has a largely rural catchment of 1816 km^2 and an Average Daily Flow of 30.56 cumecs. It is regulated to provide potable water supplies with reservoirs in the headwaters maintaining river flows in excess of 4.2 cumecs across Chester Weir during normal operating conditions. The Weir crest is overtopped by about 24% of tides (amounting to 5% of total time) and has a large fish pass, leading to an NRA operated fish trap. The estuary is long and extends from its mouth at Point of Ayr to the tidal limit at Chester Weir, a distance of 39 km. It can be divided into 3 physically distinct sections. The broad outer estuary is relatively shallow with dendritic low water channels. The narrow middle estuary is also shallow and includes a 6 km canalised section. The inner estuary, whilst narrow like the middle estuary is of greater average depth. Licensed seine nets operate in the middle and inner estuaries. Trammel nets operate in the outer estuary. In addition, the estuary receives a number of effluents including Chester Sewage Treatment Works in the inner estuary and several significant trade effluents notably to the outer estuary.

3.0. Summary of Work Carried Out.

Behavioural data were obtained in two ways. Passive tracking involved the collection of data by automatic tracking equipment sited in the estuary. Up to 9 acoustic buoys were deployed in the middle and inner estuaries, detected acoustic signals from tagged salmon and relayed the information via a radio telemetry link to one of 12 Automatic Listening Stations (ALS) sited close by and enabled individual fish tracks to be constructed. Salmon were also tracked from release in the outer and middle estuaries using a boat-mounted hydrophone. This enabled not only precise location of tagged fish in the narrower reaches but also gave detailed information about small scale movements in response to tidal state, netting activity, boat traffic and to obstructions. Routine active tracks from the air were made during low water periods to search for tagged salmon in the outer estuary and other rivers.

Continuous monitoring of dissolved oxygen, temperature and salinity was undertaken by the project team at two locations in the estuary. Level gauge data from Chester Weir and river flow data were also collected.

4.0. Summary of Results.

Three salmon tagged in the Dee estuary were subsequently detected in other catchments (2 from Lancashire rivers and 1 from the neighbouring Clwyd/ Elwy system) which indicated that there was no direct evidence of substantial mixing of salmon stocks in the middle reaches of the Dee estuary. Results showed that successful entry to freshwater reaches was achieved by a greater proportion of the middle estuary tagged population in 1992 and 1993 (44% and 51% respectively) than in 1991 (21%). Since the proportions of inner estuary net recaptures were similar during the project this provided some indirect evidence that the middle estuary was an effective barrier to migration during 1991.

Results from the outer estuary indicated that whilst very rapid progress through the outer estuary was possible, rate of upstream progress was typically lower than for equivalent distances in the middle and inner estuaries. Moreover a large proportion of salmon released in the outer estuary took more than 7 days to enter the middle reaches. Failure to locate these fish during active tracks suggested that they had moved offshore during this period.

In the middle estuary salmon typically remained stationary for between 15 and 40 minutes after release. This was typically followed by upstream movements irrespective of the state of tide. During the ebb tide and at low water upstream progress through the middle estuary was interspersed with small downstream movements producing net upstream ground speeds of the order of 0.1 m/s. Salmon responded quickly to the advent of the flood tide making use of tidal currents and ground speeds in excess of 1.7 m/s were recorded over several kilometres. The majority of salmon which were active tracked used the flood tide when migrating through the canalised reach consequently arriving at the inner estuary at high water or during the early ebb. Nevertheless upstream migrants entered the inner estuary at all states of tide which indicated that successful passage through the canalised reach was not dependent upon flood tide assisted migration. Upstream progress was generally slower through the inner estuary and ground speeds were more consistent because salmon tended to hold-up (particularly in reach 5) and large scale oscillatory movements were more frequent. Moreover, arrival times at Chester Weir suggested some inhibition of movements during daylight hours which would also tend to increase residence times.

Although there was considerable interdependency between the environmental parameters investigated, results suggested that higher water temperatures and lower river flows both acted to reduce the probability of salmon traversing the middle estuary in less than 24 hours. In contrast it was not possible to establish such a relationship with dissolved oxygen concentration. Results suggested that the probability of rapid (<24 hours) migration decreased to 50% at median water temperatures of 18 Deg C and no fish would be expected to cross the middle estuary within 24 hours at temperatures of the order of 21 Deg C. Similarly, whilst the probability of rapid migration was only 50% at river flows of 8 cumecs when flows reached 13 cumecs rapid passage was virtually assured. It was also apparent that tide size and tidal state were important in determining behaviour.

Salmon were able to pass the Weir using either the trap channel or crossing via the Weir crest itself. At the lowest river flows (4.2 cumecs) crossing via the Weir crest was not achieved unless the Weir was inundated, at flows between 4.2 and 8 cumecs about 90% of Weir crest crossings were undertaken within 2 hours of high water on Weir-topping tides. Although Weir crest passage was achieved by some fish during low water periods at flows around 20 cumecs it was not until flows in excess of 36 cumecs that Weir crest passage appeared to occur irrespective of tidal state. Time of day and tidal state were of greatest importance in determining crossing via the trap channel because for this route there were no physical limitations under low flows, at low water or during small tides. During low flows trap channel passage was most frequent at night and when the fish ladder was inundated by tide. The probability of passage increased over the range 4.2 to 35 cumecs peaking at flows of the order of 30-35 cumecs. Probability of passage decreased at flows in excess of 35 cumecs and no radio-tagged salmon used the trap channel during flows in excess of 65 cumecs (95%ile).

Delays at the Weir were short, 50% of tagged salmon were delayed for less than 12 hours and 95% for less than 7 days. River flow was only important under relatively high flows, delays during periods when median flows exceeded 20 cumecs were significantly shorter than lower flow periods probably because of the reduced reliance on tidal assistance for Weir crest passage. Weir delays were also found to increase when the trap was fishing.

About 31% of salmon reaching the Weir were displaced downstream some of which were recaptured by netsmen in the inner estuary (estimates suggested about 16% of the in-season run). Displacements often occurred at high tide and early ebb and were more frequent at flows of less than 30 cumecs. A large proportion were initiated from positions in the reach immediately below the Weir and not from the fish ladder itself. Multiple crossing was infrequent (10 fish on 13 occasions) and was not recorded by salmon crossing via the Weir crest. Where it did occur it was associated with salmon emerging from the upstream trap exit during periods when the Weir crest was overtopped or with fish tagged or recaptured at the trap during fishings when the trap was subsequently opened allowing downstream passage. Behaviour in the "impoundment" was consistent and involved rapid upstream movements (typically 1 m/s) over the 20km stretch.

85% of the tagged salmon which had spawned (kelts) arrived at the Weir during freshets because these stimulated downstream movements amongst fish holding in the lower river. Of these fish, the majority remained in the impounded reach for only short periods before crossing the Weir whilst flows were still high. Inner estuary residence times for kelts were short, typically less than 12 hours and necessarily occurred during these same freshet events, that is, when flows were elevated.

5.0 Main Conclusions.

5.1. Three salmon tagged in the Middle section of the Dee estuary were subsequently recorded in other river systems or estuaries. There was therefore no direct evidence to indicate extensive mixing of stocks in the Dee estuary.

5.2. Results from the outer estuary showed that whilst rapid entry, akin to middle estuary behaviour occurred, a substantial proportion of relocated salmon were absent for long periods which suggested that salmon were behaving differently in this zone. However, it was not possible to ascertain how the behaviour was different or where the change in behaviour occurred.

5.3. Results indicated that behaviour in the Dee estuary was similar to that previously recorded from other estuaries except for the tendency for salmon to make net upstream progress at all states of tide. The behaviour recorded may reflect the relatively high river flows which occur within this regulated system.

5.4. Differences were noted between behaviour in the middle and inner estuaries. The latter is deeper and has a reduced tidal exchange, conditions similar to those expected behind an estuarine barrage, which may have led to the increased frequency of both holding and vacillatory behaviours. These findings are important because they suggest that an estuarine impoundment could increase total estuarine residence times and result in a greater frequency of oscillatory behaviour.

5.5. Kelt emigration across the Weir and through the inner estuary was largely passive with the majority of kelts not entering the impounded reach from the lower river until stimulated by increased river flow and emigration was completed typically within one tidal cycle. This suggests that barrages with effective downstream channels and encompassing extensive tidal exchange will not delay kelt emigration. Therefore, the impact of barrages on this component of the stock will depend on the effectiveness of fish passes in attracting fish from the competing influences of turbine channels since few kelts will cross the barrage at times other than during the ebb.

5.6. Tagged salmon were recorded arriving at Chester Weir across much of the range of available conditions but peak arrivals occurred at high water during nocturnal spring tides at times of elevated flow. Such behaviour probably reflected the position of the Weir within the estuary.

5.7. Probably because of its position within the estuary, freshwater flow appeared to provide the largest single influence on Weir passage behaviour. In general delays at the Weir were short and reflected the effectiveness of the fish ladder under the majority of flow conditions. However, at flows in excess of 20 cumecs delays were shorter and more consistent. This coincided with an increased preference for the Weir crest route by salmon indicating the likely mechanism behind low flow induced delay.

5.8. About 30% of salmon arriving at the Weir were deflected significant distances downstream into the inner estuary often on more than one occasion, in some cases displacement led to net recapture. It appeared that more fish were displaced from the reach below the Weir than from the fish ladder itself possibly because of the depth in the area immediately below the Weir. Moreover, the reach between the Weir and the top netting station was thought to be too shallow to arrest such movements. Displacement was most common during high water periods when salmon were most active and suggested that such movements were extreme forms of searching behaviour.

5.9. Despite the fact that Chester Weir is not an ideal model for an estuarine barrage, results suggested that displacement was most frequent during the late flood and high water phases. Assuming similar responses to estuarine barrages, unobstructed passage by salmon at such times cannot therefore be guaranteed.

5.10. Multiple crossing was rare at Chester Weir and was not recorded amongst tagged salmon crossing the Weir upstream via the Weir crest, an encouraging result if repeated at power generating barrages. However, the low incidence of this behaviour was a result of rapid upstream migration by salmon in the "impounded reach" sited above the saline limit of the estuary which would not necessarily be exhibited in a more typical estuarine impoundment.

6.0 Main Recommendations.

6.1. There is currently a gap in our knowledge of outer estuarine behaviour which this study was unable to reduce significantly. Future studies should concentrate on estuaries which will allow tracking throughout their length and particularly in their lowermost reaches.

6.2. As soon as suitable equipment is available investigations of the swimming depths of salmon at each stage of estuarine migration should be carried out. In the mean time, current studies involving amenity barrages should examine swimming depth responses of salmon during successful and unsuccessful passage of the structures.

6.3. There is a need to evaluate the responses of salmon to fish passes and turbine outflows similar to those proposed for tidal power schemes. This will necessitate the adoption of new technology and approaches to data gathering in order to provide increased resolution of movements in the vicinity of such structures.

6.4. There is a need to establish whether first findings from the Dee concerning impoundment behaviour are valid when applied to barrages which are more frequently over-topped and sited in reaches analogous to the locations of tidal power barrages.

6.5. Results indicate that the majority of salmon undertaking landwards migration will approach barrages during the early part of the flood tide and it is therefore important that this is considered during planning for barrage schemes.

6.6. Barrages placed lower down estuaries will be more likely to impact on "alien" salmon stocks and to be sited in a zone where salmon homing correctly will undergo tidal oscillation. In both cases these fish are likely to use the ebb tide to emigrate once dissuaded from further landwards progress, they will therefore risk passage through the generating turbines. Adequate safeguards are needed to prevent a substantial proportion of such fish becoming damaged.

6.7. Facilities for successful kelt passage must be considered. It is likely that any measures adopted to address concerns raised in 6.6. above, would be suitable in protecting the passively emigrating kelt component of the fish population.

1.0 INTRODUCTION.

This report describes work undertaken during the period April 1991 to December 1993 by the Welsh Region of the National Rivers Authority to investigate the behaviour of radio-tagged adult Atlantic salmon (*Salmo salar* L.) in the Welsh Dee. Partial funding for work in 1992 and 1993 was provided by the Department of Trade and Industry under their Tidal Energy research and development programme.

1.1 Background.

Atlantic salmon are an extremely valuable economic and conservation resource within the UK; they are highly prized as a sport fish by anglers willing to pay large sums to fish for them in freshwater reaches and angling makes significant contributions to the income from tourism in many rural areas of the British Isles. In addition, salmon stocks support licensed net fisheries of local importance in Wales and include some licensed coracle net fisheries of historical significance. The true value of a fishery is difficult to determine but within the Dee catchment alone the total value of the salmon resource has been estimated to be £2.15 million.

Salmonids are sensitive to poor water quality and are therefore regarded as good indicators of environmental quality in estuaries and rivers. Thus several water quality standards have been set specifically to protect salmonids in these waters. In recent years the numbers of salmon and sea trout returning to spawn has declined in many British rivers. The early (spring) running component has suffered a particularly serious decline leading to the introduction of bye-laws to increase their protection.

Salmon pass through estuaries on both upstream (spawning) and downstream (to high seas feeding grounds) migrations. These phases of the life cycle are potentially critical because the fish experience rapid changes in osmotic conditions leading to physiological stress. Smolts have been shown to be especially sensitive to additional stressors at this time of physiological adaptation. Moreover the use of estuaries for industrial development and, recently as possible sites for the construction of amenity and tidal power barrages means that environmental conditions could become critical for salmon survival.

Another feature of estuaries in the British Isles has been the lack of scientific information relating to fish behaviour during estuarine passage. Indeed when the Dee project started (April 1991) few tracking studies of adult salmon had been attempted in UK estuaries. This was largely due to the lack of a robust acoustic passive tracking system with the result that most projects concentrated on the use of active location when tracking fish, for example, work undertaken with sea trout in the Glaslyn estuary (Milner, 1985). An active tracking approach designed to investigate the behavioural responses of adult salmon to dissolved oxygen in the Ribble estuary using environment sensing transmitting acoustic tags attached to the fish (Priede *et al.*,1988) was the first and only serious attempt to compare directly the environmental conditions fish are experiencing with behaviour. They tagged few fish because of the expense and logistical complications and consequently produced only limited results.

In the late 1980's a MAFF developed system for acoustic tracking was described by Solomon and Potter (1988) having been evaluated during research on the estuaries of two South coast rivers, Avon and Fowey. Estuary tracking using the MAFF system began in Wales in 1988 with studies on the river Tywi (Clarke and Purvis,1989) and river Usk (Aprahamian *et al.*,1988).

Following the successful completion of the Tywi study in 1990 equipment and much of the expertise were transferred to the Welsh Dee to undertake a 3 year salmon tracking project as part of the Dee Stock Assessment Programme (DSAP). DSAP was designed as a long term study of salmon and sea trout population dynamics centred on the upstream fish trap at Chester Weir.

1.2 Tidal Barrages.

A number of studies considering the feasibility of tidal power generating barrages have been carried out including projects on rivers Wyre and Conwy as well as the Severn barrage. The construction of a tidal power generating barrage within the estuary environment will inevitably lead to an alteration of the hydrodynamics of the estuary with a consequent impact on the estuarine ecosystem. Barrages constructed in those estuaries frequented by migratory salmonids will be of particular importance with salmon and sea trout coming into contact with the barrage on at least two occasions during the normal course of their life-cycle:

i) during seaward migration of juveniles (smolts), and

ii) during landward migration by the sexually mature adults returning to spawn in their home-river.

In addition, small numbers of salmon and a greater proportion of sea trout will survive spawning and emigrate (as kelts) from the river to resume feeding at sea passing a barrage for a third time. Sea trout would be expected to cross the barrage line more frequently than salmon due to their multiple spawning habit. However, this report is concerned solely with the movements and behaviour of adult salmon; salmon smolt and sea trout behaviour were not investigated and are not considered further. Salmon would pass a barrage line on at least one occasion on each of these migrations. But it is possible that wandering or vacillatory behaviour would repeatedly expose fish to these structures which could result in increased interference with passage and survival.

An estuarine tidal power barrage could affect adult salmon in two ways;

i) fish using the turbine chambers may be damaged by machinery. This topic has been researched elsewhere (Turnpenny *et al* 1992) and is not considered further within this report.

ii) migration may be interrupted either permanently or temporarily by the presence of the barrage. This could variously lead to increased straying to other catchments or to greater residence time in the home estuary. Extended estuarine residence will lead to increased exposure to any exploitation, disease and to water quality problems associated with the reach downstream of the barrage line. It would also serve to delay entry into any freshwater fishery. The potential problems therefore impact on both stock abundance and fishery performance of this valuable national resource.

These perceived potential problems lead to the commissioning of a report by the Depatment of Energy (Solomon, 1988) which recommended that studies be carried out to;

i) describe the behavioural patterns of all life history stages of salmonids using estuaries and,

ii) their behavioural responses in the vicinity of tidal barrages.

The general aim of the Dee tracking project was to investigate the estuarine behaviour of adult salmon including aspects of behaviour associated with the tidally influenced Weir at Chester; this study therefore addressed both of Solomon's recommendations.

1.3 Scope of Study.

This report concentrates solely on the aspects of salmon behaviour associated with estuarine migration and the responses of salmon to the partial tidal barrage at Chester. The objectives of work reported within this document are given in a later chapter (Section 2). Other aspects of the work programme relating specifically to NRA objectives have not been reported here.

2.0 TERMS OF REFERENCE.

2.1 Overall Objective.

To examine and describe the factors determining behaviour of radio-tagged adult salmon in the estuary of the Welsh Dee and in the vicinity of a tidally influenced weir.

2.1.1 Estuarine Objectives.

i) to describe the patterns of behaviour of radio-tagged salmon in relation to tidal regime, estuarine water quality and freshwater flow across Chester Weir.

ii) to continuously active track up to 15 acoustically tagged salmon in the outer estuary to provide information on movements outwith the passive tracking zone

iii) to provide information on the numbers of radio-tagged salmon entering neighbouring river catchments.

iv) to describe the emigration behaviour of radio-tagged kelts.

2.1.2 Chester Weir Objectives.

i) to assess the proportions of salmon ascending the Weir via the trap channel and via the Weir crest (trap efficiency) and relate these results to FW flow, tide height and tidal state.

ii) to assess the impact of Chester Weir as a barrier to migration by determining lengths of delay for radio-tagged salmon encountering the Weir.

iii) to determine the proportion of radio-tagged salmon displaced from the Weir downstream into the inner estuary.

iv) to investigate the factors (eg tidal regime, FW discharge, temperature, time of day) affecting behaviour of radio-tagged salmon at the Weir.

v) to investigate the post-tagging behaviour of trap-caught tagged salmon and the amount of straying recorded from this sample.

vi) to assess the behaviour of radio-tagged salmon in the "impounded reach" upstream of the Weir.

vii) to investigate the factors determining emigration of kelts through the "impounded reach" and across the Weir.

3. DESCRIPTION OF STUDY AREA.

3.1. The Dee System.

3.1.1. Catchment to Chester Weir.

The River Dee (Afon Dyfrdwy) rises at a height of 884 m in the Cambrian Mountain Range, and flows for some 160 km before entering the Irish Sea in Liverpool Bay below the Wirral, see Figure 1. It is a heavily regulated river, being the source of potable water supplies for over two million people. This regulation includes the maintenance of a residual flow of 4.2 cumecs across Chester Weir which exceeds natural dry weather flow from the system. Four headwater reservoirs (Bala, Alwen, Brenig and Llyn Celyn) are used to control river levels, ensuring sufficient flow to support abstraction in the lower river. Important tributaries include the Tryweryn and Alwen in the Upper Dee, the Ceiriog in the Middle Dee and the Clywedog in the Lower Dee.

The catchment area is largely rural with livestock rearing prominent, dairy farming presents some problems in the lower Dee. Industrial use is restricted to the areas around Llangollen, Chirk and Bangor-on-Dee with significant discharges of treated effluent from chemical works, paper mills and creameries in addition to treated sewage effluent from local conurbations. Surface water from Wrexham industrial estate drains to the Afon Clywedog.

3.1.2. The Estuary.

The Dee estuary extends 39 km from Chester Weir to Point of Ayr. At the mouth, between Point of Ayr and Hilbre Island on the Wirral it is 8 km wide and all upstream distances quoted refer to this line as the zero point. The estuary was classified into three areas, see Figure 2.

i) The outer estuary; extending from a line drawn between Hilbre Island and Point of Ayr landwards as far as the upstream extent of the training wall below Connah's Quay. At low water it was a wide expanse of sand and mud banks with a dendritic system of channels and at high water a shallow basin. At Mostyn Dock (GR SJ155802) within this reach, the tidal cycle was virtually symmetrical. Tidal range was large leading to high current speeds which, with its wide and shallow nature, produced a well mixed outer estuary with salinities at all states of tide in excess of 12ppt.

ii) The middle estuary; defined as the reach between the point at which the outer estuary first narrowed significantly and Saltney Ferry (GR SJ370659), reflected land reclamation and navigational projects of the last 300 years, the most notable aspect of such work being the 7km canalised section from Queensferry Bridge to Saltney Ferry. The reduction in width of the estuary in this reach produced greater tidal asymmetry from Connah's Quay to Chester. The middle estuary was also shallow with a narrow low water channel although some small areas of deeper water occurred close to jetties, piers and bridge supports. Peak salinity decreased noticeably with upstream distance in this reach and low values were recorded even at the lowest point in the reach, Summer's Jetty, where levels ranged from 4ppt to 28ppt.

iii) The inner estuary stretched 5km from "The Bar" immediately upstream of Saltney Ferry (GR SJ385655) to the normal saline limit at Chester Weir (GR SJ408658). There was no reduction in channel width between middle and inner estuaries but The Bar held water back resulting in greater average depth. Tidal asymmetry was pronounced and with some neap tides having only a negligible affect on the upper sections of the reach, tidal exchange was much reduced. The substrate changed from predominantly sand at the entry to the reach to rich organic sedimented mud in the Curzon Park reach illustrating the increasingly riverine nature of the estuary at this point, salinity ranged from 0ppt to 5ppt.

3.1.2.1. Uses of the Estuary.

i) Dilution of Effluents.

Treated effluents from both sewage treatment works and industrial premises are discharged directly into the estuary. The biggest discharge is from Chester Sewage Treatment Works into the inner estuary with a smaller volume treated sewage effluent discharged into the lower section of the canalised reach from the treatment works at Queensferry. In addition, there are a number of concerns relating to the ingress of leachate into the estuary from areas of contaminated land and from waste disposal tips. The impact of these diffuse sources of pollution is difficult to quantify. The Dee estuary includes a coal mine at Point of Ayr and there are also proposals for gas-fired power stations discharging thermal effluent to the lower middle estuary.

ii) Fisheries.

The estuary is important as a conduit for salmon ascending into freshwater reaches to spawn and therefore for those salmon angled for in the freshwater fishery. Recently the angling catch has declined on the Dee from 1400 in 1965 to less than 450 in 1991 a trend echoed in other UK rivers. Nevertheless, salmon are still the most valuable component of the fish population on the Dee. The estuary also supports a locally important salmon net fishery, with approximately 20 (of 30) draft netting licensees actively fishing in the middle and inner estuaries. Three of four trammel licences were fished in the outer estuary below Connah's Quay. Declared net catches have also fallen in recent years and during the study period were of the order of 1000 fish. In addition, the outer estuary between Mostyn and Flint is subject to illegal drift netting for salmon and sea trout.

Flounder (*Platichthys flesus* L.) are netted during the late Summer and Autumn. Problems with the interception of salmonids by this fishery resulted in the promotion of bye-laws by the NRA during 1992. These restricted the gear which could be used and the areas and periods where fishing was allowed and have been successful in protecting salmonid stocks.

iii) Recreation.

Windsurfing and yachting is popular in the outer estuary particularly from the Wirral side. The middle estuary is used by Deeside Waterski Club and canoeing is very popular at Chester Weir.

3.1.3. Chester Weir.

Chester Weir is approximately 150 m long and crosses the Dee diagonally upstream of Old Dee Bridge, see Figure 3. It was constructed on the site of an existing sandstone ridge in order to allow abstraction and the generation of hydroelectric power. The Weir crest is at a height of 4.33m AOD (above ordnance datum) and is over-topped by 24% of tides. However, the extent of tidal asymmetry at the top of the estuary means that overtopping only occurs for about 5% of the total time.

A series of pools each with a notch in the upstream face form a fish ladder running parallel to the weir leading to the fish trap and original fish pass. Hinged oversails prevent passage through the notched fish pass, diverting fish towards the trap. Penstocks enabled the trap to be isolated and allowed partial draining of the trap box when salmonids were processed and tagged as part of the Dee Stock Assessment Program (DSAP). The trap was fished on a 6 days on 3 days off rota.

4. MATERIALS AND METHODS.

4.1. Fish Capture.

Most fish used in this study were purchased from commercial draft netsmen at two sites; Connah's Quay (GR SJ295700) and Curzon Park (GR SJ398656), see Figure 2. These fish would otherwise have been killed and sold. Netting started in May and continued until the season closed at the end of August. After this date netting was continued at Connah's Quay under strict N.R.A. supervision to provide salmon for tracking in September and October. In addition, during 1993, a number of fish were transported into the middle and outer estuaries (relocated) following capture and tagging at Chester Trap.

4.2 Tagging.

Salmon of a suitable size (>500 mm) and good condition (no fresh net damage, predator marks, scale loss or signs of fatigue),and which remained free swimming in the net were selected for tagging. They were placed directly into an opaque handling bag containing anaesthetic (2-phenoxyethanol), at a concentration of approximately 0.1-0.3ml/l. The fish were then removed into an open wooden measuring box containing an inset metre rule in the base and the following comments noted; weight (g), length (fork length mm) and presence of parasites. Two scales were taken from above the lateral line for ageing purposes. Fish were also sexed from external secondary characteristics. The fish were then fitted with two tags, an external marker (floy) tag and an internal (stomach) transmitting tag. Typically the process outlined above took between 5 and 8 minutes. Following tagging fish were immediately released by being held in flowing water until sufficiently revived to swim away or to hold station unaided. To prevent immediate recapture, fish were released approximately 0.2 km downstream from the netting station at Connah's Quay, and a similar distance upstream at Curzon Park.

4.2.1. Tags.

Each salmon received two tags:

4.2.1.1. Floy tags (External Marker tags).

Floy tags were inserted by means of a 'Minitachit' tagging gun into the dorsal musculature (just below the dorsal fin), such that the plastic 'T' piece lodged behind the dorsal fin rays. The area around the base of the tag was treated with a mixture of antibiotic powder and dental adhesive in order to provide short-term protection against infection. Floy tags used were of cylindrical orange plastic (length 80 mm, diameter 2mm), they provided information relating to the location of the radio-tag, reward details and address for the return of tags.

4.2.1.2. Internal transmitting tags.

A tag lubricated with a water soluble jelly was gently inserted into the stomach of the anaesthetised fish via the oesophagus using a specifically designed 'plunger'. The tag was released from the plunger on the first sign of resistance and the plunger removed. Post mortem examinations of several fish revealed that this approach placed the tag at the intestinal end of the stomach.

In this study two types of internal tags were used, both developed by M.A.F.F. (Solomon and Potter 1988).

i) 'Sal 3' Radio Tags were 50 mm long by 16 mm diameter, encapsulated in a cylindrical polycarbonate case with biconvex ends. Tags transmitted on frequencies in the range 173.800MHz to 173.850MHz, as approved for use with telemetry by the Department of Trade and Industry (cert. no. RTD3435). They were powered by a single cell battery with a capacity of 800 mAh. Each tag produced a pulsed radio signal which was uniquely identifiable, through its combination of channel (= frequency) and pulse rate (pulses per min.). Pulse rates ranged from 20 ppm to 130 ppm, with a consequent affect on theoretical transmitting life (range 4 to 10 months).

ii) Combined Acoustic and Radio Tags (CART's) were used in the estuary because of transmission range reduction caused by the rapid attenuation of radio signals in saline and brackish water. These tags were also housed in a cylindrical polycarbonate case, (65 mm length and 16 mm diameter). They produced a simultaneously transmitted radio and acoustic pulsed signal. The acoustic signal was generated on a single frequency of 76kHz which reduced the number of tags which could be deployed at any one time. After a designated number of pulses the acoustic signal was switched off to conserve battery power and to extend the radio transmitting life of the tag. Acoustic lives were set for between 6 and 18 days in order to ensure adequate acoustic coverage in the estuary. The total theoretical battery life of the CART's used was between 4 and 8 months.

4.3 Tracking.

Two methods were used to track salmon:

4.3.1. Passive Tracking

Passive tracking involved the use of remote, continuously scanning data logging stations recording the passage of tagged fish. In the estuary underwater hydrophones detected acoustic signals from the tags, these were transduced into radio-signals and transmitted via a whip aerial to a radio receiving station (automatic listening station, ALS). The two systems are discussed in greater detail below.

4.3.1.1. Automatic listening stations (ALS).

A total of twelve ALS's were used in the estuary, see Table 1. Each ALS comprised a modified Yaesu type FT 290R radio, with 10 preset frequencies, a micro processor to cycle through the presets and both a paper and magnetic tape data storage system. They were powered by a 12V lead acid battery, and programmed either to scan the ten frequencies continuously (in practice each frequency was scanned about twice per minute) or at intervals of 2 minutes depending on location.

At the determined interval the ALS scanned each of the 10 frequencies sequentially and tag signals detected were recorded onto audio tape enabling the identification of the tag pulse rate over a 12 second period. At the same time a paper tape printout was produced detailing the date and time of the recording and its frequency. At the laboratory data were collated and each movement ascribed to a particular individual by comparing the tag frequency with pulse rate and then entered onto the tracking database.

Four ALS's were positioned in the vicinity of the Weir, see Figure 3. They each had their sensitivities adjusted and antennae positioned to give a restricted range of detection (evaluated by use of a test tag). This enabled more precise positioning of tagged fish in certain areas of the Weir which was necessary in order to interpret the behaviour of salmon close to the Weir.

4.3.1.2. Acoustic Buoys.

Acoustic Buoys were deployed at 15 different sites in the estuary over the three years of the project, see Table 2. Positions were dictated by considerations of equipment safety, effective range and likely interference from tidal currents.

Acoustic signals from CARTs were detected by the hydrophone and converted into radio signals which mimicked the acoustic signal and which was then transmitted via an aerial sited above high water level to a suitably located ALS unit (described above). Thus a recording of the passage of each acoustically tagged salmon past buoy sites was made at the bank deployed ALS. The acoustic receiver, radio transmitter (DTI type approval certificate number, RTD 3437) and interface unit were powered by a 6Ah, rechargeable, lead acid battery and housed in a waterproof case with an external hydrophone and aerial (Solomon and Potter 1988). Two types of hydrophone were used in the estuary:

b) Tidal Asymmetry.

Tide gauge data at various points along the estuary were used to calculate the proportion of the tidal cycle occupied by the flood tide during typical spring and neap tides and expressed as a percentage of the period between consecutive high waters.

c) Chemical Parameters.

In reach 2 and reach 5 use was made of the two submersible water quality monitors to describe the variations in temperature, dissolved oxygen, salinity and depth.

4.5.2. Classification of Behaviour.

The complex behavioural patterns recorded during the three fieldwork periods were reduced to a number of definable criteria in order to investigate the impact of external factors on salmon behaviour.

a) Upstream Movement.

Date/ times of upstream passage past reach defining tracking stations were extracted from the database enabling the external factors prevailing at entry to the reach for individual tagged salmon to be investigated.

b) Reach Residence Time, T_r.

Reach entry and exit times were used to calculate T_r for individual tagged salmon which enabled the conditions prevailing during residence to be calculated for each fish.

c) Ground Speed.

The net ground speed within a reach was calculated for each fish (Reach length/ T_r). This enabled not only comparison with external factors but also the distribution of speeds within each reach allowed comparison between reaches.

d) Downstream Displacement from Reach.

The prevailing conditions during downstream movements from each reach were isolated in order to examine the possible factors displacing salmon from defined areas of the estuary.

e) Probability of Passage.

Probability of passage was defined as the proportion of available tagged salmon passing upstream of a given point within a given time period and provided an estimate of migration success through the estuary. In practice, the probability of successful passage through the canalised section of the middle estuary (that is, Reach 3) over 24hrs, 48hrs and 96hrs was calculated in relation to temperature, dissolved oxygen and flow.

4.5.3. Approaches to Analysis.

In order to describe the estuarine behaviour patterns recorded during the study distinctions were drawn between natural behaviour (influenced by tides, time of day, time of release and seasonal affects) and the influence of environmental factors such as temperature, dissolved oxygen and freshwater flow. Each behavioural criterion (dependent variable) was examined with respect to the external factors listed above (independent variables) using conventional statistical approaches.

Behaviour in relation to factors which varied cyclically, that is, time of day and state of tide was examined using vector analysis (Batschelet 1981) with mean times for each distribution calculated from mean vectors. The extent of randomness within each distribution was measured by calculation of the "r" value using the Rayleigh Test and comparing with tabulated values of "r" to test for significance.

5.0. RESULTS.

5.1. Tagged Population.

5.1.1. Background.

A total of 461 salmon were radio-tagged at three locations in the Dee estuary during the three years of the project, see Table 4. In 1991 all fish were tagged at Connah's Quay, n=82. In 1992, 82 salmon were tagged at Connah's Quay with a further 20 fish released from the netting station at Curzon Park in the inner estuary. In 1993, 46 salmon were caught, tagged and released at Connah's Quay (including 2 fish held for a 12 hour period prior to release), 21 were released from the inner estuary (including 6 relocated from Chester Trap) and a further 48 salmon were relocated from Chester Trap to either the middle or outer estuaries. In addition 7 salmon were relocated to the outer estuary following capture at Connah's Quay netting station.

155 salmon were tagged and released at Chester Trap partly to meet objectives relating to freshwater migration which are not reported here.

Only tracking results from those salmon tagged or relocated to the middle or outer estuaries were considered in the analysis of behaviour in reaches 1 to 5. Salmon released from the inner estuary site and from Chester Trap have been considered only in relation to behaviour at the Weir.

5.1.2. Differences between Years.

Considering only salmon released following capture at Connah's Quay, the major difference between the years was the low entry success amongst fish tagged in 1991 (20.7%) when compared with success rates in 1992 and 1993 (43.9% and 50.9%) respectively, see Table 5. This was principally due to differences between the numbers of tagged fish not detected post-release (33% in 1991, 2.4% in 1992 and 15% in 1993) since net exploitation rates were similar (1991 23.2%, 1992 30.5% and 1993 24.5%). There was also a higher incidence of suspected mortality or regurgitation during 1991 (15%) than either of the following years.

5.1.3. Differences between months.

In analysing the data by month the results from the three years have been pooled, see Table 6. Recorded freshwater entry success rates were greater during the early and late season (April to June 67%, September and October 65%) which contrasted with the months of July and August (22% and 26% respectively). These differences were principally due to the difference between licensed netting recapture rates (11% in May/ June, 39% in July and 38% in August). Regurgitation and mortality rates exhibited no obvious trends over the tagging season and when fish not seen post-tagging were included in this category results were very consistent between months (May/ June 22%, July 26%, August 27.5%, September/ October 21%), see Figure 4. Similar results were obtained for suspicious disappearances in estuarine reaches which accounted for about 10-15% of tagged salmon between July and September. This value increased to 20% in October and such disappearances were absent during May and June but in both early and late season periods numbers of tagged individuals were restricted.

5.1.4. Relocation Experiment.

Forty eight salmon were relocated from Chester Trap to the outer or middle estuary, see Table 7. Forty five (94%) were subsequently detected moving upstream into the middle estuary and 32 (67%) were detected passing into freshwater (in addition 3 of 4 confirmed regurgitations were detected in freshwater reaches). This contrasted sharply with those fish tagged and released at Connah's Quay in 1993 (n=53) where 27 (51%) successfully entered freshwater reaches. These observed differences between the two categories of release were not significant however, Chi-Sq= 2.0, df=1, N.S.

There was a large disparity between net exploitation rates for the two samples. 10.4% of relocated fish were taken by licensed nets in 1993 which contrasted with estuary tagged fish which suffered 24.5% exploitation rates. In contrast regurgitation rates and mortality rates (including "not-seen fish") were similar between the two samples.

5.1.5. Bias in Tagged Population.

The relocation of trap-tagged salmon was adopted in 1993 to increase the numbers of early season fish tagged and to investigate concerns about the non-randomness of release times for fish tagged at Connah's Quay.

5.1.5.1. Release Times.

a) Time of Day.

Salmon tagging at Connah's Quay was conducted throughout much of the 24 hour period. Overall release times were typically concentrated in the afternoon and the distribution was significantly non-random, peak time, 14:32h, "r" = 0.277, $p < 0.05$. Whilst there were slight differences between years the overall pattern was consistent, see Figure 5. This contrasted with the early morning release times of relocated salmon, peak time, 08:16h resulting from the transportation requirements from Chester Trap. In the latter case the distribution of release times was even more significantly non-random, "r" = 0.960, $P < 0.01$, see Figure 6.

b) State of Tide.

Netting was restricted to the ebb-tide at Connah's Quay on all but the smallest of neap tides when netting was possible throughout the tide. As a result, the majority of draft net captured salmon were captured and released during the ebb, peak time 05:04h after HW, "r" =0.539, $p<0.01$, and once again the pattern between different years was consistent, see Figure 7. In contrast, trap relocated fish release times were random with respect to state of tide, "r" = 0.190, N.S., see Figure 8.

5.1.5.2. Reach 3 (R3) Entry Times.

Tagged population bias was examined by comparing the distribution of arrival times at R3 amongst fish relocated from the trap to the outer estuary with those salmon released after net capture and tagging in situ at Connah's Quay.

a) Time of Day.

Entry to reach 3 by both samples was randomly distributed in respect of time of day, outer estuary relocatees, "r" = 0.245, N.S., Quay-tagged salmon, "r" = 0.077, NS, see Figure 9.

b) State of Tide.

Entry times for outer estuary relocated fish were randomly distributed with respect to state of tide, "r" = 0.269, N.S. This contrasted with Quay-tagged salmon which were statistically more likely to enter reach 3 during the early flood, peak time, 09:02h after HW, "r" = 0.274, $p<0.05$, see Figure 10.

5.2 Straying.

Three radio-tagged salmon have been detected in other catchments following tagging in the Dee estuary, one in each of the three years.

Fish number C2E036 was detected leaving the Dee estuary in September 1991 and was later detected in the adjacent Clwyd/ Elwy catchment. This fish was detected as far upstream as Chester Weir prior to emigration.

Fish number 2C2F920 was recaptured by a draft netsman operating in the Lune estuary shortly after it was tagged at Connah's Quay, August 1992.

Fish number C2G706, tagged in August 1993 at Connah's Quay was relocated from the middle to outer estuary, tracked for a short period as it moved downstream after tagging was then lost to the tracking team and was subsequently detected in the freshwater reaches of the River Lune during an air-track in November 1993.

There was also evidence of a small number of fish potentially not destined for the FW Dee migrating above Chester Weir. Three tagged fish left freshwater reaches in the Autumn after remaining for significant periods (more than 1 month) in the lower Dee. Unfortunately none of these fish was subsequently detected during air-tracks of neighbouring catchments and cannot therefore be classified as strays.

5.3 Outer Estuary Behaviour.

Between 5-8-93 and 22-10-93 a total of 28 fish were released in the outer estuary. These were captured at the draft nets at Connah's Quay, (7 fish) or taken from Chester Trap, (21 fish) and were released at either Flint Sands (4 fish) or Greenfield Bank (24 fish) in the outer estuary.

Of the 28 fish relocated, 23 (82.1%) returned to the Middle Estuary. The remaining five fish were either tracked downstream from release, lost to the tracking team and not subequently detected in the middle or outer estuary (fish number C2G127), were not seen after tagging, (fish numbers 25JG4, 27QG7 and C2G126) or were subsequently detected outwith the Dee catchment (fish number C2G706 was located during a air track of the River Lune).

For the 23 salmon reaching the middle estuary times of travel varied from 5:12 hours to 51.3 days with a median time of travel of 90:08h. Low water air tracks failed to detect the 7 fish which were not detected in the middle estuary until more than 1 week after release. It was assumed that such fish remained in either the extreme downstream limits of the estuary where the salinity of the water prevented detection or they moved into coastal waters. Evidence from continuous boat active tracking suggested the latter was more probable.

The fastest passage of the outer estuary (5:12 hours) was achieved by fish number 28QG7 which was released 4 hours after high water at Greenfield on a 7.9m tide, 23-9-93 and whose upstream progress (net speed 2.5 km/h) was probably assisted by the subsequent flood tide. Greater detail on the behaviour of fish making rapid passage through this reach was obtained from fish number C2G723 (net ground speed 1.3 km/h) which was successfully active tracked from release into the middle estuary. This track clearly indicated the importance of the state of the tide in determining movements of salmon in this reach. Immediately after release, C2G723 made a downstream movement of 400m in the same direction as the ebbing tide, see Figure 11. It remained stationary for a period before beginning a slow (1.12 km/h) consistent movement upstream in advance of the flood tide. Ground speed increased markedly following the advent of the flood tide and the salmon was recorded moving at the same speed as the drifting boat (3.84 km/h). Generally upstream progress was maintained at this level over a distance of 8.4km during which time it remained close to the tidal wavefront and followed the low water channel. Although it is interesting to note that a short, 300m, downstream movement was recorded during this flood tide assisted migration, such behaviour was not recorded under similar tidal conditions in the middle estuary. It is also interesting that this fish waited several hours below the entry to the middle estuary before passing Summer's Jetty at 20:43h, at this time moving upstream against the last stages of the ebbing tide. This directed migratory behaviour was continued in this instance through middle and inner estuaries.

Of the other fish active tracked from relocation in the outer estuary 3 moved downstream immediately upon release, all following the main low water channel. The track of fish number C2G127 was discontinued after 2:06 hrs when it reached the downstream limit of the outer estuary. Two fish were lost in shallow turbulent water as they moved downstream shortly after release (C2G706, 1:33 hrs, C2G418, 2:30 hrs). In contrast, two fish released during the flood tide immediately moved upstream, C2G228 (1:21Hrs), C2G530 (1:15Hrs) but both were subsequently lost in shallow water as they continued to make upstream progress. On three occasions tagged fish were lost by the tracking team at or shortly after release. Two tags C2G126, C2E012 were not functioning acoustically at release. The third 2C2G622 was lost shortly after release following problems with limited detection range. This tag was subsequently found to be operating intermittently.

Of the 23 fish returning to the middle estuary precise entry times were obtained for 16 individuals, entry was random with respect to both state of tide, "r"= 0.095, N.S. and time of day, "r"=0.192, N.S.

5.4 Environmental Results.

5.4.1. Differences in Freshwater Flow between years.

Inter year differences in inner and middle estuary environment were largely influenced by changes in freshwater flow conditions brought about by elevated rainfall during the summer months in 1992 and 1993. However, the artificial maintenance of flows in the main river to support lower Dee potable water abstraction meant that the differences between 1991 and the two succeeding summers were not as large on the Dee as would have been anticipated in an unregulated catchment. This was largely as a result of the maintenance of discharge to the estuary at 4.2 cumecs (in excess of dry weather discharge) during periods of low rainfall. Although two artificial releases of 3 cumecs supplemented regulation flows during two periods in July and August 1991. They were made in response to perceived water quality problems in the tideway and further contributed to the reduction in likely impact of warm, dry settled weather.

Flows during the 1991 fieldwork season (June to October inclusive) were lower than the two following years and this reflected the higher rainfall figures for these two summers. In all study months during 1991 except July, monthly average flow (measured at Manley Hall, OSGR SJ346415) was lower than the 23 year average value and fell to only 41% of this long term value in September of that year. During both 1992 and 1993 the monthly pattern was similar with flows exceeding the long term average in all study months except July 1992 and October 1992,1993. May and June 1993 were particularly wet months and, in both, flows exceeded 150% of the long term May/ June average. The most consistent month was October, with all three seasons having flows on the dry side of the 23 year average falling to 45% in October 1993. In contrast, the greatest variability was recorded during the months of September. September 1991 was dry with resulting low flows whilst September 1992 was a wet month (mean flow 30.85 cumecs) flows were also high during September 1993. Comparison of the flows in June of each year also revealed considerable variation, see Figure 12.

5.4.2. Differences in Water Quality between Years.

Mean monthly water temperatures were highest during the 1991 tracking period (August 18.26 Deg C, September 15.79 Deg C) but never exceeded 20.01 Deg C. Temperatures during 1992 and 1993 showed a consistent pattern, see Figure 13, and were typically cooler than 1991 temperatures, August mean temperatures, 1992, 16.51 Deg C, 1993 15.95 Deg C.

Mean monthly dissolved oxygen values followed the same pattern with average values highest during 1991; August mean 9.63 mg/l, see Figure 14. On average dissolved oxygen levels were lowest during 1993 (lowest recorded minimum mean monthly dissolved oxygen, Summers Jetty, November 1993, 6.72 mg/l). However, at no time did the monthly average approach 5 mg/l, the figure commonly regarded as indicating likely physiological stress in salmonids.

5.4.3. Differences in Tidal Asymmetry.

At Mostyn Dock in the outer estuary the tidal curve was virtually symmetrical with 40-45% of the total tidal cycle taken up by the flood tide. Landwards of Flint the duration of the flood phase decreased with upstream distance, see Figure 15, with only 10.1% of total time during a Spring tide occupied by the flood phase at Chester Weir. Time of travel of first flood between Summers Jetty and several defined points in the estuary was calculated using tide gauge data from a number of sites and over two typical tides, a medium spring tide 9.4m and a medium-sized neap tide 7.3m (heights from local tables). Time of travel was plotted against estuarine distance, see Figure 16. During the spring tide, time of travel for first flood from Summer's Jetty to Chester Weir was 1:37h (a net speed of 8.9 km/h). Time of travel was increased to 3:34h during the neap tide examined (a net speed of 4.2 km/h). The duration of the flood tide decreased with distance up the estuary and this meant that time differences between high water at Summers Jetty and at Chester Weir varied between 00:22 hrs and 1:47 hours on typical spring and neap tides respectively.

5.4.4. Differences in Reach Depth.

Average reach depth (defined as the depth of water over the low water channel at Low Water) in the middle and inner estuaries was greatest in reach 4 (2.6m) and least in reach 3 (1.4m). Reach 3 contained the greatest range in depth 0.6m to 4.9m. Most of the reach was shallow, < 1.0m deep, at low water with deep areas restricted to those parts of the channel close to bridge supports and other man-made structures. Reach 5 had the most consistent depth with an average depth of 1.8m ranging from 1.1m to 2.3m. Low water depth was increased in reaches 4 and 5 because of water held back by "The Bar" (the shallowest part of the low water channel in the middle and inner estuary, upstream distance 32.5km). In general, reaches 2 and 3 were predominantly shallow, reaches 4 and 5 were more riverine in nature possessing a deeper and more consistent low water channel, see Table 2.

5.4.5 Differences in Water Quality between Reaches.

Water quality data from the estuary revealed much similarity between the two monitoring sites in each year despite the distance between them. Variation in the observed values of temperature at Summer's Jetty were closely correlated with Curzon Park, $r = 0.74$, ($r^2 = 0.54$) this association was significant, $p < 0.05$. In contrast it was also apparent that median dissolved oxygen concentration at Curzon Park was consistently greater than Summer's Jetty, and this difference was statistically significant, "t" =-49.19 n=9277, $p < 0.001$. This was further emphasised by between site correlation of dissolved oxygen values (paired analysis) which revealed an extremely low correlation coefficient, $r=0.036$ $r^2=0.0013$, N.S, which contrasted with the above findings for water temperature. These differences were principally the result of the greater amplitude of variation in both dissolved oxygen and temperature values at Summer's Jetty in the lower middle estuary when compared with Curzon Park in the inner estuary.

In order to examine the differences, changes in the two main parameters were considered during two specimen tides, one neap and one spring tide. Differences between middle and inner estuaries were most apparent during the neap tide, when dissolved oxygen levels at Curzon Park remained between 8.5 mg/l and 9.5 mg/l which contrasted with a range of 7.1 mg/l at the middle estuary site, see Figure 17a). Similarly, temperature had a range of 1.49 Deg C at Summer's Jetty compared with 0.55 Deg C at Curzon Park during the neap tide, see Figure 17b). Differences during the studied spring tide were also noted; once again greater variation in both dissolved oxygen and temperature values at Summer's Jetty, see Figure 18. These differences reflected the greater tidal exchange in the lower middle estuary and the essentially riverine nature of the upper half of the inner estuary.

A third temperature logging station was employed during the summer of 1993 (GR SJ328683) close to the downstream extremity of the canalised section. Comparison of the temperatures at this location with both other sites revealed that the closer association was with Summer's Jetty with 41% of the variance in the temperature logger data explained by the variation in Summer's Jetty values, correlation coefficient = 0.63, $r^2 = 0.41$, $p < 0.05$. This compared with only 33% of variance explained by temperature values from Curzon Park ($r = 0.57$, $r^2 = 0.33$, $p < 0.05$). In both cases the derived associations were significant.

5.5. Behaviour in the Middle and Inner Estuaries.

5.5.1. Upstream Movements.

Entry times at each reach for individual salmon were related to prevailing estuarine conditions to establish factors governing upstream passage by tagged salmon.

5.5.1.1. Water Quality.

Upstream migration was recorded over a wide range of dissolved oxygen levels (2.71 mg/l to 14.41 mg/l) and occurred across much of the range of recorded temperatures (6.98 Deg C to 20.12 Deg C), see Table 8. Moreover, no trends in environmental quality requirements were revealed in different estuarine reaches. The "noisy" distributions were difficult to interpret and it appeared that they merely reflected available conditions, see Figures 19,20. For example, upstream migration was achieved in all studied reaches of the estuary at temperatures in excess of 20 Deg C, see Table 8, illustrating the lack of a barrier to successful migration posed by the estuary during the study period.

5.5.1.2. Residual Freshwater Flow.

The modal flow class for upstream movements was 4-5 cumecs, with the minimum flow at which successful upstream passage was recorded= 4.22 cumecs, see Table 8. Under conditions of normal regulation, freshwater discharge to the estuary was maintained at 4.2 cumecs. These results suggested that during periods of base flows on Dee, upstream estuarine passage was achievable and the estuary presented no barrier to salmon migration and the distribution of flow conditions during upstream migration merely reflected the underlying availability, see Figure 21. However, there was a tendency for salmon to arrive at Chester Weir at times when freshwater flows were elevated above those flows occurring during estuarine residence. Although median flow at arrival 10.21 cumecs was greater than median available flow during estuarine passage, 6.98 cumecs, the difference was not statistically significant, "t"= 1.45, p= 0.08, N.S.

5.5.1.3. Day of Week.

Tagging day was found to be important in determining the success of estuarine passage. This was attributed to netting activity particularly in the inner estuary (allowed between Midnight on Sunday and Midnight on Thursday during the period 1st March to 31st August) removing salmon from the estuary. Amongst salmon tagged during the net season the daily distribution reflected this with more than 50% of successful arrivals at the Weir doing so during either Friday or Saturday when nets were absent. In contrast, salmon released outside the netting season arrived at the Weir in a more consistent fashion during the week (modal class, Thursday 38%), see Figure 22. Further evidence of the importance of netting was illustrated by the fact that freshwater entry success rates increased significantly for days towards the end of the week, peaking on Thursdays (62%) and contrasted with Monday and Tuesday (25% and 26% respectively), see Figure 23. This relationship was not noted amongst Curzon Park tagged salmon where arrivals were determined by day of tagging because this site was less than 0.8 km from Chester Weir.

5.5.1.4. Time of Day.

Reach entry amongst Quay-tagged salmon was found to be random for all reaches in the middle and inner estuary except for arrival at Reach 6 (Dside ALS), where although fish arrivals were not prohibited at any time of day, most activity occurred during the hours of darkness, mean time 02:30h, "r"= 0.189, $p<0.05$, see Figure 24.

5.5.1.5. State of Tide.

Unlike the lack of behavioural responses recorded in response to time of day, upstream entry to middle and inner estuarine reaches were found to be related to particular states of tide. Entry to reach 3, less than 1 km above the point of release was closely related to release time tending to occur during the late ebb/ early flood period, peak time 09:26h after HW, "r" =0.330, $p<0.01$. Inner estuary entry (reach 4) was also significantly associated with particular states of tide, peak time for entry 01:13h after HW, "r"= 0.471, $p<0.01$, see Figure 25. Continued upstream migration against tidal flow within the inner estuary was suggested by the distribution of reach 5 entry times which were also significantly correlated ("r"= 0.351, $p<0.01$) with the first two hours of the ebb tide, and with the peak time, 01:50h after HW, succeeding reach 4 entry by 37 minutes.

Salmon arrived close at the downstream extent of Chester Weir (ALS Dside) throughout the whole tidal cycle but peak movement was found to occur during the middle ebb, 03:16h after HW at Summer's Jetty, this relationship was significant, "r"= 0.321, $p<0.01$. Peak movements into the Weir reach were later on the tide than reach 5 entry by some 1.5 hours this supports earlier results which indicated generally continued migration through this part of the estuary albeit at a reduced net rate. Level data from the Weir was used to obtain information about the exact state of tide at Weir arrival. As expected a similar pattern was revealed but showed that because of the time lag, peak arrival occurred earlier on the ebb-tide, peak time 02:44h after HW, "r" = 0.327, $p < 0.01$ and at times when, for all but the smallest neap tides, water levels at the Weir were still elevated by tide, see Figure 26.

5.5.1.6. Passage Upstream of Chester STW.

The distribution of environmental conditions (measured at Curzon Park site) prevailing during successful upstream passage above the Chester STW effluent was compared with the distribution of conditions prevailing during residence downstream of the outfall for each fish for temperature, dissolved oxygen and freshwater flow.

a) Temperature.

Upstream movements past the outfall occurred at most of the recorded temperatures and followed closely the distribution of available temperatures. However, amongst the tagged sample median passage temperature (15.06 Deg C) was significantly lower than median available temperature during residence below the discharge (17.57 Deg C), "t" = 8.335, $p < 0.05$.

b) Dissolved oxygen.

Conditions during passage above the outfall reflected the underlying distribution of available oxygen concentrations over the study period with upstream passage achieved across the full range. Moreover, mean dissolved oxygen concentration at upstream passage (8.58 mg/l) was not found to be significantly greater than median available oxygen level (8.42 mg/l), $t = 1.90$, N.S.

c) Freshwater Flow.

Similar results were obtained for freshwater flow with conditions during fish passage upstream of the sewage outfall reflecting the underlying distribution. There was a slight departure from expected frequencies towards the top of the flow range and mean passage flow (14.1 cumecs) was found to be significantly greater than mean available flow during downstream residence (8.4 cumecs), $t = 5.30$, $P < 0.05$. It was not possible to directly attribute these observed responses to freshwater flow to the presence of the effluent discharge because the results may have merely reflected a generally increased reliance on elevated flows for upstream migration within this zone.

5.5.2. Reach Residence Time, (T_r).

Entry data for all reaches were available for 71 salmon. For each fish the time spent in each reach was calculated as a percentage of total estuarine residence time, see Table 9. Although a great deal of variation was recorded in each reach, on average more than 60% of total estuarine residence time was spent in the inner estuary and at Chester Weir which together comprise less than 32% of the total length of estuary studied. The difference between mean residence time in the two sections was not statistically significant however, "t" = 1.22, p = 0.887, N.S.

A small proportion of tagged salmon (< 5%) remained in the inner estuary (principally the deep reach immediately above the entry to reach 5) for substantial periods of time. For example, fish number 25JE6 was resident in the inner estuary for 63 days before ascending into freshwater. Some fish adopted this behaviour during July and August but all were recaptured by seine nets within 10 days. It is likely that inner estuary residence times were underestimated because of the removal of fish by netting which were not then included in the analysis.

5.5.3. Net Reach Velocity, (V_r).

Derivation of net ground speeds (V_r) enabled comparison of migration rate between reaches. In general, rate of migration increased from reach 2 into reach 3 where it was at a maximum and decreased during passage through the inner estuary where ground speeds were some of the lowest recorded. Inner estuary ground speeds were most variable, particularly in the very short reach, reach 4, see Figure 27.

Migration rate increased significantly as fish moved from reach 2 (median V_r = 0.41 km/h) into reach 3 (median V_r = 1.64 km/h), "t" = 7.245, p<0.001. It was not possible to determine whether such a finding indicated actual differences in the behaviour between these reaches or merely reflected time taken for tagging recovery in reach 2. Salmon migration tended to slow following entry to the inner estuary. Median ground speed during passage through reach 3 (1.64 km/h) was significantly larger than median inner estuary ground speed for reaches 4 and 5 combined (V_r = 1.11 km/h), "t" = 2.25, p< 0.05. This reduced progress was primarily attributable to behaviour in the upper half of the inner estuary (reach 5) where comparison of net ground speeds revealed that median ground speed in reach 4 (1.48 km/h) was significantly greater than median ground speed in reach 5 (0.92 km/h), "t" = 3.22, p< 0.001, reflecting the increased frequency of holding behaviour in this section. Similarities in behaviour between the middle estuary and the lower half of the inner estuary were suggested by the finding that there was no significant difference between median ground speeds in reaches 3 and 4, "t" = 0.57, p= 0.57, N.S. Although ground speeds in reach 4 displayed a certain amount of bimodality and some fish held-up for lengthy periods in this section in contrast to the virtual absence of this behaviour in the middle estuary.

5.5.3.1 The Impact of Reach Depth.

Data from fish continuously active-tracked through the middle and inner estuaries revealed that periods of reduced net upstream progress usually occurred in deeper turbulent areas close to bridge pilings and alongside wharves. Often fish encountering such areas would make repeated small-scale oscillatory movements, interpreted as searching behaviour, in the vicinity of the obstructions, for example see Figure 28. In this particular case the subsequent behaviour of fish number 2C2G108, involving emigration from the middle estuary, suggested that this fish may not have been of Dee origin and had strayed into the "wrong" estuary consequently this behaviour may not be typical of salmon migrating through their home estuary and may explain the contrast with the typical holding behaviour recorded in deeper runs, where fish remained stationary, for example fish number C2G913 at the downstream extent of reach 5, see Figure 29.

5.5.3.2 The Impact of Tidal Regime.

a) Tide Height.

Results clearly demonstrated the importance of tidal currents in determining passage time through the estuary with the most rapid progress and the widest variation in ground speeds associated with the largest tides. In reach 3, ground speeds were found to be more variable during tides in excess of the mean recorded tide height (8.6 m, from local tide tables) with a median value of 2.04 km/h, see Figure 30. In contrast, during tides smaller than the mean tide height ground speeds had a reduced range with maximum ground speed typically not exceeding 2.8 km/h. In addition they were generally lower (median 1.3 km/h) although this difference was not statistically significant.

In the inner estuary, a similar pattern of greater variability in ground speeds recorded during spring tides was observed. However, in contrast to the middle estuary, the difference between ground speeds during tides in excess of 8.6 m (median V_r = 1.41 km/h) and during tides smaller than 8.6 m (median V_r = 0.38 km/h) was highly significant, "t" = 4.87, p< 0.001.

b) State of Tide.

Typically salmon made upstream progress at all states of tide in the lower middle estuary although at low water and during the ebb-tide these movements were often vacillatory in nature and/ or included periods of holding, see Figure 31. Fish number C2F316 demonstrated a substantial increase in net ground speed with the advent of the flood tide and this was a typical response amongst salmon active tracked through the middle estuary. Moreover, salmon movements tended to be the same speed as tidal currents (and not noticeably faster) during flood tide assisted migration because salmon were often detected moving upstream at the same rate as the drifting boat being used to track them. Fish number C2F517, for example, was tracked for 3 km during the flood phase of an 8.3m tide, over this distance the fish was travelling at a net speed of 3.8 km/h which active tracking notes confirmed to be the same as the drifting boat.

Speed of migration within the canalised reach (reach 3) was closely related to the state of tide at entry to reach 3. Net ground speeds were greater amongst those salmon entering the reach during the flood tide, typically migration speed was 1.6 times faster for those fish arriving during the early flood phase and illustrated the importance of tidally assisted migration in determining upstream passage through the middle estuary, see Figure 32.

5.5.3.3. The Impact of Changes in Water Quality and Flow.

Migration rate (V_r) was examined using multiple linear regression with the factors dissolved oxygen, temperature and flow being treated as co-related variables. The analysis was conducted by looking at the middle and inner estuaries as both a series of reaches and as one single section. The linear model produced for the latter attributed small but statistically significant contributions from minimum dissolved oxygen and maximum temperature (see Table 10a). Minimum residual flow was not found to be significant in determining V_r at the $p=0.05$ level. Removal of residual flow from the model showed that for all reaches only 5.2% of the variance within calculated V_r could be explained by the recorded minimum dissolved oxygen and maximum temperature. This result was significant at the $p=0.01$ level, $n=421$.

Product moment correlations of estuary environmental parameters demonstrated an association between minimum flow and maximum temperature (-0.49, $p<0.01$) and between maximum temperature and minimum dissolved oxygen (-0.278, $p<0.01$). Correlation of individual environmental parameters against V_r were all significant at the $p=0.01$ level although the magnitude of this relationship was minor and in all cases was found to be less than that observed between environmental parameters, see Table 10b).

The same linear model was used with the environmental and V_r data divided on a reach basis to investigate more closely the potential affects of each parameter over smaller areas within the middle and inner estuary. All three parameters were held within the model for comparsison purposes and the proportion of explained variance in ground speed (V_r) improved over the entire estuary model. Within reaches 2,3 and 4 calculated R^2 values revealed that the three parameters were likely to contribute 18% - 22% of the variation in calculated V_r at $p<0.01$. The closeness of fit was less in reach 5 with R^2 values indicating 7% overall contribution to the variation, $p<0.01$. The relative contribution of each factor in determining V_r per reach indicated that minimum dissolved oxygen had the greatest influence and that residual flow appeared to be a poor predictor of ground speed, see Table 11.

In general, it was evident that variation within V_r could not be strongly associated with variation in the measured environmental parameters (dissolved oxygen, temperature and freshwater flow) and their use in predicting estuarine ground speeds amongst salmon tagged during this study was poor. It was clear that the relationship was either non-linear, that other factors such as state and height of tide were important in determining ground speed in the estuary or that migration rate was independent of any of these factors.

5.5.4. Downstream Displacement.

The probability of displacement was calculated for each reach. Fish confirmed as having been displaced were required to be detected within the immediate downstream reach. Downstream movements of sufficient magnitude to be detected by the passive tracking system were confined to 57 occasions indicating that such behaviour was uncommon.

5.5.4.1. Estuarine Reach.

Displacement was most commonly recorded from the inner estuary and was virtually absent from the middle estuary. This was probably the result of both the nature and position of the reach and the impact of Chester Weir. Certainly, a significant proportion of those salmon displaced from reach 5 into reach 4 were deflected from Chester Weir (48%).

5.5.4.2. Time of Year.

Downstream movements appeared to be more widespread amongst early (April) and late (September) estuarine entrants with summer salmon and grilse less likely to exhibit this behaviour. This was probably because of the increased chance of recapture by draft nets in the latter category which would limit the extent of any displacements and prevent detection by the tracking array.

5.5.4.3. State of Tide.

The limited incidence of displacement prevented analysis of the behaviour except for reach 5 where movements were compared with tidal state at Curzon Park. Results showed that displacement was most frequent during the early ebb-tide, peak movement 02:07h after HW, "r"= 0.539, $p < 0.01$, see Figure 33.

5.5.4.4. Time of Day.

Downstream movements from reach 5 were random with respect to time of day, "r"=0.125, N.S. There were insufficient observations to allow worthwhile examination of displacements in relation to time of day for any other reach.

5.5.4.5. Water Quality and Flow.

Conditions prevailing during each displacement were examined and compared with available temperature, dissolved oxygen and freshwater flow during reach residence prior to displacement. None of the reaches showed any significant difference between the two samples. This reinforced the previous finding that little evidence was available to suggest that the estuarine reaches represented a significant barrier to salmon migration, see Table 12.

5.5.5. Probability of Passage through the Middle Estuary.

The probability of successful migration through the middle estuary in 24, 48 and 96 hours was examined in relation to contemporaneous environmental data. Salmon were placed into one of two mutually exclusive migration categories depending on whether or not the fish migrated into the inner estuary within that time period. For each fish the minimum available flow, maximum temperature and minimum dissolved oxygen conditions prevailing during each time period were calculated and distributions made. Probabilities of migration within each environmental variable class and for each time period were derived and examined by relating probability to the mid-point of each variable class.

5.5.5.1. Temperature.

Probability of successful migration through the middle estuary appeared to decrease with increasing temperature although there was great variation between the probability values, see Figure 34. At temperatures of 22 Deg C the probability of successful migration over all three time periods had fallen to zero which reflected the available temperature conditions in the estuary, maximum recorded temperature, 22.1 Deg C.

Attempts to model behaviour were first made using linear regression on a reduced number of temperature categories (n=8) of both maximum and median temperature with the probability of not migrating (1- P) for each of the three time periods and in each case produced a negative relationship. Furthermore it suggested that maximum temperature provided a weaker correlation with migration than median available temperature. Over the shortest time period (24 hours) both were significantly correlated with migration probability but 83% ($r^2 = 0.833$, $p<0.01$) of the variance was explained by variation in median available temperature of the tagged population whilst the equivalent contribution of maximum temperature was only 19% ($R^2 = 0.192$, $p<0.05$), see Table 13. The model was not important in explaining the variation in probability of not migrating and temperature for either 48 or 96 hour time periods.

The reduction to 8 intervals from 16 decreased the "noise" within the relationship, and increased the numbers within each class and therefore the precision of the probability calculations and enabled further modelling of the response to increasing water temperature. When the probability of not migrating (1- P) within 24 hours was plotted against median temperature a close fit was obtained using a quadratic function. When extrapolated the relation provided an estimate of 22.4 Deg C as the temperature at which all migration through the middle estuary within 24 hours would cease, see Figure 35. There are problems with the application of this particular expression because probability could never exceed 1 nor be less than 0. It is probably reasonable to expect that a logistic relationship would be of greater use in predicting salmon response to temperature on the Dee. The slowing down of the rate of change of probability (plateau) at the higher temperatures inherent in the logistic model would suggest that the quadratic expression proposed here, despite the high regression coefficients derived, may have produced a lower value for temperature likely to produce zero migration in less than 24 hours. Unfortunately, two cool summers when temperatures never exceeded 20.2 Deg C prevented empirical testing of the model.

Considering only those salmon which migrated successfully upstream, the cumulative distribution of temperature over each time period was calculated, see Figure 36. Results suggested that maximum available temperatures were lower for those fish migrating more quickly through the middle estuary, 50%ile (24 hour)= 16 Deg C, 50%ile (48 hour)= 16.6 Deg C, 50%ile (96 hour)= 16.8 Deg C. This may have also merely reflected the increased likelihood of high temperatures during the longer time periods.

5.5.5.2. Dissolved oxygen.

The probability of successful migration through the middle estuary was consistent across the range of dissolved oxygen concentrations, even at minimum dissolved oxygen levels of <2 mg/l probability of migration was high, >0.5. However, trends in the data were hard to ascertain because of the "noise" in the relationship, see Figure 37.

Linear regression of the probability of migration and minimum dissolved oxygen produced non-significant positive correlations over all three time periods. This contrasted with the significant negative correlation between median dissolved oxygen concentration and probability of upstream migration. Results indicated that variance in median available dissolved oxygen accounted for about 80% of the observed variation in migration probability over 24, 48 and 96 hours, with the closect relationship occurring over the shortest period, see Table 13. The presence of significant negative correlation between migration success and median dissolved oxygen is difficult to explain. It may illustrate either the important contribution of oscillations in dissolved oxygen concentration in determining estuarine passage success of salmonids or the lack of a causal relationship between these variables on the Dee estuary.

The cumulative distribution of minimum available dissolved oxygen over each time period was calculated for those salmon successfully migrating upstream, see Figure 38. Results suggested that salmon migrating more slowly were exposed to lower oxygen concentrations, 24 hour 50%ile= 5.1 mg/l, 48 hour 50%ile= 4.8 mg/l and 96 hour 50%ile= 4.3 mg/l. However, the observed results could also merely reflect the greater chance of low dissolved oxygen conditions being encountered by salmon migrating during the longer time periods.

5.5.5.3. Residual flow.

Examination was restricted to the flow range 4 to 30 cumecs, where numbers of observations were sufficient to avoid wide variation in derived probability values. Upstream passage occurred at all flows encountered during the study but there was a close relationship between increasing probability of successful migration and increasing flow except at the lower end of the flow range, see Figure 39. The probability of migration approached "1" for all three time periods at flows of the order of 13-15 cumecs (46-50% ADF) and in general the most rapid transit (24 hours) appeared to be recorded at slightly higher flows than for the two longer periods. Moreover, the cumulative distributions for those salmon successfully migrating upstream suggested that salmon migrating within 24 hours did so during periods when minimum available flows were greater than those flows during the two longer time periods, 24 hour 50%ile= 8.2 cumecs, 48 hour 50%ile= 7.5 cumecs, 96 hour 50%ile= 6.1 cumecs, see Figure 40.

Linear regression of migration probability over 24,48 and 96 hours with minimum available flow yielded no significant correlations. This contrasted with the relationship between migration probability and median available flow for the tagged population where significant positive correlations were obtained, see Table 13. The linear model was most valid for the

24 and 48 hour periods with variance in median available flow accounting for about 50% of the observed variance in the probability of migration. For the longer time period (96 hours) the model explained less (c. 28%) of the observed variation, however it was nevertheless significant, ($R^2 = 0.281$, $p<0.01$).

5.5.6. Kelt Emigration Behaviour.

Data were available for 26 kelts which emigrated from freshwater reaches of the Dee in early 1992 and 1993. Data were limited because of progressive tag battery failure, the lack of tracking data from 1993 tagged fish and the lack of water quality monitoring data over the kelt migration period. Emigration through the inner estuary was rapid following passage across Chester Weir, median residence time 5:27h ranging from 1:15h to 43:06h. Timing of passage out of the inner estuary was random with respect to state of tide, "r"= 0.198, N.S. In contrast, emigration appeared to be closely associated with elevated flows with a median flow at exit from inner estuary of 26.46 cumecs (86.58% ADF).

5.6. Behaviour at Chester Weir.

Results from 156 fish tracks have been used in examine salmon behaviour at the partial tidal barrier of Chester Weir. To facilitate analysis, the area around Chester Weir was divided into a number of sections;

i) arrival in the vicinity of the Weir, defined as detection by ALS Dside, considered earlier as entry to reach 6,

ii) arrival in the fish ladder, defined as detection by ALS Weir,

iii) entry to the fish trap, defined as detection by ALS Trap,

iv) entry to freshwater, defined by Weir crossing time as either last detection at ALS Weir, trap entry time or detection at ALS Queens (500m upstream of the Weir crest).

5.6.1. Fates of Tagged Sample.

Each tagged fish was ascribed to one of four mutually exclusive categories depending upon tracking results. Fish were classified as;

i) "NX"; fish which did not achieve successful passage upstream of Chester Weir after having been detected at or upstream of ALS Dside.

ii) "TC"; fish interpreted as having crossed the Weir via the trap channel during periods when the trap was not fishing.

iii) "TR"; fish caught in the upstream trap at Chester Weir.

iv) "WC"; fish interpreted as having crossed via the Weir crest.

5.6.1.1. Differences Between Years.

Results combined over three years showed that 34% of tagged salmon crossed via the trap channel outside of trap fishing times (TC). Results were consistent between years; 33% in 1991 and 1993, 35% in 1992, see Table 14. Similarly the proportion of salmon crossing via the Weir crest (WC) was 34.6% when data were combined with only small differences between years; 38% in 1991, 35% in 1992 and 33% in 1993. These results were in contrast with the proportion of fish arriving at Chester Weir but which failed to cross (NX), 3 year average 10.9%. Large differences were noted between years with a reduction in incidence of this behaviour over the three years, 1991 19%, 1992 12% and 1993 8%. Over the same period the proportion of trap recaptures (TR) increased from 10% in 1991 through 18% in 1992 to 26% in 1993, see Table 14.

5.6.1.2. Differences Between Months.

Failure to cross Chester Weir was recorded in 34% of July arrivals whilst early and late season fish were much less likely to exhibit this response (April to June and October to November NX= 0%), August arrivals failed to cross in 8% of cases, see Table 15. The high figures in July probably indicate the impact of net recapture rates on displaced fish.

The proportion crossing via the Weir crest was lowest during July (13%) but was consistently in excess of 25% in all other months and this passage behaviour was adopted by the majority of salmon during early (59%, April to June) and late (57% October and November) periods. This produced correspondingly low values for use of the trap channel by early and late running salmon (April to June 41%, October to November 43%). Trap channel use peaked during September 71% but this route was also heavily utilised by July (53%) and August (51%) salmon.

5.6.2. Weir Pool Arrival.

Weir pool arrival (= fish ladder entry time) was defined as first detection at ALS Weir. A number of factors were found to influence behaviour in this section.

5.6.2.1. Time of day.

Whilst entry to the fish ladder occurred throughout the 24 hour period salmon showed a tendency for arrival during the hours of darkness, peak arrival time 01:52h, "r"= 0.267, $p < 0.01$, see Figure 41.

5.6.2.2. State of Tide.

Salmon appeared able to enter the fish ladder at all states of tide but arrival was most frequently recorded during the early half of the ebb tide, weighted mean time, 02:08h after HW, "r"=0.211, $p<0.05$.

5.6.2.3. Height of Tide.

Mean tide height (predicted) at Weir pool arrival (8.02m) was not significantly greater, ($p=0.063$) than mean tide height at arrival in the vicinity of the Weir (7.75m) indicating that upstream movements into the fish ladder were not restricted by the size of tide. Weir pool entry was recorded at tide heights ranging from 7.25m to 10.05m.

5.6.2.4. Residual Flow.

Fish entry to the fish ladder appeared to occur across the full range of flows encountered (range 4.14 to 91.68 cumecs). Paired analysis of medians revealed that there was no significant statistical difference between median entry flow (12.00 cumecs) and median available flow (10.94 cumecs) during residence in the downstream vicinity of Chester Weir, $p= 0.565$, N.S.

5.6.2.5. Trap Status.

Chester Trap was fished for 57.4% of the study period (ranging from 47.9% in 1991 to 63.3% in 1992) during which time only 40% of tagged salmon were recorded arriving in the Weir pools. Examination of whether this was consistent with the trap acting as a deterrent was attempted using Chi-Square; pooling data for all three years these differences were found to be 's significant, Chi-Sq= 13.23, n=135, $p<0.05$, df=1. Although when the each year's data was examined individually only 1993 results were significantly different from expected frequencies and this highly significant deviation from expected may have been responsible for the overall result, see Table 16.

5.6.3. Trap Channel Arrival.

Precise times of entry to the vicinity of the trap were available for 33 tagged salmon.

5.6.3.1. Time of Day.

Trap channel arrival reflected the distribution of arrivals in the weir pools with peak activity recorded during the hours of darkness (57.6% of trap first detections were recorded between 20:00 and 04:00). Peak time for movements into the trap entrance was 02:04h, "r" = 0.385, $p < 0.05$, $n = 33$, see Figure 42.

5.6.3.2. State of Tide.

Tagged salmon were recorded at the trap entrance at all states of tide, "r" = 0.0996, $p = 0.744$, $n = 33$, N.S, see Figure 43. This possibly indicated the overriding importance of light intensity (=time of day) in determining entry to the fish trap.

5.6.3.3. Trap Status.

Salmon did not appear to be deterred from approaching the trap during periods when it was fishing. The proportion of salmon first detected at the entrance to the trap (15 out of 33, 46%) was not significantly different from the proportion which arrived in the fish ladder during trap fishing (17 out of 33, 51.5%), Chi Square = 0.49, $n = 33$, $df = 1$, N.S.

5.6.4. Weir Crossing Behaviour.

Data from the passive tracking scanner array were used to decide whether individual salmon had crossed via the Trap channel or the Weir Crest. Two "notches" were present in the Weir crest which at times allowed easier access to freshwater reaches. When the wooden oversails preventing passage via the "v" notch fish pass in the Weir close to the trap house were removed for a period in 1991 3 salmon used this route to cross the Weir. No tagged salmon were interpreted as having used the fish pass during such open periods in either of the subsequent two years. Similarly, when the hinged metal plate preventing Weir crest passage via the "boat pass" was damaged during high river flows in August 1992 at least 2 tagged salmon were believed to have used this route to cross the Weir.

5.6.4.1. Time of day.

Tagged salmon achieved Weir crest passage throughout the 24 hour period but most movements were recorded during the period around midnight with a smaller peak in the distribution towards midday, see Figure 44. This showed the importance of spring tides where high water times occurred close to midday and midnight. Although many fish crossed the Weir crest at night the clustering of crossing times close to midday produced a random distribution with respect to time of day, "r" = 0.210, $n = 54$, N.S.

Trap channel activity was greatest during darkness and peaked around midnight (23:43h) when high tide (springs) and darkness coincided, see Figure 44. Unlike Weir crest crossing, tagged salmon passage via the trap channel was not random, peak time 23:43h, "r" = 0.307, $n = 85$, $p < 0.01$ and this indicated the greater influence of light intensity in determining trap channel passage.

5.6.4.2. State of Tide.

Examination of data from all tagged salmon interpreted as crossing Chester Weir via the Weir crest indicated that passage was restricted to periods close to high water, peak crossing time 11:28h after H.W, "r" = 0.413, $p < 0.001$, $n = 53$. This relationship was not recorded for those fish crossing the Weir via the trap channel, where movements were random with respect to state of tide, "r" = 0.029, $p > 0.9$, $n = 85$, N.S, see Figure 45.

5.6.4.3. Size of Tide.

The distribution of downstream water levels at the time of Weir passage for both Weir crest and trap channel routes were calculated and compared with the distribution of all levels occurring during the study period. For each level category the number of Weir crest or trap channel crossings was divided by the number of times these levels occurred within each category and the probability of passage per unit level plotted against each level interval, see Figure 46. The relationship indicated that the probability of Weir crest passage increased substantially at water levels in excess of 4.5m AOD (equivalent predicted tide height= 9.4m) when the Weir was overtopped to a depth of about 0.2m. In contrast, trap channel passage was most likely at levels of 3.6m (predicted tide height= 8.5m) and moreover, the probability of trap channel passage was zero at levels in excess of 5.1m (predicted tide height= 10.0m). Furthermore, comparison of the water level at Weir crossing revealed that median level at Weir crest passage (3.0m) was significantly greater than the median level during trap channel passage (2.67m), "t"= 1.91, $p < 0.05$.

5.6.4.4. Residual Flow.

Route of passage was more closely controlled by residual freshwater flow than any other single factor. Residual discharge across Chester Weir when salmon arrived in the downstream vicinity was shown to affect the proportion of salmon passing through the trap channel. As freshwater flow increased the proportion of migrants using the trap channel reduced and there was a corresponding increase in the proportion using the Weir crest, see Figure 47. Rank correlation of the percentage "preference" indicated a strong negative correlation between the two routes with increasing flow, Spearman's Rho= -0.9, further emphasising the relationship. It was also interesting that fish to which the Weir was a total barrier arrived at the lower end of the flow range. However, because the Weir was only a total barrier when fish were recaptured by inner estuary nets, fish in this category exclusively arrived during the net season, mostly in July and August, when flows tended to be low. Indeed, the fact that displacement from the Weir was no more likely under low flows supports the idea that low flows in themselves were not responsible for contributing to reduced numbers of salmon which reached the Weir entering freshwater reaches of the Dee.

The importance of freshwater discharge across Chester Weir in determining passage behaviour was further demonstrated by the different distributions of passage flows amongst those salmon using the Weir crest and those crossing the Weir via the trap channel. Weir crest passage typically occurred at higher flows (mean flow at crossing, 31.58 cumecs) and this value was significantly larger than the mean flow during trap channel Weir passage (17.01 cumecs), "t"= 3.6, $p < 0.001$.

In contrast, considering only those fish using the trap channel; flows at trap recapture (mean= 15.34 cumecs) were not significantly different from flows prevailing during upstream movements through the open trap channel (mean= 18.02 cumecs), "t"= 0.876, $p = 0.384$, N.S.

Closer examination of the role of residual flow in stimulating Weir crest passage was attempted by comparing, for each fish which crossed via the Weir crest, median (available) flow in the period Weir arrival to Weir crest passage with Weir crest passage flow. This revealed that available flows were lower (median= 16.7 cumecs) than crossing flow (median= 21.4 cumecs) but the difference was not statistically significant, "t"= -0.876, N.S.

For each of a series of flow categories the number of crossing flows was divided by the number of flows occurring within the category. This was done for both Weir crest and trap channel passage and the derived "probability" of upstream passage by route per flow category was plotted against flow, see Figure 48. Peak probability of trap channel passage occurred at about 33 cumecs (108% ADF) and decreased with increasing flow with no movements via this route recorded at flows of the order of 75 cumecs (250% ADF). In contrast, the probability of Weir crest passage was lowest at flows of less than 20 cumecs (67% ADF) and increased with increasing flow reaching a maximum at flows of 60 to 65 cumecs (200% ADF).

5.6.4.5. The Combination of Tidal State and Freshwater Flow.

Salmon passage across the Weir crest was dictated by a combination of freshwater flow, state of tide and light intensity. Tide state and river flow at Weir crest passage were derived for each fish which was then placed in the appropriate flow/ tide category, see Table 17. About 89% of Weir crest movements during flows of less than 8 cumecs (23% ADF) were undertaken within 2 hours of high water and none were recorded at low water under these flows, see Figure 49. These values were significantly different from expected frequencies, Chi Sq= 12.72, df=1, n=9, $p<0.05$. In contrast, at flows in excess of 36 cumecs (112% ADF) only 42% of recorded Weir crest movements occurred within 2 hours of high water, in this case there was no significant difference from expected frequencies Chi Sq= 1.63, n= 19, df= 1, N.S., inferring random movements with respect to state of tide during high flows. Low water Weir crest passage was not recorded at regulation flows and was only a significant component of Weir crest passage behaviour at flows in excess of 20 cumecs (67% ADF).

In contrast, salmon passage via the trap channel was quite consistent throughout the flow range studied, see Figure 50. Although there was limited evidence that passage close to high tide was most likely amongst trap channel entrants (45.8%) when freshwater flows approached the regulation value and that this reliance on tidal inundation of the fish ladder was reduced by the time flows reached 20 cumecs, with only 29.6% of migrants passing at these flows did so around the time of high water, see Table 18.

Considering behaviour at flows towards the lower end of the range (< 22 cumecs, 75% ADF) these observed differences in behaviour between Weir crest entrants and those using the trap channel were tested. Chi-square analysis revealed that tidal state preferences amongst the two samples were significantly different from expected frequencies, Chi square= 7.14, df= 2, n= 85, $p< 0.05$, see Table 19.

5.6.5. Post Crossing Behaviour.

Once across the Weir salmon typically made rapid upstream movements over significant distances through the "impounded reach". Mean time of travel between Weir crossing and the upstream extent of the impounded reach (as defined by ALS, D2) was 04:48h and ranged between 02:34h and 77:30h, equating to maximum net ground speed of 3.63km/h with mean speed of 1.94km/h. The only departure from this behaviour was recorded in the case of 10 salmon discussed in Section 5.6.9.1.

5.6.6. Weir Residence Time, (T_w).

The impact of Chester Weir as a temporary barrier to migration was investigated by determining the delay to migration. Residence time in the downstream vicinity was defined as the total time spent at ALS Dside or upstream of ALS Dside prior to Weir crossing.

Precise Weir delay values were known for 154 radio-tagged salmon and delays ranged from 00:05h (fish number 23KG3) to 369:39h (fish number C2E012). Closer examination of the data revealed that delays were not significant for the majority of fish with 50% of tagged salmon remaining below the Weir for less than 12 hours (median 11:44h) and 95% of fish delayed for less than 1 week.

5.6.6.1. Residual Flow.

There was no clear relationship between median available flow during Weir residence and the length of the delay period, see Figure 51. Whilst numbers of recordings were more limited at higher flows it nevertheless appeared that at flows in excess of 20 cumecs residence times were shorter and less variable. This was reinforced by the finding that mean residence time at flows of less than 20 cumecs (19:32 hours) was significantly greater than mean residence time during periods when flows exceeded 20 cumecs (08:06 hours), "t"= 1.94, $p< 0.05$.

5.6.6.2. Temperature.

Weir passage by tagged salmon was recorded at daily average temperatures ranging from 6.49 Deg C to 20.09 Deg C. Unfortunately no data relating to the coldest water conditions (less than 5 Deg C) were collected and it was therefore not possible to examine behaviour at low temperatures. Weir passage was achieved by tagged salmon at temperatures approaching the maximum recorded (20 Deg C) and high water temperatures were not believed to have been important in determining residence times below the Weir.

5.6.6.3. Size and State of Tide.

Factors which varied over short time periods such as state of tide, were investigated by examining the behaviour of salmon delayed for less than 12:30 hours. When considering this sample it was not possible to demonstrate a clear relationship with state of tide at arrival at Dside, "r"= 0.140, p= >0.14, n=63, N.S, suggesting that whilst tidal affects were important they were not of principal importance in dictating residence time at Chester Weir. Moreover, examination of the sizes of tides encountered by fish delayed for periods of the order of two weeks provided no evidence that their increased delays were the result of arrival at the Weir during neap tides. Although numbers were restricted, 4 of 5 fish delayed for 2 weeks before crossing the Weir crossed during tides of the same magnitude (1) or smaller than (3) the size of tide at arrival.

5.6.6.4. Trap Status.

Accurate fish ladder residence times were available for 109 radio-tagged salmon. The impact of trap status on residence in the Weir pools was tested by comparing the residence times of those arriving during trap fishing (n=67) with those arriving outside of trap fishing times (n=42). Median Weir pool residence for the sample arriving during trap fishing (23:48h) was found to be significantly greater than the median residence time for salmon arriving during periods of non-fishing (7:35h), "t"= 2.19, p< 0.05.

5.6.7. Displacement from the Weir.

Displacement was defined as a detectable downstream movement from Dside ALS. Because a number of small-scale, unresolvable movements may have occurred the incidence of this behaviour may have been underestimated. However, the important downstream movements into the draft netting station, less than 1 km below the Weir were all of sufficient magnitude to be detected by the network of ALS's within the inner estuary. 49 tagged salmon were displaced on 93 occasions from the vicinity of the Weir during the study representing 31.4% of the total population (n=156) reaching Chester Weir.

5.6.7.1. Residual Freshwater Flow.

In July 1992, under the lowest flow conditions experienced in that season, three salmon tagged at Curzon Park were displaced following lengthy residence close to the Weir and the importance of flow was also suggested by results which indicated that the vast majority of displacements occurred at flows less than the ADF (96%ile displacement flow= 30 cumecs). However, considering displaced fish on an individual basis the movements did not appear to be associated with falling flows; mean displacement flow (13 cumecs) was not significantly lower than mean available flow during Weir residence (13.8 cumecs), p= 0.43, N.S. although this was possibly the result of the typically short periods of residence prior to displacement.

5.6.7.2. Time of Day.

There was no apparent relationship between displacement and hour of the day, movements were distributed randomly throughout the 24 hour period, "r"= 0.084, p= 0.528, N.S. The slight peak recorded at midday probably reflected the importance of high water during spring tides in determining displacement behaviour, see Section 5.6.7.4.

5.6.7.3. Trap Status.

It was not possible to demonstrate that trap status was important in determining displacements from the fish ladder. A total of 158 movements from Weir ALS to Dside ALS were recorded by 36 fish and trap status was noted at the beginning of each downstream movement. Of the 158 movements, 91 (57.6 %) occurred during trap fishing which was not substantially different from the proportion of time for which the trap was fishing, 64%.

Larger scale displacements below Dside were instigated from the entrance to the trap channel on only two occasions which lead to draft net recapture. Both displacements were undertaken during an extreme low flow period during July 1992 (see Section 5.6.7.1.) and cannot necessarily be attributed to trap avoidance.

5.6.7.4. State of Tide.

Displacements from ALS Dside were found to be significantly correlated with state of tide, movements were most frequent during the high water and early ebb-phases, and whilst the modal categories were late flood and high water slack periods the weighted peak time was 02:24h after HW at Chester Weir, "r" = 0.5, $p<0.01$, see Figure 52. The results suggested that some downstream movements from the vicinity of the Weir were made against the flood tide as well as at high water slack and ebb-tide periods reflecting the general increase in activity in the Weir reach which occurred when it was inundated by tide.

5.6.7.5. Time of Year.

Displacement appeared to be most common during April (57% of available fish) and in the Autumn (34% of available fish were displaced in September). In contrast, salmon arriving at the Weir in July and August were much less likely to become displaced, 16% and 13% of available fish respectively, see Table 20. Despite these behavioural differences, the impact of displacement was unrelated to the frequency of occurrence because of the role of netting. Hence, during the peak netting period (June to August) a high proportion of the small numbers of displaced fish were caught in the net fishery, resulting in lower success rates for freshwater entry amongst this component of the run.

5.6.8. The Weir as a Total Barrier.

Of 49 salmon displaced from the downstream extent of Chester Weir, 30 fish were displaced during the draft netting season (1st March to 31st August). 15 of the in-season drop-back sample were subsequently recaptured which represented an exploitation rate of 50% for this sample, the remaining 15 subsequently re-crossed the Weir. In contrast, the results from the 19 fish displaced outwith the netting season, recorded greatly increased freshwater entry success with 18 (94.7%) subsequently re-crossing the Weir (the remaining fish disappeared suspiciously from the inner estuary during September 1991 probably as a result of poaching activity). This illustrated that the Weir in itself did not present a total barrier to salmon and was only a total barrier to those fish displaced and subsequently recaptured in the inner estuary.

In overall terms 107 of 156 tagged salmon (68.6%) were indicated as having entered freshwater reaches without displacement from the Weir, a further 21.1% achieved successful entry following displacement behaviour and the remainder, 10.3%, failed to cross Chester Weir as a result of displacement-induced net exploitation by inner estuary nets (9.7% licensed, 0.6% illegal). Considering only salmon arriving at the Weir during the netting season results were very similar; of 94 arrivals 64 fish (68.8%) crossed into freshwater reaches directly, 15 fish (15.6%) entered freshwater after having exhibited displacement behaviour and 15 fish (15.6%) failed to enter freshwater because of displacement-induced net recapture in the inner estuary.

5.6.9. Vacillatory Behaviour.

Vacillation was defined as exploratory behaviour involving upstream and downstream movements between different areas within reach 6 and was categorised as either movements involving multiple passages across the Weir or oscillatory behaviour close to the trap entrance.

5.6.9.1. Multiple Weir Crossing.

This behaviour was limited to a few individuals with three distinct forms recognisable but only one category fell within the stated objectives of this study. It was typified by salmon which were displaced downstream across the Weir after a short period upstream of the Weir following trap release or displacement from the trap channel release pond when the trap was opened and allowed downstream access.

This behaviour was exhibited by 10 tagged salmon on 13 occasions during the study, all 10 fish subsequently re-crossed the Weir. Precise times of downstream passage were available on 10 occasions and rigorous analysis was therefore not possible, see Table 21. Downstream passage was recorded throughout much of the tidal cycle and at flows ranging from 5.49 cumecs to 35 cumecs. Results indicated that it often occurred when fish exited downstream out of the trap channel when the trap had been opened during non-fishing periods. At these times downstream access through the open trap channel was readily available. When the trap was fishing, downstream movements only occurred during the high water period, presumably because the Weir crest would serve as a barrier to displacement at other times. Four salmon were recorded behaving in this fashion and it appeared that they may have become disorientated by the depth of water and tidal currents prevailing during tidal inundation of the Weir when they left the Trap and were displaced across the Weir as a result. In 3 of the 4 cases the salmon re-crossed the Weir in less than 1 hour.

5.6.9.2. Trap Channel Oscillatory Behaviour.

These were small-scale movements typically restricted to the top Weir pool (defined as return movements between Weir ALS and Trap ALS) and were recorded amongst 29 tagged salmon which reached Weir ALS. A number of salmon exhibited multiple movements in this category and aggregate times for this behaviour by individual fish ranged from 3 minutes (1 movement) to 14:53h (37 movements) with a median time of 00:41h (11 movements), each individual movement was typically of a few minutes duration. Such vacillatory behaviour was interpreted as indicating searching behaviour and was used to provide an index of the extent of the barrier to successful migration through the trap channel.

a) Trap Status.

The increased incidence of vacillatory behaviour amongst those salmon which had arrived in the Weir pools during times when the trap was fishing suggested that trap operation was impacting upon Weir pool behaviour, see Table 22. Trap channel oscillation occurred on 54% of occasions when the trap was fishing at time of arrival in the Weir pools whilst it occurred on only 29% of occasions when the trap was not fishing during Weir pool arrival. However, these differences were not significant, Chi-Square= 2.21, p=0.05, n=29, df=1, N.S. Nevertheless, trap fishing was believed to be the most important factor in bringing about trap channel oscillation.

b) State of Tide.

Trap channel oscillation was not related to specific states of tide with movements randomly distributed throughout the tidal cycle, "r" = 0.028, N.S.

c) Tide Height.

There was no evidence for increased trap channel oscillation during larger tides; mean tide height at which trap channel oscillatory behaviour occurred (8.9m) was not significantly larger than median tide height on those occasions when salmon were present in the weir pools but oscillation did not occur (8.8 m), "t" = -0.47, p= 0.64, N.S.

d) Time of Day.

Trap channel oscillation was typically initiated during darkness and close to the dawn period, peak time, 03:16h, "r" =0.279, $p<0.05$, with a reduction in incidence of this behaviour during the afternoon period. Whilst a weak significant relationship was indicated, trap channel oscillation appeared to follow a similar diurnal pattern to that of Weir pool arrival and is likely to be best explained by increased activity immediately after Weir pool entry rather than a response to light intensity.

5.6.10. Trap Efficiency.

Simple trap efficiency over three years;

% Trap Efficiency = No. trapped/ No. available *100

=> 32/139 *100

Trap Efficiency => 23.0%

Assuming a Poisson distribution 95% confidence limits for this estimate were calculated using upper and lower values taken from tables (after Ricker). Because of the small number of recaptures the derived range was wide (15.7% to 32.5%).

5.6.11. Trap Avoidance.

Data from 36 salmon were used to examine trap avoidance behaviour. 19 of these fish arrived at the entrance to the trap during periods when it was fishing, 11 were recaptured shortly afterwards, 3 remained in the fish ladder until the trap was not fishing before crossing the Weir, 3 crossed the Weir via the crest and 2 became displaced and failed to cross the Weir. Of 17 fish arriving during periods when the trap was not fishing, 16 passed through the trap channel and one avoided the open trap channel crossing via the Weir crest, see Table 23. Although numbers of fish in the avoidance categories were small, the results suggested that 8 of 19 salmon (about 42%) which arrived in the fish ladder during periods of trap fishing physically avoided the trap. In contrast, the level of trap channel avoidance by salmon arriving during periods when the trap was open was 6%.

5.6.12. Kelt Emigration.

During 1992 and 1993 26 fish were detected leaving the river as kelts. This represented a minimum estimate because of progressive battery exhaustion induced tag failure.

5.6.12.1. Behaviour in the Impounded Reach.

For the purposes of the report the impounded reach was defined as the 9.3km reach between ALS D2 (GRSJ422601) and Chester Weir. Typically fish entered the impounded reach on elevated flows and downstream progress was steady. 52% of tagged kelts took less than 24 hours and impoundment residence times were short with only four fish exhibiting delays of greater than 4 days, see Table 24. All four of the kelts which remained in the impoundment for substantial periods arrived at the Weir during low flows or on falling flows. Whilst two of these fish remained close to the weir during their period of residence two exhibited vacillatory behaviour during impoundment residence making a number of extensive oscillatory movements within the zone.

5.6.12.2. Weir Crossing Behaviour.

a) Freshwater Flow.

Downstream migrating tagged kelts tended to cross Chester Weir during periods of elevated river flow (mean crossing flow= 36.04 cumecs, 118% ADF) see Figure 53. However, a comparison of mean flows at impoundment entry (38.08 cumecs) and at Weir crossing (36.04 cumecs) revealed no significant difference between the two samples, "t"= 0.24, p= 0.81, N.S. Considering four long-delayed kelts there was evidence that low flows were important in determining the extent of their delay. All four crossed at flows in excess of the flows during arrival in the impounded reach and soon after the advent of those elevated flows, see Table 24. It seemed that when kelts arrived in the impounded reach during low flows the Weir prevented them from emigrating until suitable flows prevailed, however the majority of kelts arrived during periods of elevated flow and emigrated from the impounded reach with the minimum of delay.

b) Tide Height.

There was a tendency for emigrating kelts to cross Chester Weir during larger than average tides, mean tide height at Weir passage, 8.5m which was in excess of the mean tide height during the study period (8.2m). However, comparison of tide heights at impoundment entry and Weir passage revealed that whilst mean tide height at Weir passage (8.5m) was greater than mean tide height at impounded reach entry (8.3m) the difference was not statistically significant, "t"= 1.33, p= 0.09, N.S.

c) State of Tide.

Timing of downstream Weir passage by kelts was randomly distributed with respect to state of tide at Chester Weir, "r"= 0.187, N.S, with movements occurring throughout much of the tidal cycle, see Figure 54.

d) Time of Day.

Downstream passage was not found to be related to time of day with movements randomly distributed throughout the 24 hour period, "r"= 0.119, N.S. However, results suggested that there was some aggregation of movements in the pre-dawn and post dusk period, see Figure 55.

e) Repeat Crossing.

Of 26 kelts tracked during 1992 and 1993 none was recorded crossing the Weir on more than one occasion.

6.0. DISCUSSION.

Estuaries are complex habitats which have been shown to produce unique behavioural patterns amongst the salmon populations migrating through them, however, common themes in behaviour have also emerged. It is important to understand the mechanisms which determine these similarities and paradoxes in estuarine behaviour in order to make informed predictions about how alterations to estuarine hydrodynamics, such as tidal power generating barrages will affect salmonids.

6.1. Straying amongst estuary-tagged salmon.

The number of tagged salmon detected in catchments outwith studied river system has been found to vary between studies. An estimated 27% of salmon tagged in the Fowey estuary entered other rivers (Potter, 1988). In contrast no salmon were recorded straying from the study river during work on the Spey (Laughton, 1991) and Tay (Webb, 1990). Straying rates from other studies have tended to fall in the region of 10% (Milner, 1989) although the overall impression is one of considerable variation between studies brought about by both differences in tagging location as well as site specific differences.

Salmon are known to orientate to cues emanating from their home river, however there has been considerable discussion concerning which particular factors are of most importance. It has been argued that the position within the estuary where salmon begin to make directed movements against the direction of the ebb tide ("active migration") is the point at which "alien" salmon will discontinue their migration through an estuary. For a given alien salmon the location of this point will vary depending on the degree to which the smell of the estuary mimics the salmon's own river. Clearly, in rivers with shared estuaries straying rates would be anticipated as being higher than the norm, 10-15% of salmon tagged in the Avon estuary were tracked into the Stour (Solomon, 1992), whilst remote catchments with few competing salmon rivers close-by, eg the Dee, would be expected to have lower straying rates (observed rate in this study was about 1%). Equally, during low flow years larger numbers of salmon would be predicted to enter alien estuaries because of the greater dilution of olfactory cues in coastal waters. During 1991, a large number of tagged salmon were not detected upstream of the estuary tagging site on the Dee, but only one salmon was subsequently detected in another catchment, a similar straying rate to the subsequent two study years. The whereabouts of these missing fish remains unclear. Low river flows in 1991 may have led to a greater proportion of non-Dee salmon reaching the tagging zone. This idea cannot be discounted because rivers in the Lancashire area (Ribble, Lune), later found to be likely destinations for Dee strays were not overflown during 1991. It was also a possibility that high temperatures and low freshwater flows in the middle estuary brought about either elevated tagging mortalities in 1991 or prevented access to the inner estuary and that these deflected fish were subsequently taken in an illegal net fishery in the outer estuary. Although the latter idea was supported by anecdotal evidence from the bailiff force and the return of one tagged salmon during a poaching investigation the large numbers of missing fish involved were unlikely to be explained solely by illegal netting. Assuming similar tagging mortality rates and some outer estuary net recapture the most plausible explanation appears to be that the straying rate was higher during the dry summer of 1991.

Dee estuary tagged salmon were found in two rivers more than 80 km from the estuary. Similar findings have been recorded during other studies; one salmon tagged on the Fowey in Cornwall was recaptured some 160km from its release point (Potter, 1988) indicating that some salmon make extensive coastal migrations following their return from high seas feeding grounds. This suggests that estuarine barrages may impact on salmon populations from rivers considerable distances from the estuary in question. However, it is also apparent that the frequency of this behaviour is low and the impact on salmon stocks outside the catchment directly affected by the barrage is likely to be too small to measure and too complicated to mitigate against. Where competing rivers are in close proximity the indirect effects of a barrage on neighbouring catchments may be important and therefore consideration should be given to this aspect when siting estuarine barrages. Barrages located in an estuary below those areas where alien salmon "decide" to leave non-target rivers will subject stocks from other rivers to any dangers associated with barrage passage on two occasions. Clearly, the greater the number of competing salmon rivers in the locality the more profound will be the impact and the greater consideration needing to be given to this issue.

It is possible that the presence of the barrage itself will preferentially dissuade further estuarine progress by alien salmon which come into contact with it. One salmon was deflected from Chester Weir into a neighbouring catchment during a period of low river flows. This suggested that the Weir brought about emigration in this instance, albeit in the case of a Weir sited at the extreme top of an estuary where straying rates would be expected to be low. In contrast, results from the river Taff have indicated that a small proportion of fish tagged from positions upstream of the proposed barrage line have emigrated into other catchments when relocated back into the outer estuary, (NRA in prep.). It will be interesting to compare these findings with similar trials conducted once the Taff barrage has been completed.

6.2. Modelling of Estuarine Behaviour.

A number of factors are likely to combine to determine salmon behaviour in estuaries. Broadly these can be sub-divided into;

i) "natural" factors, e.g. time of day, size and state of tide, and

ii) estuary-specific factors, e.g. the physical features of the estuary, river flow and water quality.

Establishment of the relative importance of each of these factors is complicated by their interdependency which makes it difficult to predict how changes in one will affect salmon behaviour.

Results from a number of studies principally undertaken in the late 1980's led to the development of a simple model summarised by Milner (1989). Broadly it stated that, within the main body of an estuary salmon tended to move in relation to tidal influences (upstream with flood, downstream with ebb). This pattern could last one or many tidal cycles (weeks) appearing to be largely unaffected by river discharge and during this time fish may hold-up in sheltered locations, particularly those committed to river entry, whilst others may drop out of the estuary altogether for long periods (> 100 days) prior to returning. Some, presumably, non-natal salmon never returned having left the estuary after tagging. The model indicated the importance of freshwater discharge as a stimulus to river entry increasing in importance as distance from the tidal limit decreased.

6.3. Dee Estuary Behavioural Model.

The bulk of the data used in establishing the Dee behavioural model were gathered during 1992 and 1993 which both had cool wet summers when river flows were higher than normal. The importance of river discharge in determining estuarine behaviour described by other studies undoubtedly means that the Dee results will have been influenced by the high prevailing flows and conclusions will probably need to be modified in order to describe behaviour across the full range of estuarine conditions.

6.3.1. Bias in the Tagged Population.

The consistently rapid upstream progress recorded in all three years but particularly in 1992 and 1993 produced a significant relationship between inner estuary entry times and middle estuary release times although this effect was not noticeable by the time tagged fish had reached the Weir. This bias was demonstrated by the different distributions recorded for relocated fish and estuary tagged fish. Fish relocated from the trap had release times associated with the early morning but release was random with respect to state of tide. Inner estuary entry times for this sample were consequently biassed towards certain times of day. Conversely, estuary tagged salmon tended to be released during the middle to late ebb phase of the tide and as a result the distribution of inner estuary entry times were similarly biassed. It seemed unlikely that the observed bias affected the validity of the finding that salmon achieved successful upstream migration through the middle estuary at all states of tide. Indeed, it seems likely that the extent to which migration through the canalised reach was dependent upon passive (tidally assisted) movements, particularly during elevated flow periods, may have been overstated through biased release times.

where tidal currents are reduced and under low flows in freshwater when water clarity is increased. The mechanism responsible for this behaviour is not known but the overriding affects caused by freshets in freshwater suggest that received light intensity is important, therefore it would follow that swimming depth could be altered to compensate and that migration through deeper reaches would be achieved at lower turbidity values. Interestingly, salmon migration in the lowermost freshwater reaches of the Dee, which are relatively deep, did not follow behaviour at the top of the inner estuary and was not constrained by time of day. This suggests a localised affect of either the Weir itself or the shallow reach immediately below the Weir produced this response to light intensity. Information about swimming depths of salmon in estuaries under different conditions of turbidity may be of value in predicting behaviour in impoundments behind barrages where tidal flushing and hence turbidity will be reduced with a possible impact on residency in such reaches.

6.3.5.2. The Impact of Freshwater Flow.

The importance of freshwater flow in determining entry into the lowermost reaches of the river was evident with a close association between freshets and river entry on the Fowey (Solomon and Potter, 1988). Freshwater entry on the Tywi was more common during high flows and low flows stimulated nocturnal passage (Clarke and Purvis, 1989). On Dee, successful migration appeared to occur at lower flows than for many studies although similar responses by salmon to small changes in flow have been reported for the Avon (Solomon, 1991) and Test and Itchen (Fewings, pers comm.). Regulated discharge from headwater reservoirs on the Dee maintains flows at levels allowing abstraction from the lower reaches of the main river and a guaranteed minimum flow across Chester Weir limits the occurrence of extreme low flows in the estuary. The similarity of behaviour between salmon entering chalkstreams and those migrating into the heavily regulated river Dee probably reflects the similar hydrological regimes where Summer basal flows are increased to a point above the natural catchment discharge (if it were a true spate river).

6.3.5.3. The Impact of Water Quality.

There was no direct evidence of toxic effects in the inner estuary with only small numbers of salmon corpses observed in each year. It was not possible to rule out stresses associated with tagging causing those deaths of radio-tagged fish which were recorded because numbers were consistent with expected levels of tagging-induced mortality. Furthermore, it was not possible to demonstrate any correlation between water quality and salmon behaviour suggesting that conditions were above the threshold required for successful migration. This was largely because of two cool, wet summers (1992 and 1993). Although the summer of 1991 was warm and dry two releases of water from reservoirs in the upper catchment maintained inner estuary water quality during a potentially vulnerable period and enabled salmon reaching the inner estuary to successfully negotiate the reach, unless recaptured by netsmen.

6.3.6. Variation in Behaviour at Different Times of year.

6.3.6.1 Early Running Salmon.

Relocation of salmon to Connah's Quay following capture and tagging at Chester Trap during April and May 1993 enabled the study of behavioural responses amongst early-running, multi seawinter (MSW) salmon. This group was most likely to enter freshwater reaches and were also more likely to make large oscillatory movements between inner and middle estuaries. Netting was the most significant factor influencing freshwater entry success rates amongst tagged salmon and the fact that it was less intense during April, May and June probably explained this finding, particularly because the observed increase in oscillatory behaviour would tend to make salmon more available for net capture. This suggests genuine differences in estuarine behaviour between run components which would be important when assessing the impacts of estuarine barrage developments because early running salmon are both valuable to the fishery resource (they are larger fish) and they are the component of salmon populations most threatened currently.

6.6.3.2. Autumn Entrants.

Freshwater entry success rates for September-tagged fish varied markedly between years. It was very low during 1991 (11%) which contrasted with high values during 1992 and 1993; 96% and 79% respectively. The principal difference in external environmental factors between the three months was freshwater flow; September 1991, mean= 12.3 cumecs; 1992, mean= 31.4 cumecs; 1993, mean= 22.5 cumecs and based on these figures successful freshwater entry was positively correlated with mean monthly flow. Moreover, the different estuarine responses by groups of salmon arriving at the estuary at the same time of year in different years provided evidence of the importance of external factors in determining estuarine behaviour suggesting that behavioural differences between run components do not occur and can be explained solely by external factors. These results contrast with findings from freshwater tracking studies on the Welsh Dee (NRA, in prep.) and evidence from Scottish rivers, Laughton and Smith (1990) which have both indicated that migratory behaviour by earlier running fish was substantially different from summer fish probably because of requirements associated with their ultimate spawning strategy. Irrespective of whether the varied behavioural patterns observed were caused by external factors or by diffferences in behaviour per se, the value of spring salmon to the resource and their current conservation status necessitates the careful consideration of such differences when assessing the impact of changes to estuarine environments, including barrages.

6.4. Behaviour at Chester Weir.

Freshwater entry on the Dee was complicated by the presence of the partial physical barrier of Chester Weir which forms the saline limit of the estuary except under conditions of low flows and large spring tides. In general, 3 basic types of behaviour were identified;

i) salmon migrated past the Weir without significant interruption to their rate of upstream progress,

ii) fish arrived at the Weir and remained in the immediate downstream reach for a significant period before crossing the Weir,

iii) fish arrived at the Weir and were displaced downstream into the main body of the estuary,

It is difficult to predict how salmon behaviour would change in the absence of Chester Weir but is likely to be similar to those behaviours already recorded from other estuaries without barrages at head of tide. On small spate rivers, entry to freshwater was principally controlled by freshwater flow with salmon preferentially entering on freshets, eg Fowey in Cornwall (Potter, 1988). Behaviour was different on the Hampshire Avon where salmon responded to small changes in flow (Solomon, 1991). This was attributed to the nature of the hydrograph of this chalkstream where basal flows were maintained during the Summer because of the groundwater source and where significant freshets during the Summer period were rare. Similarly, flow was less important for salmon entering the larger Scottish rivers. On the Scottish Dee it was thought that elevated flows for a greater proportion of the year brought about by snow-melt and the consistent release of water from the large catchment influenced responses to flow (Hawkins and Smith, 1987). Perhaps not surprisingly, a similar response was observed on the artificially regulated Welsh Dee with salmon recorded crossing the Weir at all available flows, minimum crossing flow = 4.25 cumecs (13.7% ADF) which was the 3.4%ile flow for the period April to October 1993 and effectively represented the minimum flow across the Weir experienced during the year.

Other studies have also indicated the importance of relative changes in flow rather than absolute migration flows, salmon migrating through the lower reaches of the Tamar did so under lower flows during drier years (Sambrook and Broad, 1988). This flow-graded response was noted from the Usk (Mills *et al*, 1991) and, despite the possibly moderating influence of river regulation it was also evident for freshwater entry on the Dee. The trend in median weir passage flows (salmon) each year, (1991, 7.9 cumecs, 1992, 19.4 cumecs and 1993, 15.1 cumecs) reflected the median available flows, 1991 7.3 cumecs, 1992 11.7 cumecs and 1993 11.0 cumecs.

6.4.1. General Weir Behaviour Model.

6.4.1.1. Fish Ladder Arrival.

More than 90% of salmon which crossed Chester Weir entered the fish ladder. The timing of entry to the fish ladder reflected the timing of arrivals at Dside demonstrating the combination of nocturnal activity and preference for the early ebb tide in determining behaviour. This relationship was less well defined during high flow periods. The majority of fish spent only a short period in the fish ladder before Weir passage.

6.4.1.2. Weir Crossing.

Salmon were more active at night during residence in the vicinity of the Weir and this was reflected in Weir crossing times where trap channel passage was uncommon during daylight hours. The distribution of Weir crest passage times demonstrated the impact of both Spring tide high water times and the influence of time of day which produced peak passage times around midnight. Elevated flow encouraged Weir crossing by both routes but was of greater influence in promoting Weir crest passage which reached peak probability at flows of 60-65 cumecs and contrasted with trap channel passage where probability was greatest at flows of 30-35 cumecs and was not recorded at flows in excess of 65 cumecs. Weir crest passage was restricted to periods when the Weir was inundated at flows of less than 8 cumecs.

6.4.1.3. Trap Avoidance.

On average, fish were delayed in the fish ladder for longer periods when the trap was fishing than when the trap channel was open. There were three reasons for this;

i) salmon remained in the fish ladder until the trap was opened before crossing,

ii) salmon ignored the trap channel route and waited until passage was possible via the Weir crest route

iii) salmon took longer to negotiate the entrance to the fish trap.

Trap avoidance (i) and ii) above, followed by large scale displacement from the Weir was only rarely recorded. Therefore whilst trap fishing increased the time spent at the Weir it did not have a significant impact on the numbers of fish entering freshwater. Barrages may be designed with fish traps in situ and their impact over and above that of the obstacle itself should be recognised. Trap fishing regime and trap design should be considered accordingly.

6.4.2. Factors Affecting Delays at the Weir.

Concerns have been expressed that tidal barrages will modify salmon behaviour by increasing residence time in the immediate vicinity (both landwards and seawards) in areas where predation, water quality or netting exploitation could combine to reduce the numbers of salmon reaching freshwater. Extended delays will be caused either by salmon failing to find fish passes, turbine chambers or other routes across the barrage line or by salmon deliberately avoiding passage through the routes provided because they are unsuitable. A number of factors will influence this.

Freshwater flow is important in determining behaviour particularly in inner estuaries. Under low flows attraction to fish passes may be impaired increasing delays, equally too much water travelling too quickly through fish passes will prevent passage. Whilst few studies have measured the impact of changes in flow on weir behaviour, work on the Loire (Baril and Guenau, 1982) demonstrated that passage across a freshwater weir was closely related to freshet events. Although in their case temperature and freshwater flow were closely linked they concluded that the fish were responding to increases in temperature which had been a physiological barrier to upstream passage rather than responding to elevated discharge.

Where fish ladders are included in Weir design, passage success will depend on the ability to detect the potential route and to move unhindered through the channel. Delays at Chester Weir appeared to become quite consistent at flows greater than 30 cumecs (about ADF) inferring that elevated flow was overriding all other factors determining delay once it reached this level. Interestingly, during flows of this magnitude increased uptake of the Weir crest route was noted suggesting that some fish were delayed at the Weir because of the unsuitability of the fish pass. At the high flow end of the range, trap channel passage was reduced to zero at flows of the order of 65 cumecs, presumably because of both, the ease of Weir crest passage and the lack of competitive attraction flow from the trap channel outflow. At flows between 30 and 60 cumecs the fish ladder was attracting fish and these fish were able to pass with minimal delay but at flows of less than 30 cumecs delays were influenced by a number of factors acting in unison to produce delays below the Weir.

The low success rate of salmon attempting to pass Pitlochry dam on the river Tummel (5 of 11 available fish) was attributed to the lack of an adequate outflow from the fish pass when compared with the attraction flow from the turbine chamber tail race (Webb, 1990). This compared with more than 90% of fish which used the fish ladder at Chester Weir and 67% of fish crossing the Weir via the trap channel which were attributed to the ability of the fish pass to both attract and retain salmon. The performance at Chester Weir represents a substantial improvement compared with the situation at Pitlochry, even assuming that all of those fish not using the trap channel would have failed to cross the barrier. However, neither dam is strictly comparable with low-head tidal barrages such as would be promoted in estuaries, nevertheless it demonstrates the importance of obtaining sufficient attraction flow through fish passes in order to achieve adequate passage success by salmon. Similar low success rate for salmonids in the lower Taff at Blackweir (Gough, 1992) and in the Tawe estuary (Stonehewer *et al*, 1993), have suggested that the main cause was the inability of "denil" fish passes to allow passage. On the Taff evidence suggested that whilst some fish passed through the fish pass quickly, failure to find the pass rather than avoidance of the trap was attributed with causing the poor crossing success (up to 60% of radio tagged migrants). In contrast, the current speeds in the fish pass on the amenity barrage in the Tawe estuary appeared to physically prevent the passage of salmon entering the fish pass under anything but the lowest of flows (Stonehewer *et al* 1993). Whilst very few salmon passed Chester Weir without substantial reduction in net ground speed, in general salmon were not delayed excessively prior to passage across the Weir. This success in promoting rapid passage was largely because of the effectiveness of the fish ladder in attracting and retaining salmon prior to crossing and the suitability of two of the three possible passage routes. The third route, "trap channel during trap fishing", deterred some fish resulting in increased delays. Salmon deterred in this way exhibited small scale investigative movements which were restricted to the confines of the trap channel which were only recorded during periods when the trap was fishing and were probably the result of attempts to find the small opening to the fish trap (30cm wide). However, the avoidance of this route was not important in displacing salmon from the Weir. The combination of the ability of the fish ladder to retain salmon, the availability of "open trap" periods and weir-topping tidal events provided adequate opportunities for those fish dissuaded from immediate crossing via the constricted trap channel to cross the Weir.

In the case of tidal power generating barrages, landwards turbine chamber passage will be impossible during the ebb generation cycle. Results suggest that the outflow from generating turbines will serve to override any attraction flow from fish passes (if operational during the ebb) effectively restricting barrage passage to the flood tide and consequently increasing delays (albeit for only a few hours) assuming subsequent successful passage during the flood tide.

6.4.3. Displacement from the vicinity of the Weir.

Concerns have been expressed that tidal barrages will modify salmon behaviour by downstream deflection of fish which come into contact with the obstruction. This would be particularly important if as a result such fish were prevented from entering the impoundment. On the Dee, large scale oscillations were more common in the inner estuary than the middle estuary and were often associated with downstream displacements from the vicinity of Chester Weir. Furthermore, this displacement behaviour occurred over large distances and salmon were recorded making up to 8 such movements.

Individual estuaries will have particular problems resulting from estuarine barrages. For example, the Weir at Chester on the Dee was found to contribute to the catches of inner estuary netsmen because of its tendency to displace fish and it thereby contributed to a reduction in the spawning potential of the Dee system. It is important to bear such likely behaviour in mind when planning an estuarine barrage and to look closely at the areas seawards of such structures.

6.4.3.1. The Importance of Searching Behaviour.

Movements indicative of searching behaviour were less common in the inner reaches of estuaries lacking obstructions towards their tidal limit. Oscillation was less common prior to entry to freshwater reaches of the Tywi, for example, where typical behaviour involved active directed movements often during elevated flows or at night under low flows and replaced the vacillatory behaviour typical of migration through lower estuarine reaches (Clarke and Purvis, 1989).

There have been few studies which have examined the impact of estuarine dams within the UK. It was apparent on the Dee that despite the lack of comparable studies, obstructions not only delayed fish but also led to an increased incidence of oscillatory behaviour. Similar findings have been reported from freshwater; studies at Pitlochry Dam revealed that 30% of tagged salmon coming into contact with the dam were displaced more than 800m downstream (Webb, 1990) and in the lower reaches of the R Taff where similar wandering behaviour was recorded amongst tagged salmon (Gough, 1992). Both results were attributed to the failure of fish to locate the fish pass and both suggested that this failure resulted in fish failing to migrate above the obstruction at all. Similarly, displacements from the trap channel were rare at Chester Weir with most fish deflected from the area below Old Dee Bridge indicating that large scale displacement as a result of trap avoidance was rare and suggesting that failure to locate the outflow from the fish ladder was more important. However, in contrast, Chester Weir was only a total barrier to those displaced fish which were subsequently caught in the inner estuary net fishery, the remainder all crossing the Weir successfully during a later visit.

During the normal operation of a power generating tidal barrage it would be possible to dredge deeper areas reasonably close to the structure. It has been suggested that such areas would promote holding behaviour and stop salmon becoming displaced downstream. Certainly, holding behaviour in the inner Dee estuary appeared to be stimulated by the presence of deeper water. However, at Chester Weir salmon behaviour was inconsistent; a number of deeper areas existed close to the downstream extent of the Weir some of which were utilised for extensive periods by salmon whilst other fish seemed to ignore these areas and become displaced downstream. Notwithstanding this fact, it is likely that vacillation occurred because some fish failed to negotiate the obstacle resulting in fish making larger searching movements overriding any responses to deeper water. The idea that displacements were extreme manifestations of searching behaviour might also explain why a large number of these movements have been recorded close to high water when the directional cue from freshwater reaches above the Weir may have become confused. Whether dredging deeper areas close to barrages in order to restrict displacement will be successful will be difficult to predict until more is known about the way salmon negotiate obstacles and the features of an area which promote holding-up. If the nature of the downstream area below a barrage means that displacement is expected to result in a reduction in salmon numbers crossing the barrage line the best solution would be to ensure adequate opportunity for rapid passage for salmon across the Weir at their first visit. This will not be possible with tidal power schemes where ebb tide generation will prevent access for salmon arriving at that state of tide with the risk of displacement occurring before flood tide passage routes become available. Therefore an alternative approach would be to concentrate on making the "displacement zone" as safe as possible because evidence suggested that salmon displaced from Chester Weir were no less likely to cross the Weir following displacement unless succumbing to netting. Unfortunately, the extent of the zone which encorporates all displacement movements will depend upon site-specific features of the estuary. On the Dee, the majority of salmon were displaced less than 2km, and licensed netting was the only major influence in the affected reach, therefore a limit on netting in that zone would have substantially increased the numbers of salmon entering the river during the netting season. Evidence suggested, assuming the non-displaced component of the net catch remained unaffected, removing the nets from the upper half of the inner estuary would have produced an increase of as many as 400 fish entering freshwater reaches.

6.4.3.2. The Importance of Tidal Effects.

A substantial proportion of displacements occurred either during the late flood or at high water. These findings were both surprising and potentially of considerable concern because of the suggestion that salmon could become displaced from tidal barrages during the flood tide. This represents the only realistic state of tide for successful salmon passage across tidal power barrages and is the period when successful passage would have been expected to occur without interruption. It was not possible to establish conclusively whether displacement was caused by a failure to locate a route across the Weir but it seems that fish were most active around times of high water and the oscillations were a manifestation of extreme searching movements with the timing reflecting the times of peak salmon activity. Clearly, it is plausible that salmon would respond differently to a barrage placed further seawards than Chester Weir where tidal exchange would be significant during every tide. However, whilst not all tides were of sufficient size to inundate Chester Weir there was no evidence that displacement was more likely during non-overtopping tides. Furthermore the finding that factors such as freshwater flow and time of day although important for Weir passage made only slight contributions to the probability of displacement also suggested that this type of behaviour could be expected amongst fish encountering a barrage further seawards during their estuarine migration.

6.4.3.3. The Time of Year.

Interestingly, displacements were most common during early (57%) and late season (34%) with a substantial reduction in the proportion exhibiting this behaviour during July and August (16% and 13% of arrivals respectively). The reasons behind this apparent behavioural difference between components of the stock were not obvious but provided further evidence that the early season increase in displacement activity from the inner into the middle estuary was not an artefact of the failure of netsmen to catch salmon undergoing displacement and in fact reflected real responses to the Weir at Chester. If this behaviour was repeated at a barrage line located further seawards, a tidal barrage could have a disproportionate impact upon early running salmon which are a particularly important component of the stock. It is possible that measures to reduce the impact of the barrier at certain times of year would be necessary.

6.4.4. Post Weir Crossing Behaviour.

Another concern relating to estuarine barrages has been that returning adult salmon will "hold-up" in the impoundments formed immediately upstream of estuarine barrages. This would lead to increased exposure to any water quality problems which may arise within these bodies of water and will reduce the angling potential of freshwater reaches upstream if salmon spend significant periods in these areas.

6.4.4.1. General Behaviour Patterns.

Care must be taken when considering the results from the Dee because of differences in the nature of the impounded reach formed behind Chester Weir and the likely impoundment behind a tidal power generating barrage. The Dee impoundment can be best described as a sluggish riverine reach with current speeds of the order of 0.2 m/s during regulation flows. River regulation elevates flows above the natural catchment discharge at Chester Weir and, because the major abstractions occur within a few km of Chester Weir, flows in the upper half of the defined impounded reach are always in excess of 11 cumecs except during the operation of drought orders when flows to the estuary could theoretically fall to the natural catchmental discharge (a reduction of 50% on the regulation discharge). It is likely that these artificially elevated flows will profoundly affect the behaviour of salmon during migration through the lowermost reaches of the Dee.

Tagged salmon which crossed the Weir made rapid upstream progress through the impoundment with movements recorded across the full range of available flows and there was no evidence that salmon would use this reach to hold-up. This contrasted with results from the river

Tawe where impoundment residence times amongst tagged salmon and sea trout were highly variable (Stonehewer *et al*, 1993) and fish took up to 12 days to traverse the 5.4km reach.

The response of salmon to impounded areas is likely to depend heavily upon where the barrage is sited within the estuary and the nature of the barrage. Tidal exclusion amenity barrages (eg Taff) will produce a static body of water which would be anticipated to have little impact on salmon undergoing directed, active upstream migration similar to that recorded by salmon on the Dee above Chester Weir. However, salmon undergoing passive, tidally-assisted migration would be more likely to have their landwards migration interrupted in such static bodies of water because of disruption to tidal cues. In truth impoundments behind tidal power barrages will not be of this type, tidal flushing will occur with every tide but the presence of the barrage will reduce the strength of the currents and the extent of tidal exchange. The net result will be to create a deeper zone with the hydrodynamics of an inner estuary extending landwards from the barrage line. In this respect some tidal assistance for salmon undergoing passive migration would occur albeit at a reduced level. Work on the Dee would predict the extension of inner estuary type behaviour further seawards in the estuary. Namely, an increase in total estuary residence time as a result of a greater incidence of large scale oscillatory movements and more frequent holding behaviour. Evidence from the Dee suggests that this would reduce net upstream migration rate by about 40% on avearge. Currently it is not possible to predict whether oscillations would involve multiple passages across the barrage line which would result in some biological impact but it does remain a possibility.

Multiple barrage crossing is important because it is likely that large fish passing through turbines whether upstream or downstream would suffer high rates of mechanical strike injury leading to both acute mortality and to the impairment of spawning potential through a reduced spawning fitness resulting from chronic injuries. Supporting evidence from Chester Weir must be treated with caution because of the position of the Weir in the estuary but assuming that fish behave in a similar fashion at a tidal power barrage then the frequency of multiple crossing will be insignificant in terms of impact on the stock. However, there is a need to examine behaviour at a more suitable location in order to model responses to a tidal barrage because whilst multiple crossing at Chester Weir was limited it always occurred during periods when the Weir was inundated by large tides and although it was not recorded amongst fish using the Weir crest the most important stimulus for Weir crest passage was freshwater flow which will be virtually irrelevant at obstructions placed further seawards in estuaries.

6.4.5. Kelt Emigration.

Although kelt survival rates vary between sexes, river systems and between different years typically about 5% of returning adult salmon have spawned previously. The proportion is significantly increased in the case of sea trout where repeat spawning is the norm. Despite the fact that they are a numerically small component of the stock, previous spawners can be a valuable part of the angling catch (they are by definition larger than 1 SW grilse). Larger size often confers advantages to recruitment through improved redd construction and increased average egg-size. It is apparent that the protection of salmon kelts is therefore desirable and of even greater significance in the case of sea trout. Despite the importance of this phase of salmon migration no major studies have been undertaken. Clearly, knowledge of the factors determining estuarine passage by emigrating kelts will be important in predicting the impact of changes to the estuarine habitat. This is of particular importance in the case of estuarine barrages, construction of which will profoundly alter the lowermost riverine reaches of impounded estuaries as well as the estuary itself and present salmon kelts with an additional barrier during emigration.

Kelt emigration through the lower river and inner estuary was for the most part a completely passive activity which suggested that passage across a barrage placed in this estuarine reach would only occur on the ebb tide, during power generation. Furthermore whilst empirical evidence was not available it is likely that residence times in the estuary will exceed those of upstream migrants because kelts will be less able to make progress against tidal currents and this will increase the probability of multiple crossing. Clearly, kelt emigrations in the lower estuary need to be investigated in order to establish residency and the degree of oscillation, this will be particularly important for the multiple spawning sea trout.

It is important to remember that Chester Weir's impoundment is not strictly representative of likely impoundments behind tidal power generating barrages which will be much larger and less riverine and lead to the dissipation of some of the impetus of freshets at the upstream interface with the impoundment. During periods of low flows results suggest that fish will not enter the impoundment at all. In addition, the larger impoundments may prevent fish entering during elevated flows from crossing the barrage during the lifetime of a freshet and hence increase impoundment residence times for kelts. This is of particular concern because of the importance of freshwater flow in stimulating kelt emigration. Once at the barrage line emigration success will depend on the proportion of fish attracted to the "fish passes" during ebb-tide generation. Kelts, being in poor condition and with reduced swimming capabilities compared with upstream migrants can be expected to be more likely to become entrained into the flow entering the turbine chambers and hence run a greater risk of damage by the blades. As with mature returning adult fish and smolts there is no data available concerning how kelts will respond to underwater tunnels and turbine chamber entrances. However, assuming some degree of comparability between Dee results and power generating barrages, it appears likely that barrages which provide some significant overtopping or have surface level fishways will not represent a significant barrier to emigrating kelts.

7.0 CONCLUSIONS.

7.1 Introduction.

The majority of tracking data were gathered in 1992 and 1993 because of improvements to the passive tracking array instituted following year 1 (1991) of the project. During the summers of 1992 and 1993 cool wet weather allied to the effects of river regulation produced correspondingly mild estuarine conditions. Continuous water quality monitoring at this time revealed that dissolved oxygen levels and water temperatures rarely attained levels thought to be stressful to adult salmonids. Furthermore, true summer low flow conditions were prevented by a release of water for several weeks during the late summer of 1991 when although low dissolved oxygen concentrations and high water temperatures occurred they were restricted to limited periods within the tidal cycle. Therefore, it was unlikely that the behavioural analysis included the description of behaviours across the complete range of available environmental conditions on the Dee.

7.2. Outer Estuary Behaviour.

Few data were collected in the outer estuary because of the harsh environment which prevented effective passive tracking nevertheless two distinct types of behaviour were suggested. Some relocated salmon traversed the outer estuary rapidly and behaviour was similar, if less rapid, to middle estuary behaviour with active upstream migration throughout the tidal cycle suggesting that fish were responding to river flow in the outer estuary. In contrast, the larger proportion of relocated salmon were absent from the middle estuary for more than 1 tidal cycle and some for considerable periods indicating a different behaviour pattern. It was not possible to establish where these fish spent this time but it was thought that they were offshore rather than in the area of the outer estuary upstream of the release point.

7.3. Behaviour in the Middle and Inner Estuaries.

Despite the fact that at no time did it appear that the middle estuary was a complete barrier to upstream migration by salmon, net migration rate through the middle estuary was found to decrease during periods of lower freshwater flows and at higher water temperatures but low dissolved oxygen conditions were not implicated in reducing the probability of upstream migration. Substantial alterations to rate of passage was recorded at flows of the order of 8 to 12 cumecs and temperatures between 15 and 17 Deg C. Behaviour also reflected the importance of both tide height and tidal state and provided strong evidence that salmon were actively swimming in a continuous fashion towards freshwater during passage through these reaches.

Water depth was also important; salmon tended to avoid shallow areas when adopting holding behaviour which probably contributed to the rapid nature of the movements in the canalised reach as well as the increased frequency of holding behaviour in the deeper inner estuary. Increased holding behaviour and oscillatory behaviour which was also more common in the inner estuary could not be attributed solely to water depth because of other factors, principally the presence of draft nets and the amount of tidal flushing, associated with the position of the reach within the estuary.

The behavioural model produced compares favourably with previously documented estuarine behaviour assuming that either; the tracking zone in the Dee estuary comprised only those areas relating to the inner reaches of a general estuary, or that the "natural", less directed behaviour pattern expected in the middle estuary was superceded by directed active migration as a result of the cool and wet conditions.

7.4. Straying.

Straying of biological importance occurs when salmon enter an alien estuary and as result fail to spawn in their natal river. Confirmed straying rates on the Dee suggested that a barrage placed at Connah's Quay would result in few non-Dee salmon (<1% of total population reaching that point in the estuary) coming into contact with the barrage. This probably reflects both the isolation of the Dee catchment and the relatively high freshwater discharge to the estuary from this regulated river system both of which will tend to inhibit straying. Indications are that straying rates vary a great deal between estuaries and it is likely therefore that this uniqueness of estuaries and the site specificty relating to the positioning of the barrage will require empirical study before the impacts of individual barrage schemes on straying salmon can be evaluated. However, ultimately the low incidence of straying behaviour may mean that impacts on alien salmon will be of less importance than barrage-induced alterations to the olfactory cues used by salmon which are entering their home estuaries.

7.5. Kelt Behaviour.

Limited information was available concerning the behaviour of kelts in the inner estuary with none available for the middle or outer estuaries. In general kelt emigration was passive with inner estuarine residence brief and was determined by passage across Chester Weir. Consequently, the vast majority of kelts emigrated from the river during periods of elevated freshwater flow because of the reliance on these freshet events to stimulate downstream migration from the lower river into the impounded reach and because of the lack of suitable downstream passage routes under low flows at the Weir and multiple crossing of the Weir was not recorded amongst kelts. This suggests that the majority of kelts will cross an estuarine barrage during the ebb tide but that tidal oscillation may not be significant although more data on movements in the lower sections of estuaries need to be collected because kelts crossing Chester Weir were responding primarily to changes in freshwater flow.

7.6. The Effectiveness of the Fish Pass.

The ability of fish passes to attract upstream migrants has been called into question at some dams. The fish ladder at Chester Weir was thought to be the major factor in promoting rapid passage across the Weir. It is a large structure for the size of the Weir possessing 5 large pools and a low gradient between each pool, consequently maximum current speeds within the pass are generally less than 0.8m/s. Furthermore, the Weir itself is set at an angle to the bank and serves to concentrate fish towards the entrance to the fish ladder. More than 90% of tagged salmon utilised the fish ladder irrespective of their subsequent route of passage. Moreover it was successful in retaining fish unable to cross the Weir, 80% of salmon which entered the fish ladder remained within the pools until crossing the Weir. These two features combined with the extent of inundation of the Weir crest (25% of tides) were of major importance in producing successful Weir passage across the full range of available conditions recorded during the study.

7.7. Interruption to Migration.

Despite the fact that a substantial proportion of total estuarine residence time was spent close to the Weir, the delays were still comparatively short (median delay 12:49 hours with 75% of fish delayed less than 36 hours) and not in themselves believed to have impacted on migration success. Although some fish were delayed for a number of days the Weir was not in itself a complete barrier to migration. The position of the Weir at the effective saline limit of the estuary was important in determining the range of recorded behaviours, particularly the response to freshwater flow where flows in excess of 30 cumecs reduced delays below the Weir. The trap at the head of the fish ladder was found to have discouraged passage leading to increased delays for fish during periods when the trap was fishing. However, this did not increase the proportion of salmon which ultimately failed to cross the Weir. Most rapid passages under low flows were achieved via the trap channel despite the presence of Weir inundating tides, indicating that some salmon were dissuaded from crossing the structure without delay when effectively the barrier was removed suggesting that flood tide assisted passage at an estuarine barrage may not occur without some delay.

7.8. Factors Affecting Weir Passage.

Weir crest passage was controlled by a combination of freshwater flow, tidal state, tide height and light intensity (at low flows). One salmon was able to cross the Weir when the downstream water level was below the crest height but the majority crossed when significant inundation was occurring or during FW flows of greater than 13 cumecs. In contrast, although peak trap channel passage occurred at freshwater flows of the order of 30 cumecs higher flows inhibited the probability that salmon would use this route and as a result light intensity and state of tide were most important in governing trap channel passage. In addition the state of the trap itself affected passage behaviour with trap channel passage less likely when the trap was fishing. This was attributed to the constriction at the mouth of the trap dissuading fish passage and may be important if the only routes available across estuarine barrages are narrow. At best such obstructions will reduce the speed of passage and at worst they will prevent it altogether.

Irrespective of the influences of tide, time of day and trap operation, the fish ladder at Chester Weir was effective for flows ranging from 4 to 65 cumecs. Peak passage efficiency occurred at 30 cumecs and it only became ineffective at flows greater than 65 cumecs. Largely because of this, more than 65% of salmon crossed Chester Weir via the trap channel and the greatest cause for concern indicated by the results was the tendency for some salmon to be deflected from the vicinity of the Weir, frequently without having come into contact with the fish ladder.

7.9. Displacement of salmon from the Weir.

The most significant biological impact of the Weir was the tendency for it to displace salmon downstream into the inner estuary. More than 30% of Weir arrivals behaved in this way with some fish deflected more than once, 75% of displacements were of less than 2 km. No salmon was displaced a significant distance following successful crossing of the Weir. There was no indication that repeat visits in themselves reduced the probability of Weir passage but they inevitably increased netting exploitation amongst this component of the population. Estimates showed that approximately 10% of the in-season population failed to cross Chester Weir as a result of net recapture following displacement from the Weir.

The majority of these displacements were initiated from the area immediately below the fish ladder and displacement was less likely following entry to the fish ladder. Unfortunately resolution of movements in the reach immediately below the fish ladder was not undertaken and it was not possible to ascertain whether; the stretch between Old Dee Bridge and the Weir presented an effective barrier to upstream migration in certain instances or, salmon were unable to locate the entrance to the fish ladder and became displaced from the Weir as a result. Whichever was true it was apparent that the obstacle resulted in a proportion of fish becoming displaced whilst undertaking searching behaviour and this should be expected at any structure placed in the migration path. The magnitude of the problem will depend upon site specific factors and cannot easily be predicted in advance of the construction of particular schemes.

7.10. Multiple Crossing and Impoundment Passage.

Few salmon (5 fish) crossed the Weir more than once during their upstream migration and it was not recorded in the case of salmon crossing the Weir via the Weir crest. The low incidence of multiple crossing was largely a result of the consistent and rapid upstream migration through the impounded reach which contrasted with the holding behaviour frequently recorded amongst fish in the inner estuary. This implied that passage of fish through estuarine impoundments will be rapid and concerns about increased residence time and repeat crossing will not arise. Unfortunately the position of Chester Weir within the estuary and the hydrodynamics of the Dee impoundment limit the applicability of results to estuarine barrages. Indeed it is most likely that impoundment behaviour will follow the types of behaviour recorded in the inner Dee estuary where a deeper reach with reduced tidal flushing (similar to an impoundment behind an estuarine barrage) produced a net reduction in migration rate through a greater incidence of both stationary holding behaviour and oscillatory behaviour. This would lead to longer residence times in the estuary with the added possibility that the increased vacillation would result in multiple crossing of the barrage line. Both of these are undesirable and moreover, the latter is likely to have a biological impact in reducing the numbers of adults surviving to spawn.

8.0 RECOMMENDATIONS.

8.1 More information is required concerning the responses of salmon in the outermost sections of estuaries and how this behaviour changes as salmon migrate further up estuaries. It is therefore suggested that a future major study of return migrations amongst adult salmon be undertaken within an estuary which allows acoustic tracking throughout its full length.

8.2 Little empirical evidence has been accumulated relating to the depth of swimming of salmon during estuarine migration. Tagging of salmon with depth sensing tags would provide this information and would improve understanding of salmon responses to the rapid reduction in depth occurring at an estuarine barrage.

8.3.Currently, technological limitations to equipment restrict achievable objectives in some areas of the generic research programme. It is recommended that as soon as products become commercially available in the U.K. the following aspects should be studied.

i) Investigation of responses to cues in coastal and outer estuarine areas will be possible following the development of data storage tags for attachment to salmon which measure a number of parameters including; position, depth, temperature and salinity.

ii) An assessment of the energetics of estuarine migration using tags which record the metabolic activity of salmon via electromyogram output, opercular rate or tail beat frequency.

iii) The conditions, in particular responses to water flow and the features of fish pass design, which promote successful salmon passage through fish passes. Telemetry systems resolving movements to less than 1m will enable such studies to be undertaken and should be attempted at suitable locations once the performance of such equipment (operating on both acoustic and radio frequencies) has been assessed.

8.4. Results indicate that salmon respond quickly to the advent of flood tide and movements are of a similar speed to tidal currents. Assuming similar behaviour in reaches below power generating barrages, salmon will tend to arrive at the downstream face of a barrage in the early part of the flood-tide. It is therefore important that this is considered during the implementation of barrage schemes.

8.5. It is possible that power generating barrages will bring about both increased holding behaviour in the reach below the barrage and lead to the displacement downstream of some migrants as suggested by results from Chester Weir. Therefore, it will be necessary to consider estuary use below the proposed barrage line, for example, commercial netting performance below the barrage may improve as a result and lead to damage to salmon stocks.

8.6. Holding behaviour was more frequent in deeper reaches of the Dee estuary. Assuming this to be generally applicable and that it is desirable to restrict displacement to the immediate vicinity of the barrage, measures designed to increase average depth in that zone will be of value in promoting such behaviour. It is therefore recommended that the maintenance of deep water seawards of the barrage-line be considered a high priority fisheries issue.

8.7. Multiple crossing of Chester Weir by salmon was not recorded which probably merely reflected its position towards the saline limit of the estuary. It is likely, however, that multiple crossing would be more common at a barrage located further seawards. Therefore it is important that barrage designs include safeguards to allow sufficient numbers of salmon moving seawards to bypass turbines during generation. This would reduce the impact on both emigrating kelts and "alien" salmon returning to sea after straying across the barrage-line.

8.8. A number of assumptions about behaviour in estuaries affected by barrages have been made and it is recommended that these should be tested via studies on estuaries with impoundments more typical of those behind energy barrages. Unfortunately there are currently no energy generating barrages in the U.K. and it will be necessary to involve estuaries encorporating amenity barrages within their lower reaches. This may be most easily accomplished by studying the two amenity barrages (Taff and Tawe) in South Wales.

REFERENCES CITED.

Alabaster J.S. (1989). River Axe Fish Study- Stage 2, Environmental Assessment for River Abstraction. Report to Mander, Raikes and Marshall, Bristol.

Alabaster J.S. (1990). The Temperature Requirements of Adult Atlantic Salmon, *Salmo salar* L., during their Upstream Migration in the River Dee (North Wales). J. Fish. Biol. **37**, p 659-661.

Alabaster J.S. and Gough P.J. (1986). The Dissolved Oxygen and Temperature Requirements of Atlantic Salmon, *Salmo salar* L., in the Thames Estuary. J. Fish. Biol. **29**, p 613-621.

Aprahamian *et al* (1988). Movement of Atlantic Salmon (*Salmo salar* L.) into the River Usk, South Wales, in Relation to Water Quality. J. Fish. Biol. **33** (Supplement A), p 245-247.

Baril D. and Gueneau P. (1986). Radio Pistage de Saumons Adultes (*Salmo salar* L.) en Loire. Bull. Fr. Peche Piscic. **302**: 86-105.

Batschelet E. (1981). Circular Statistics in Biology. London: Academic Press, 371 pp.

Clarke, D.R.K, Purvis W.K. (1989), Migration of Atlantic Salmon in the River Tywi system South Wales. Paper presented at the Atlantic Salmon Trust Conference on the Effects of Water Quality on Salmonid Migration, Bristol.

Clarke, D.R.K., Purvis, W.K. and Mee, D.M. (1990). Use of telemetric tracking studies to examine environmental influence on catch/effort indicies. A case study of Atlantic salmon (*Salmo salar* L.) in the R. Tywi, South Wales. N.R.A. REAU (Llanelli) Internal Report.

Gough P.J. (1992). Apparent Delayed Migration of Radio-Tagged salmon below Blackweir, R. Taff. Technical Memorandum, National Rivers Authority, Welsh Region, SE Area, Number **EAE/92/23**.

Hawkins, A.D. and Smith G.W. (1987). Radio Tracking Observations on Atlantic salmon (*Salmo salar* L.) ascending the Aberdeenshire Dee. Scottish Fisheries Research Report, **36**.

Hawkins, A.D., Urquhart G.G. and Shearer W.M. (1979). Movements of Returning Atlantic Salmon, *Salmo salar* (L.). Scotish Fisheries Research Report Number **15. ISSN 0308-8022.**

Laughton R. (1991). The Movements of Adult Atlantic Salmon (*Salmo salar* L.) in the R. Spey as Determined by Radio Telemetry during 1988 and 1989. Scottish Fisheries Research Report Number, **50**.

Laughton R. and Smith G.W. (1991). The Relationship between the date of river entry and the estimated spawning position of adult Atlantic salmon (*Salmo salar* L.) in two major Scottish East coast rivers. In Wildlife Telemetry Remote Monitoring and Tracking of Animals, Editors Priede I.G. and Swift S.M. Published by Ellis Horwood Series in Environmental Management, Science and Technology.

Mills M.J. *et al* (1991). A Study of the Migratory Behaviour of Salmon in Relation to Critical Environmental Criteria in the Usk Estuary, National Rivers Authority, Welsh Region, SE Area, Report Number **EAE/91/3**.

Milner N.J. (1985). The Influence of River Flow on Glaslyn Sea Trout Net Catches, National Rivers Authority, Welsh Region, N Area, Technical Memorandum, Report Number **PL/EAN/TM07**.

Milner, N.J. (1989). First movements in relation to freshwater flow and quality, Atlantic Salmon Trust/Wessex Water, Workshop proceedings

Potter, E.C.E. (1988). Movements of Atlantic salmon in an estuary in South-West England. J.Fish.Biol. 33 (Suppl.A), p153-159.

Potter, E.C.E., Solomon D.J., Buckley A.A. (1992). Estuarine Movements of Adult Atlantic Salmon *Salmo salar* L., in Christchurch Harbour, Southern England. In Wildlife Telemetry Remote Monitoring and Tracking of Animals, Editors Priede I.G. and Swift S.M. Published by Ellis Horwood Series in Environmental Management, Science and Technology.

Priede, I.G. et al (1988). Behaviour of adult Atlantic salmon, *Salmo salar* (L.), in the estuary of the River Ribble in relation to variations in dissolved oxygen and tidal flow. J.Fish.Biol. **33** (suppl. A), p133-139.

Sambrook H. and Broad K. (1988). Roadford Water Resources Scheme: Migration of Atlantic Salmon in the River Tamar. In, Proceedings of the Atlantic Salmon Trust Workshop (1989), Edited by N.J. Milner.

Solomon, D.J. (1988). Fish Passage through Tidal Energy Barrages, Contractor Report Number, **ETSU TID 4056**.

Solomon D.J. (1992). Hampshire Avon, Salmon Tracking 1986-90, Final Report.

Solomon, D.J. and Potter, E.C.E. (1988). First results with a new estuarine fish tracking system. J. Fish. Biol. **33** (suppl. A), p127-132

Stonehewer R.O. *et al*(1993). A Draft Report on the Results of the Tawe Barrage Fisheries Impact Studies, 1993. National Rivers Authority Welsh Region, SW Area, Report Number **PL/EAW/93/6.**

Turnpenny et al (1992). Experimental Studies Relating to the Passage of Fish and Shrimps through Tidal Power Turbines, Report Prepared for Energy Technology Support Unit, Harwell.

Webb J. (1989). The Movements of Adult Atlantic Salmon in the River Tay, Scottish Fisheries Report Number **44**.

Webb J. (1990). The Behaviour of Adult Atlantic Salmon Ascending the Rivers Tay and Tummel to Pitlochry Dam. Scottish Fisheries Research Report Number **48**.

ACKNOWLEDGEMENTS.

The authors would like to take this opportunity to express their gratitude to a number of people who have been involved with the project in various guises during its three year existence.

To Ian Davidson, Richard Cove, Dave Clarke, Guy Mawle, Nigel Milner, Nick Frost, James Edwards and Ewan Campbell-Lendrum all of whom have contributed to the success of the project.

FIG.1. DEE SYSTEM

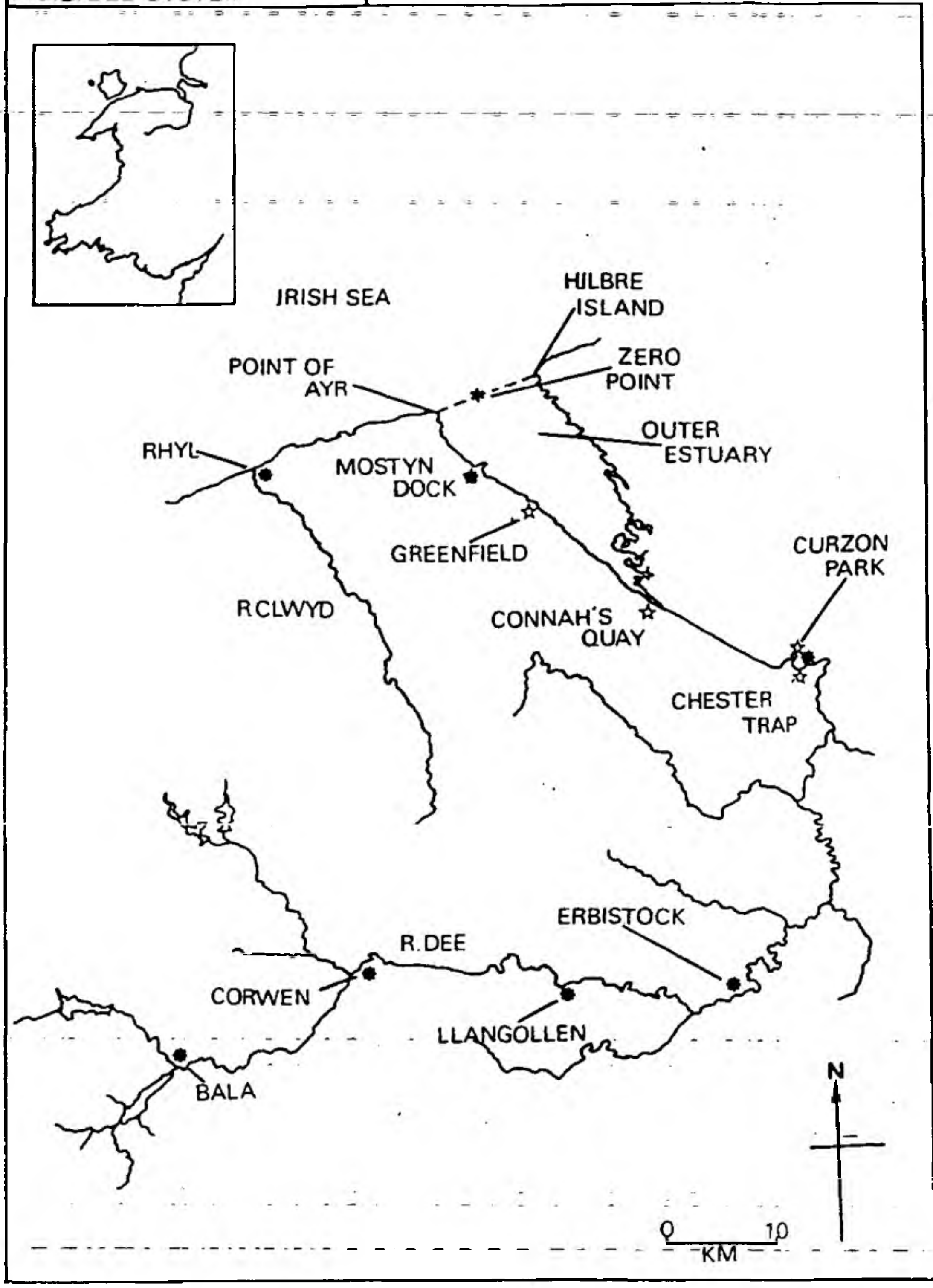


FIG. 2. DEE ESTUARY.

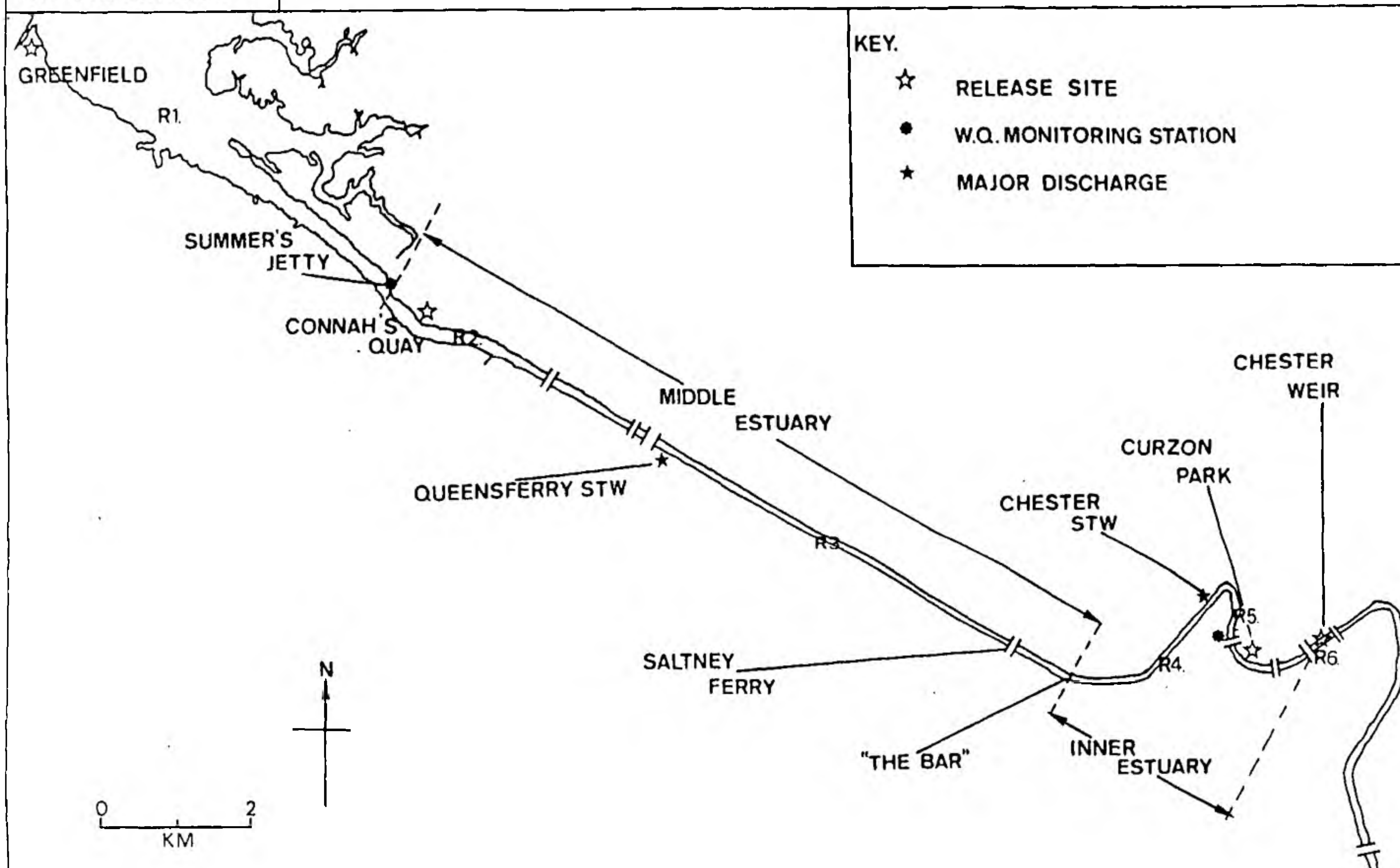


Fig. 3 Location of Chester Weir Fish Trap and Automatic Listening Stations(ALS).

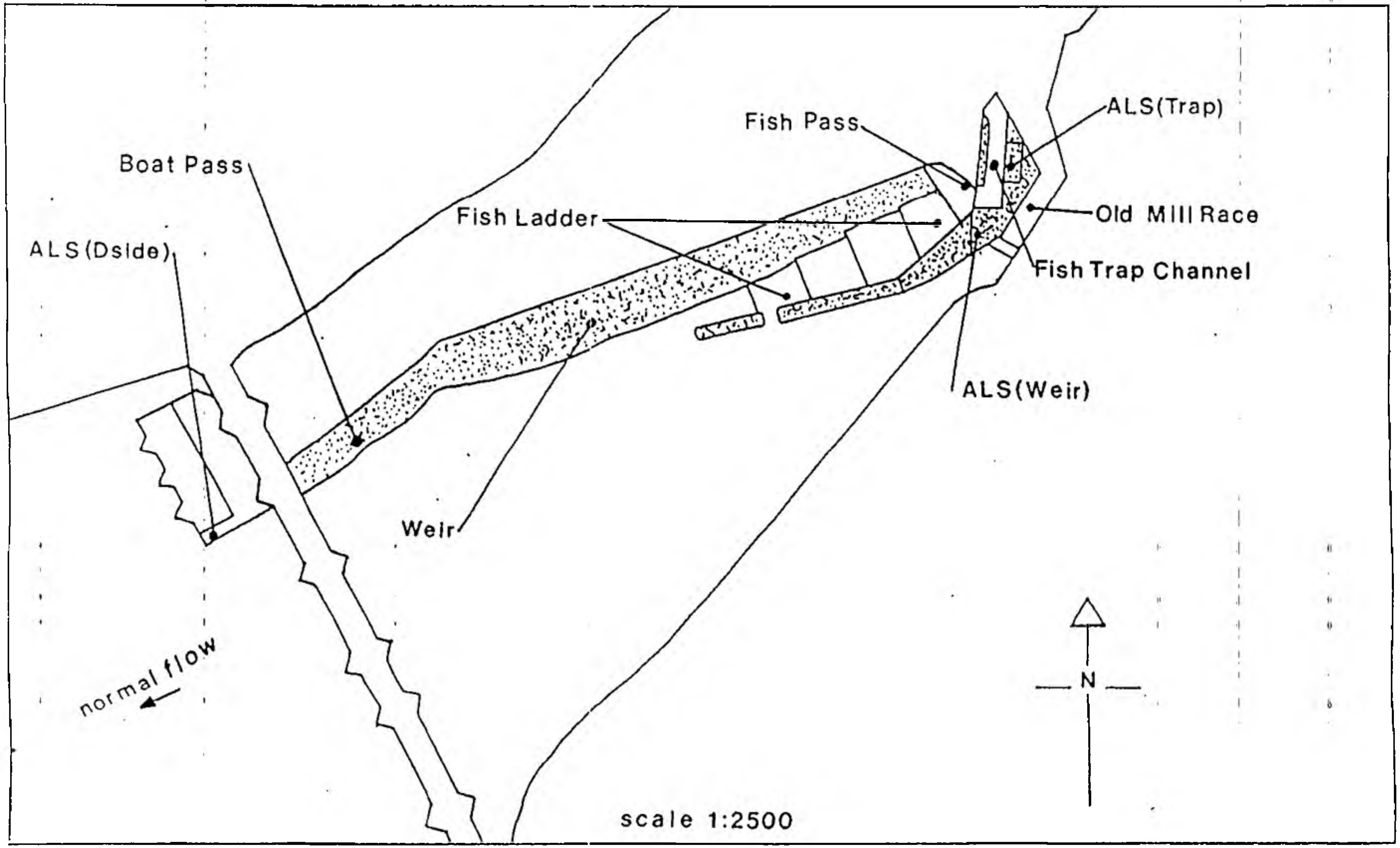


Fig.6. Time of Day of Release, Salmon Relocated from Chester Trap to the Middle Estuary, peak time 08:16h, "r"= 0.96, p<0.01 .

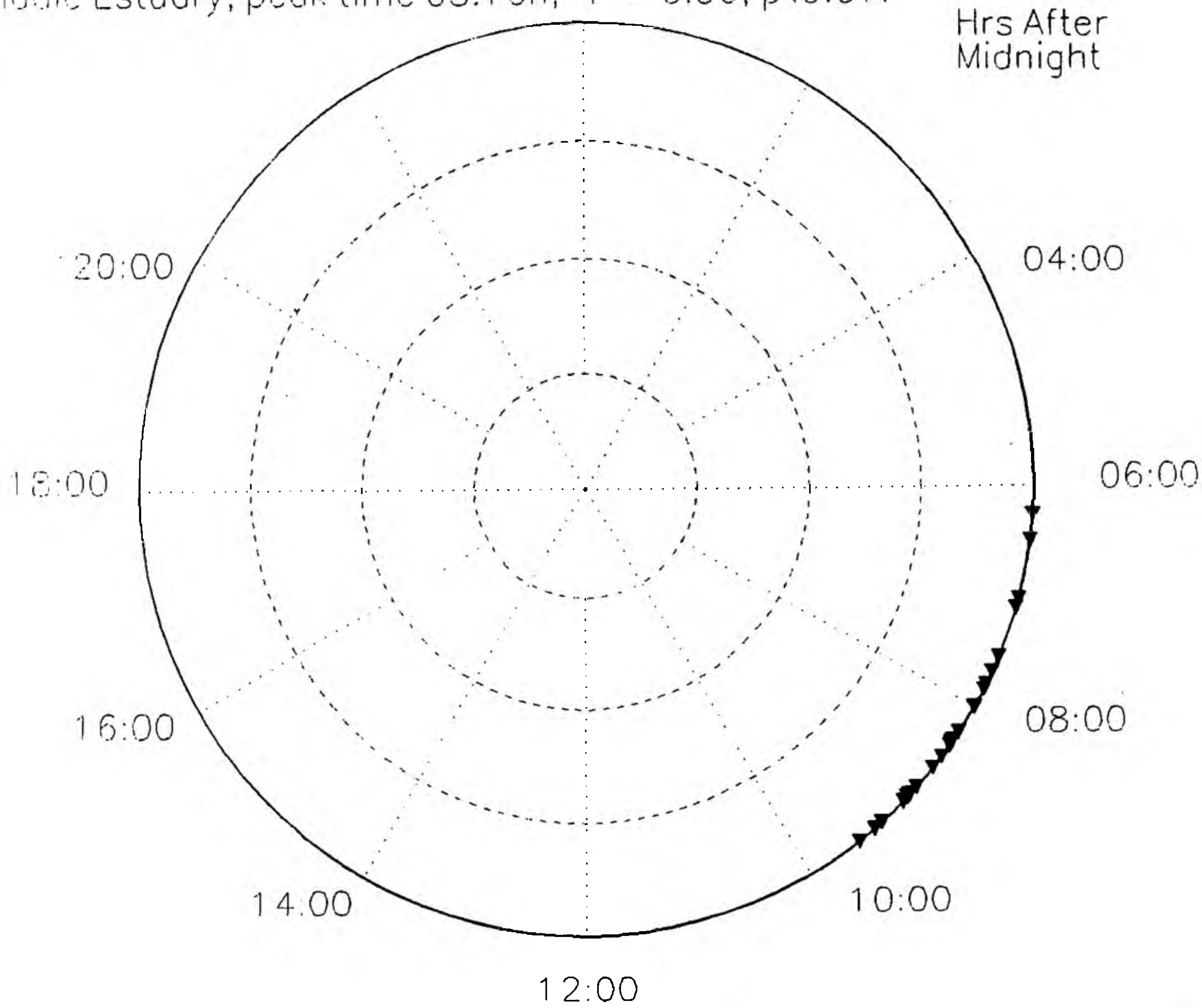


Fig.7. Distribution of Release Times in Relation to State of Tide.
Hours After HW Summer's Jetty

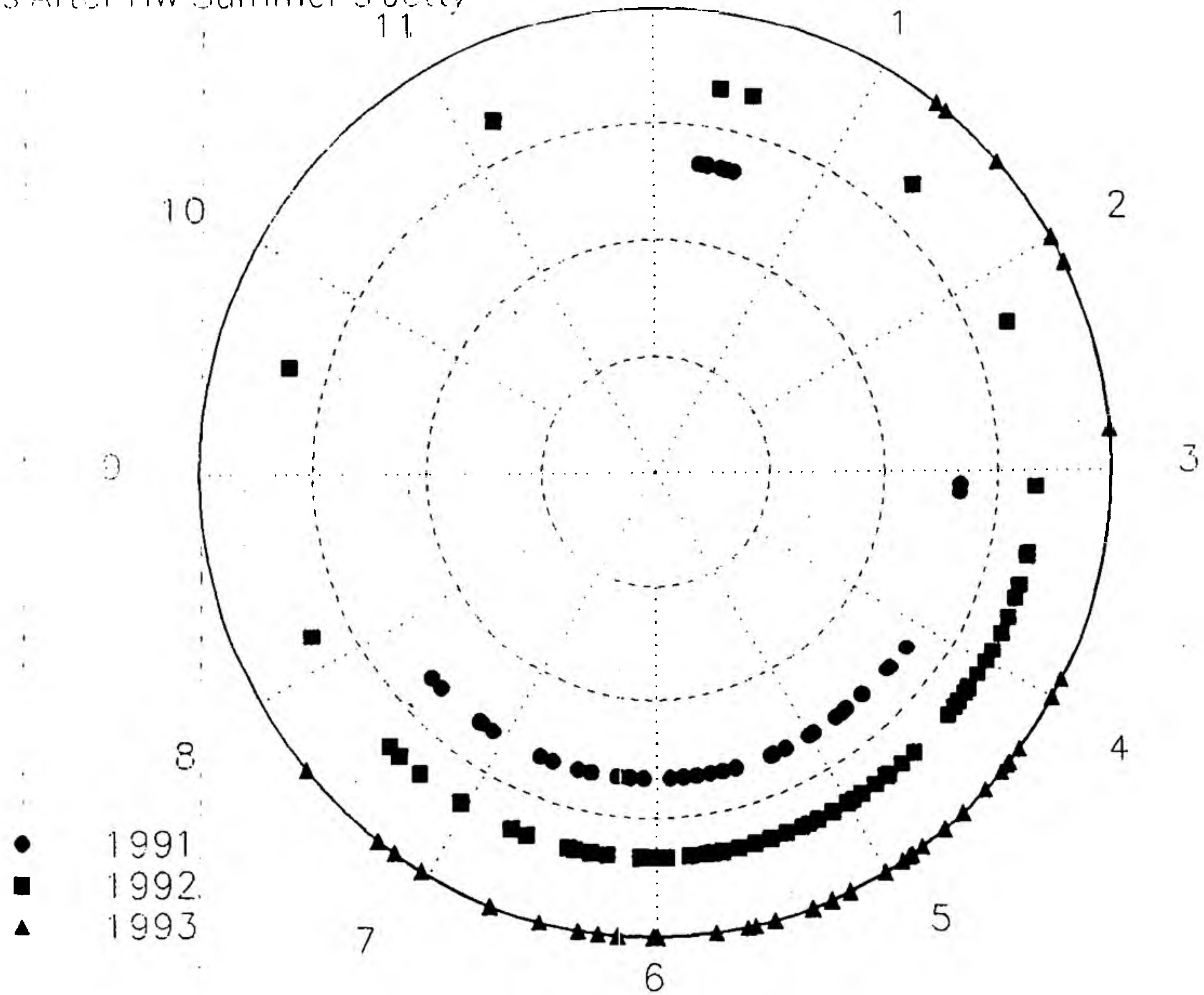


Fig.8. State of Tide at Release, Salmon Relocated to Connah's Quay, r= 0.190, Random.

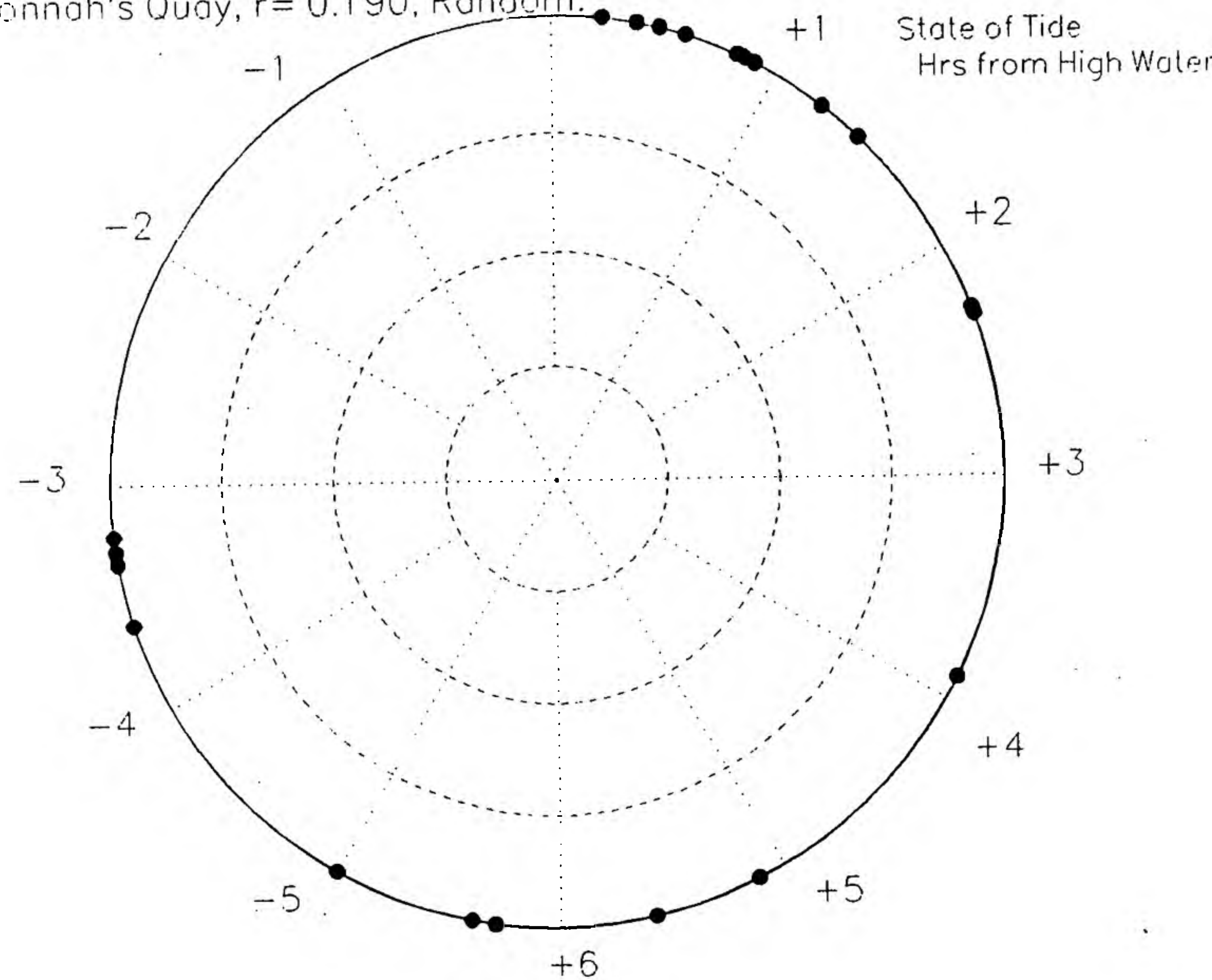


Fig.9. Distribution of Entry Times to Reach 3 Related to Time of Day for Connah's Quay Tagged Salmon, "r"=0.08, Random.

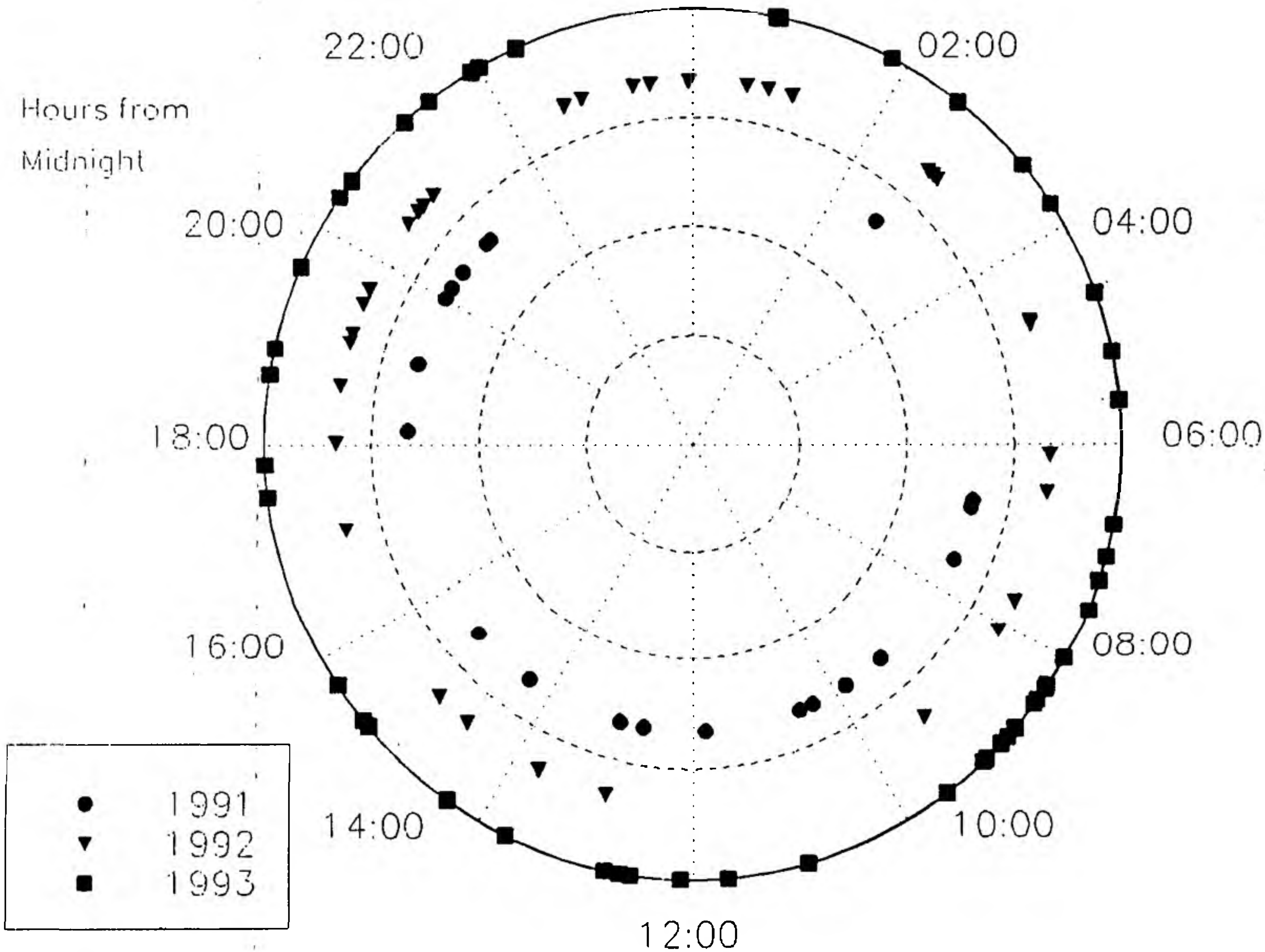


Fig. 10. State of Tide at Entry to Reach 3, Connah's Quay Tagged salmon, Non-Random, peak time, 02:24h from HW, "r"= 0.274, p< 0.05.

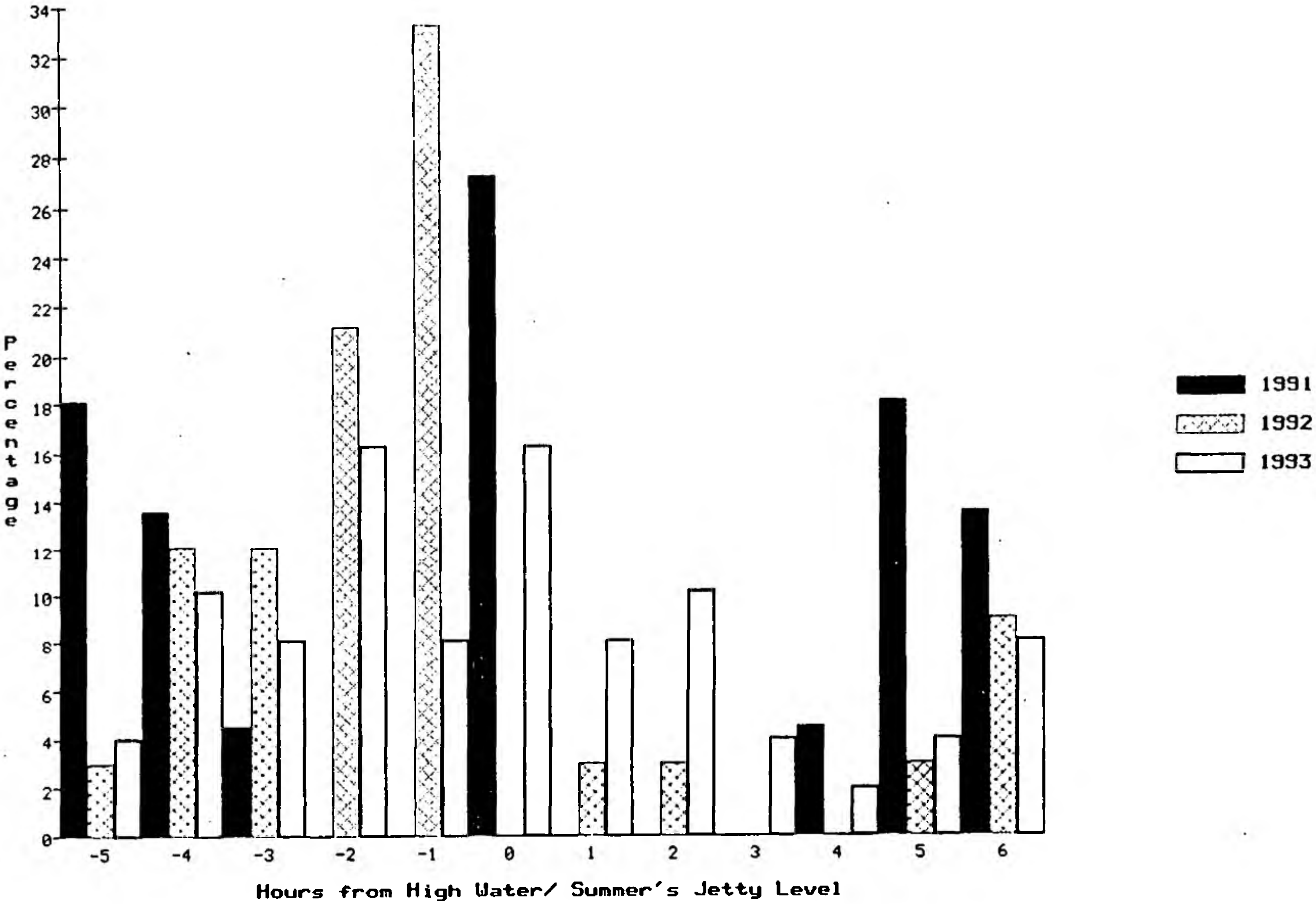


Fig. 11. Movements of salmon, number C2G723, in the Outer Dee Estuary.

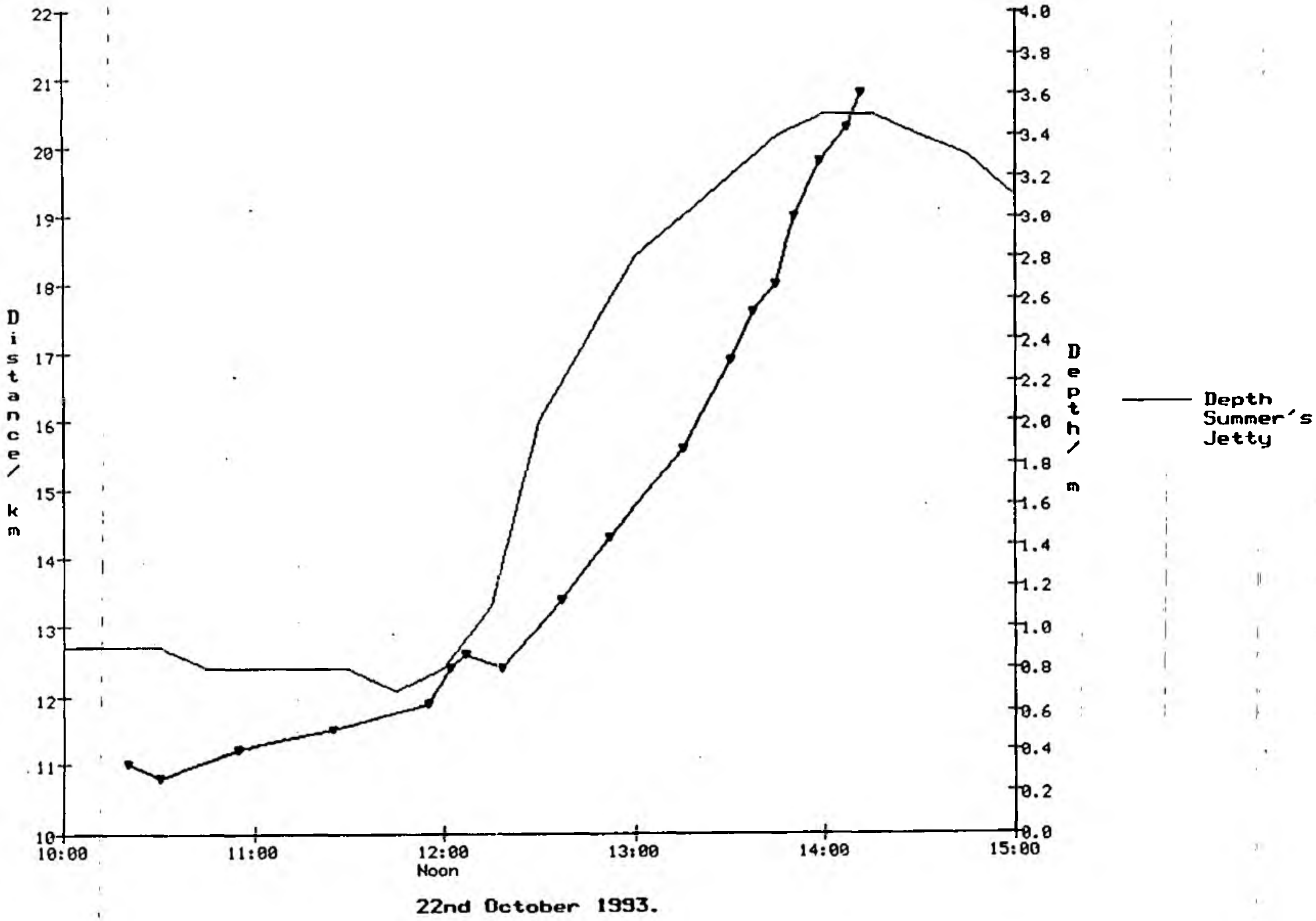
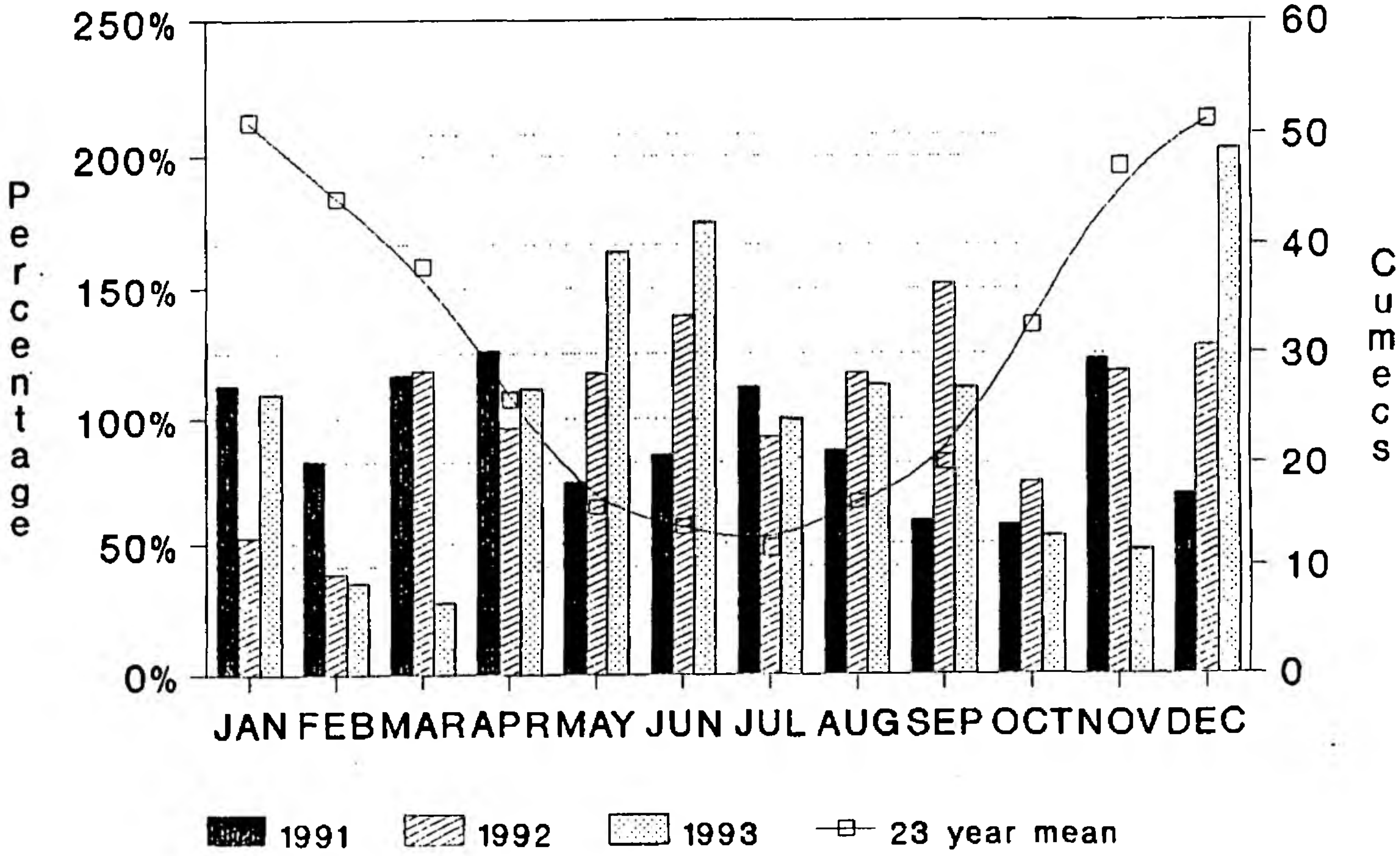
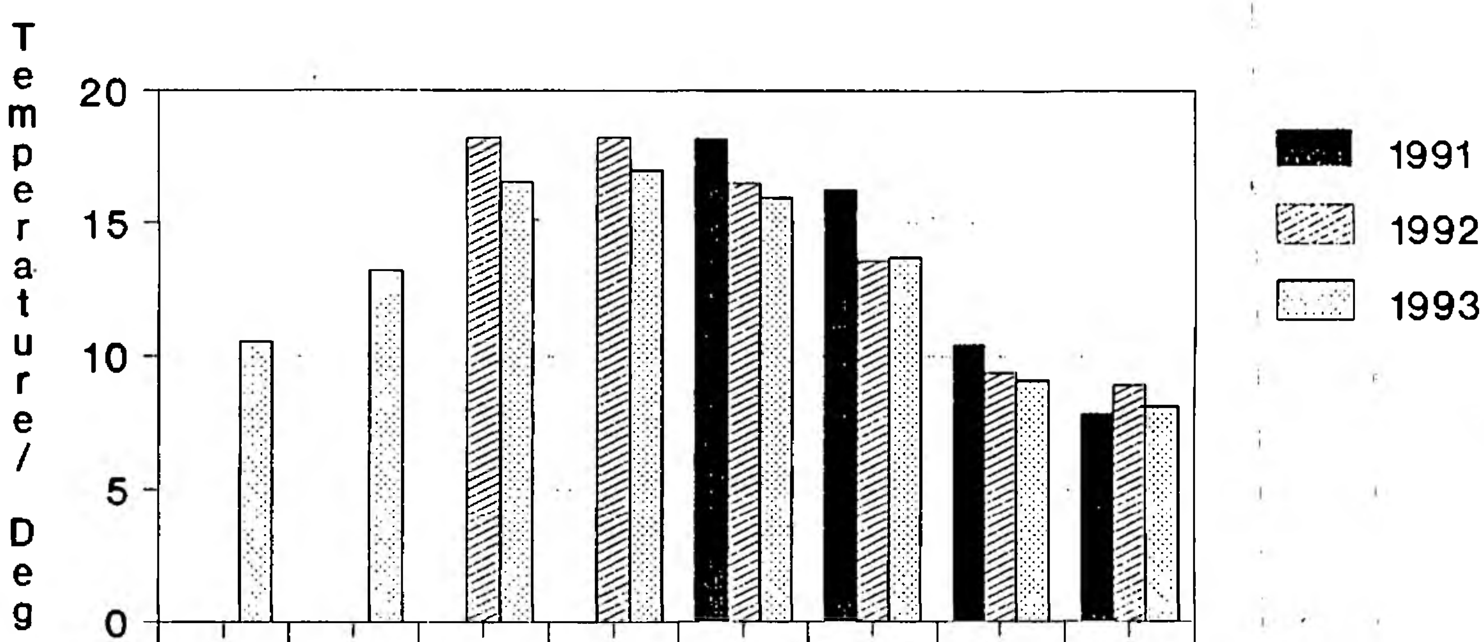


Fig. 12. Freshwater Flow during study as a percentage of the 23 year mean.



River Dee

Fig. 13. Comparison of Temperatures at Summer's Jetty between years.



	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
1991					18.21	16.26	10.41	7.84
1992			18.25	18.24	16.51	13.57	9.4	8.94
1993	10.54	13.21	16.55	17.02	15.95	13.68	9.09	8.13

Monthly Mean, Summer's Jetty

Fig. 16. Time of Travel of First Flood from Summer's Jetty to Different Points within the Dee Estuary on one Spring and one Neap Tide, 1990.

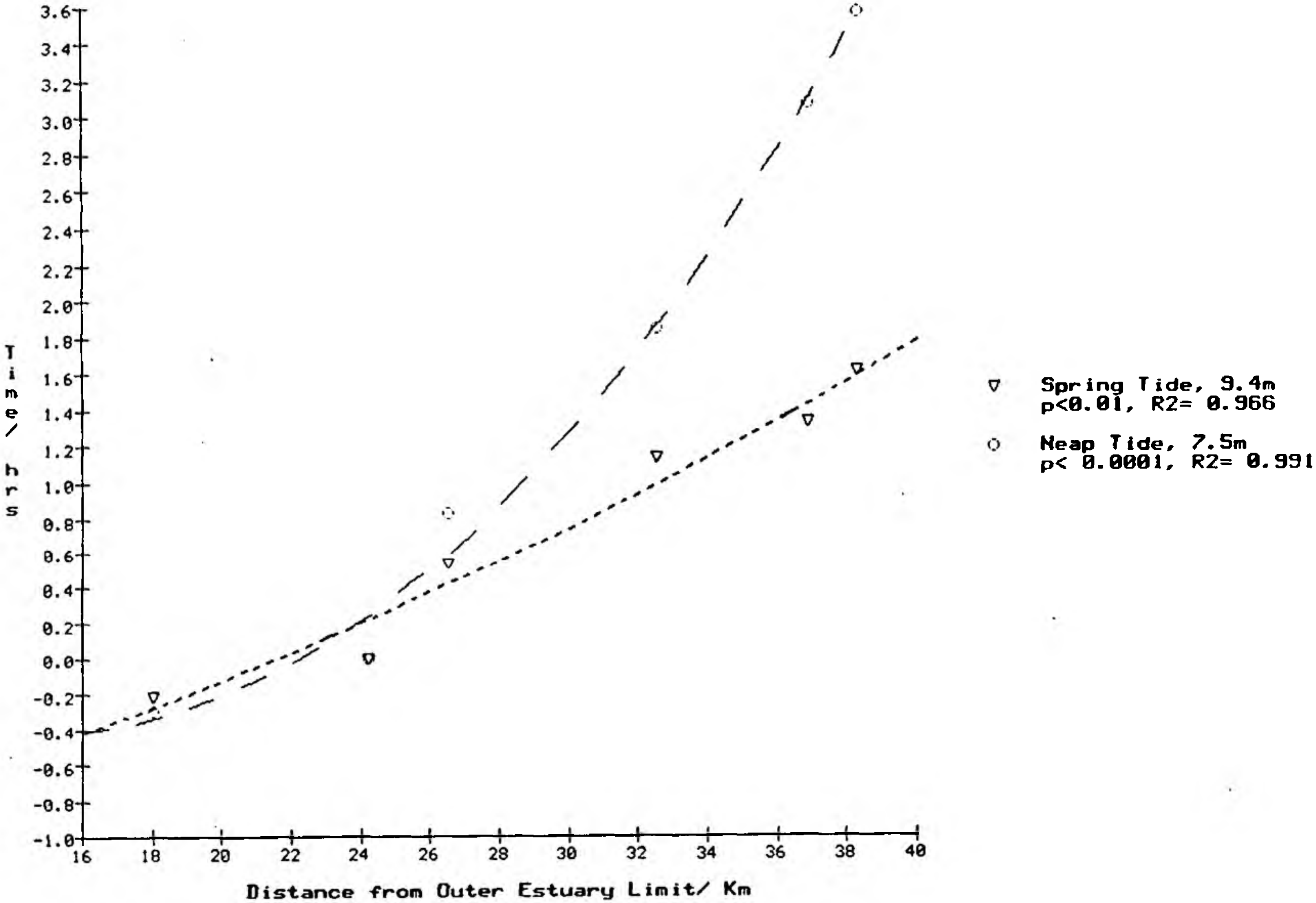


Fig. 17a). Trends in Dissolved Oxygen, Dee Estuary, Neap Tide.

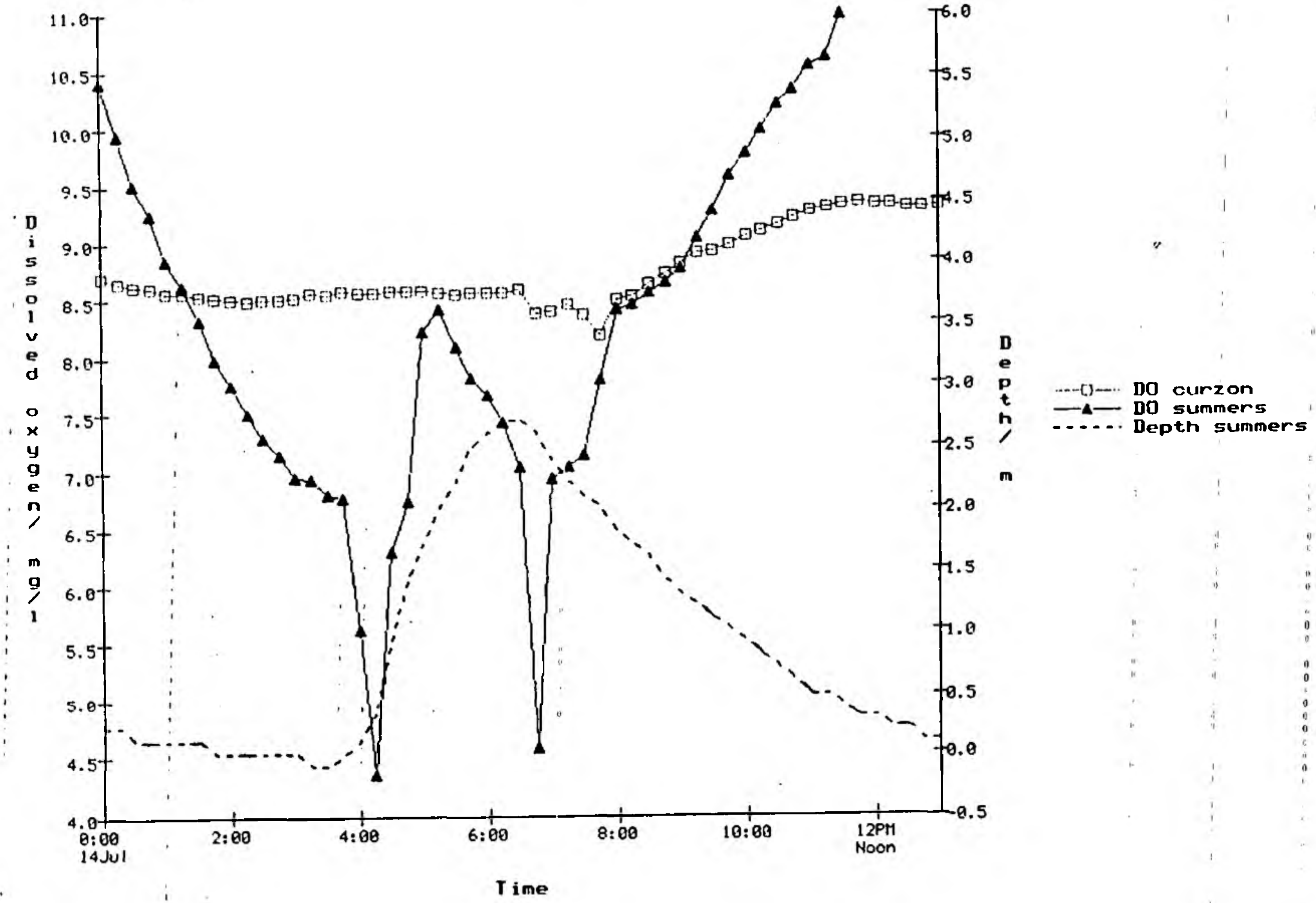


Fig. 17b). Trends in Temperature, Dee Estuary, Neap Tide.

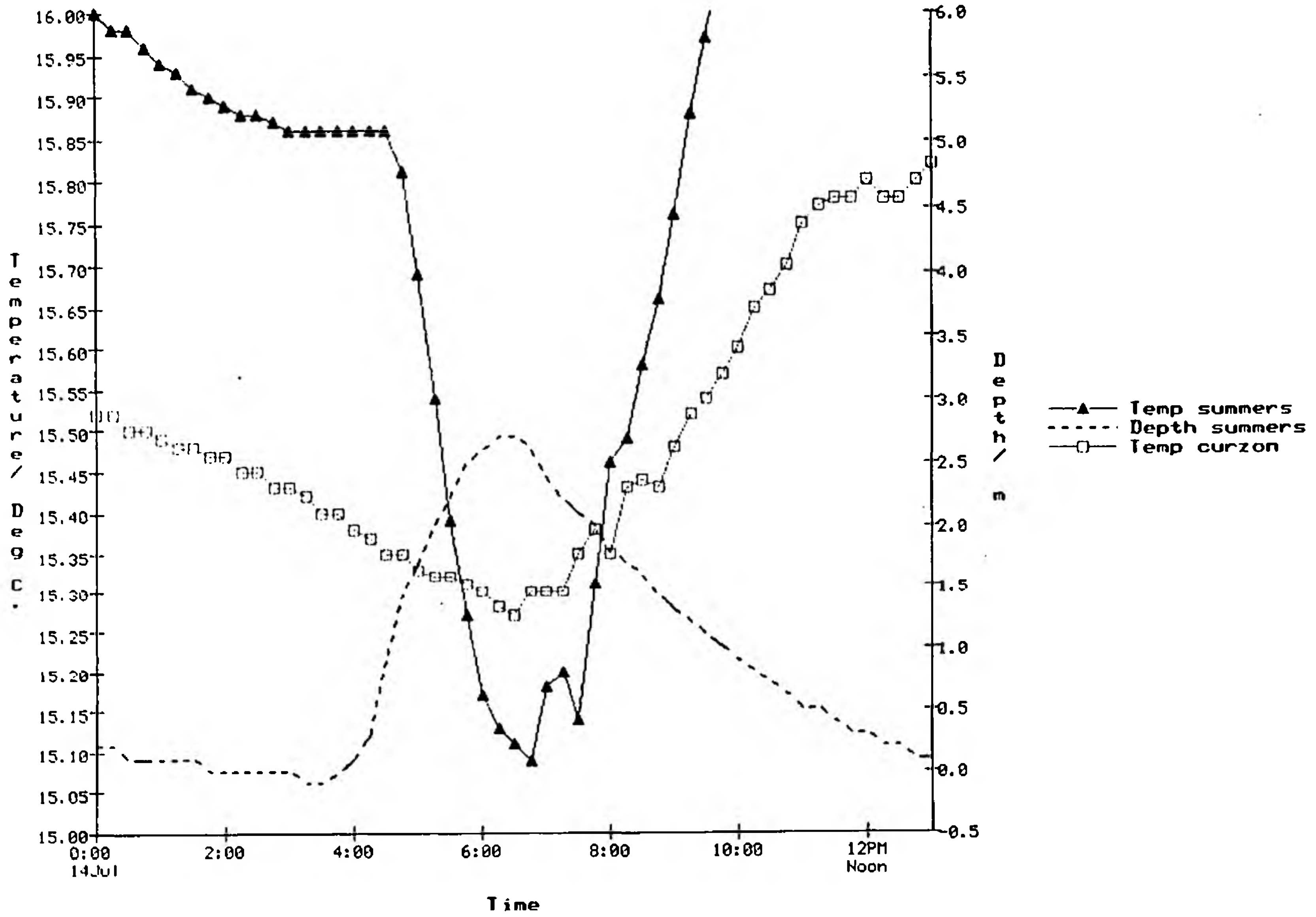


Fig. 18a). Trends in Dissolved Oxygen, Dee Estuary, Spring Tide.

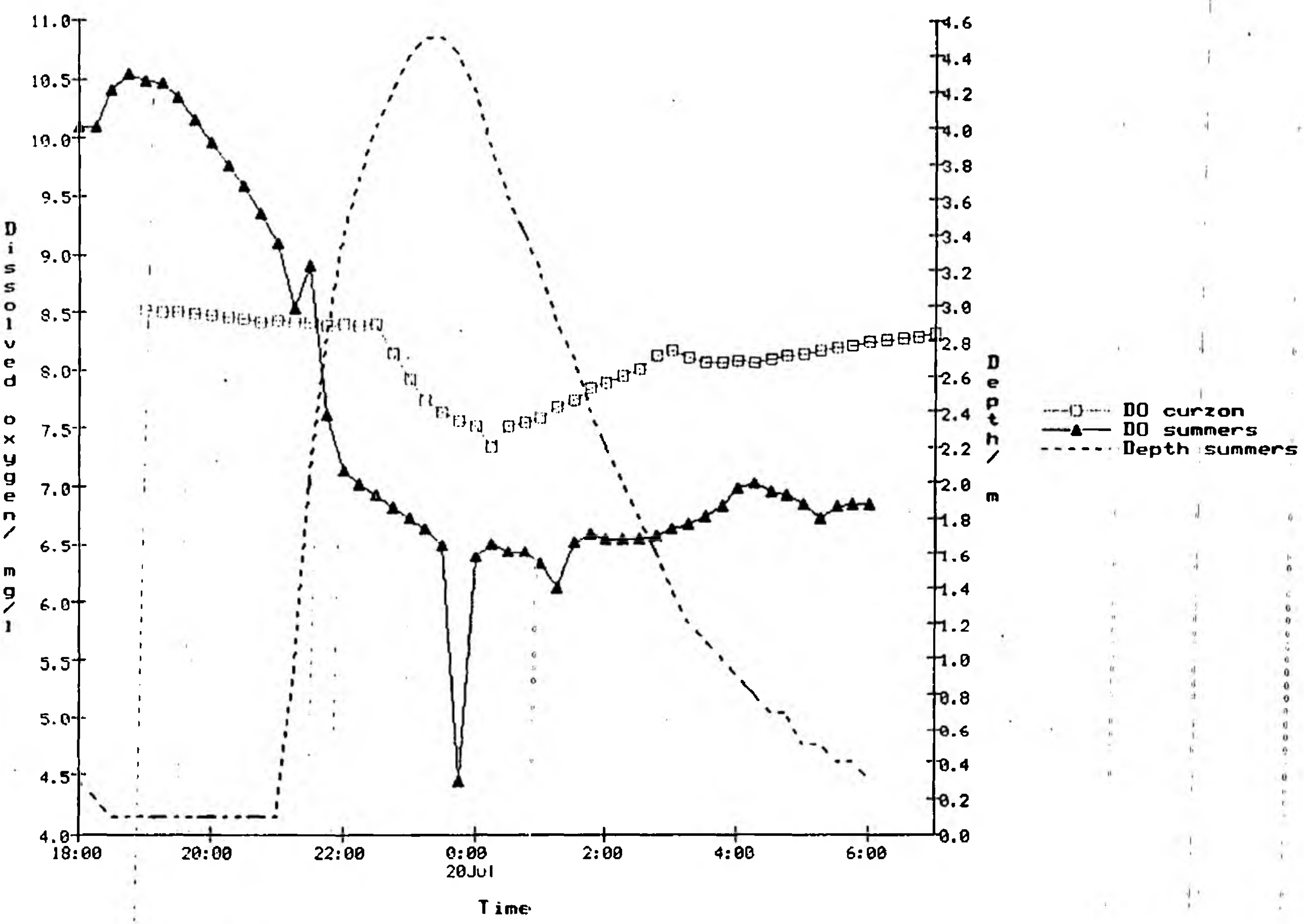


Fig. 18b). Trends in Temperature, Dee Estuary, Spring Tide.

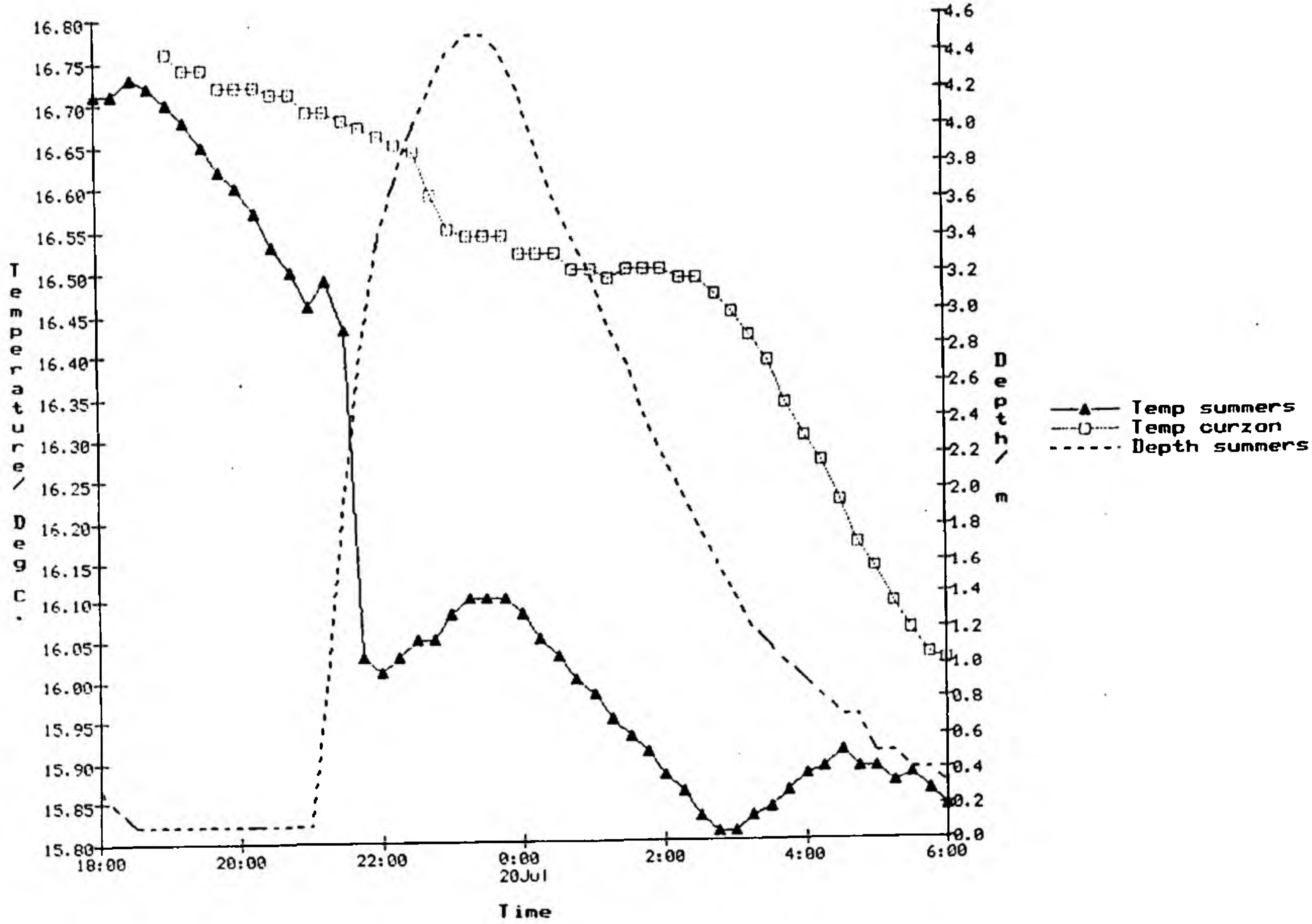


Fig. 19. Distribution of dissolved oxygen concentration at reach entry during upstream migration by radio-tagged salmon, Dee Estuary.

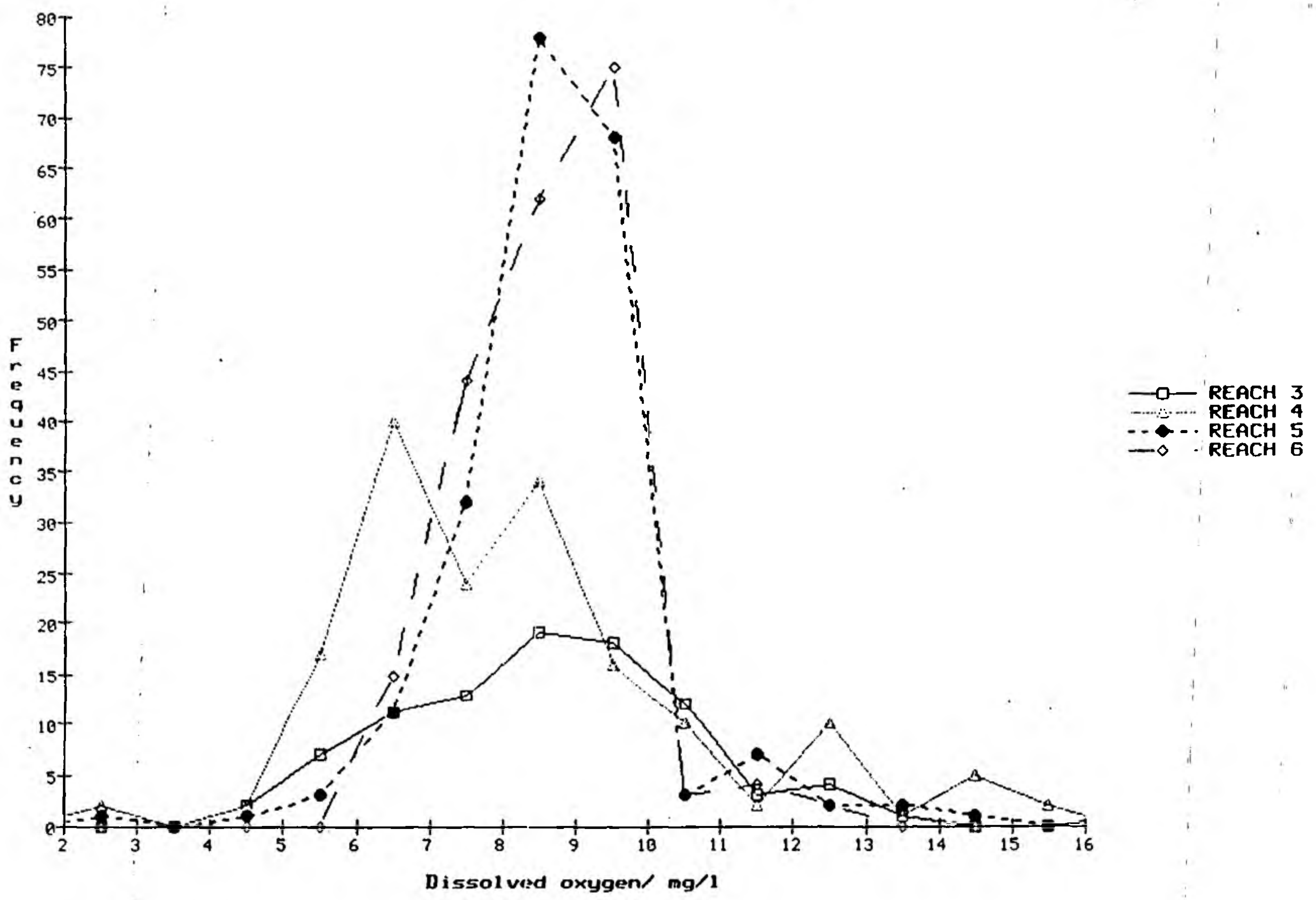


Fig. 20. Distribution of Temperatures at reach entry during upstream migration by radio-tagged salmon, Dee Estuary, 1991-93.

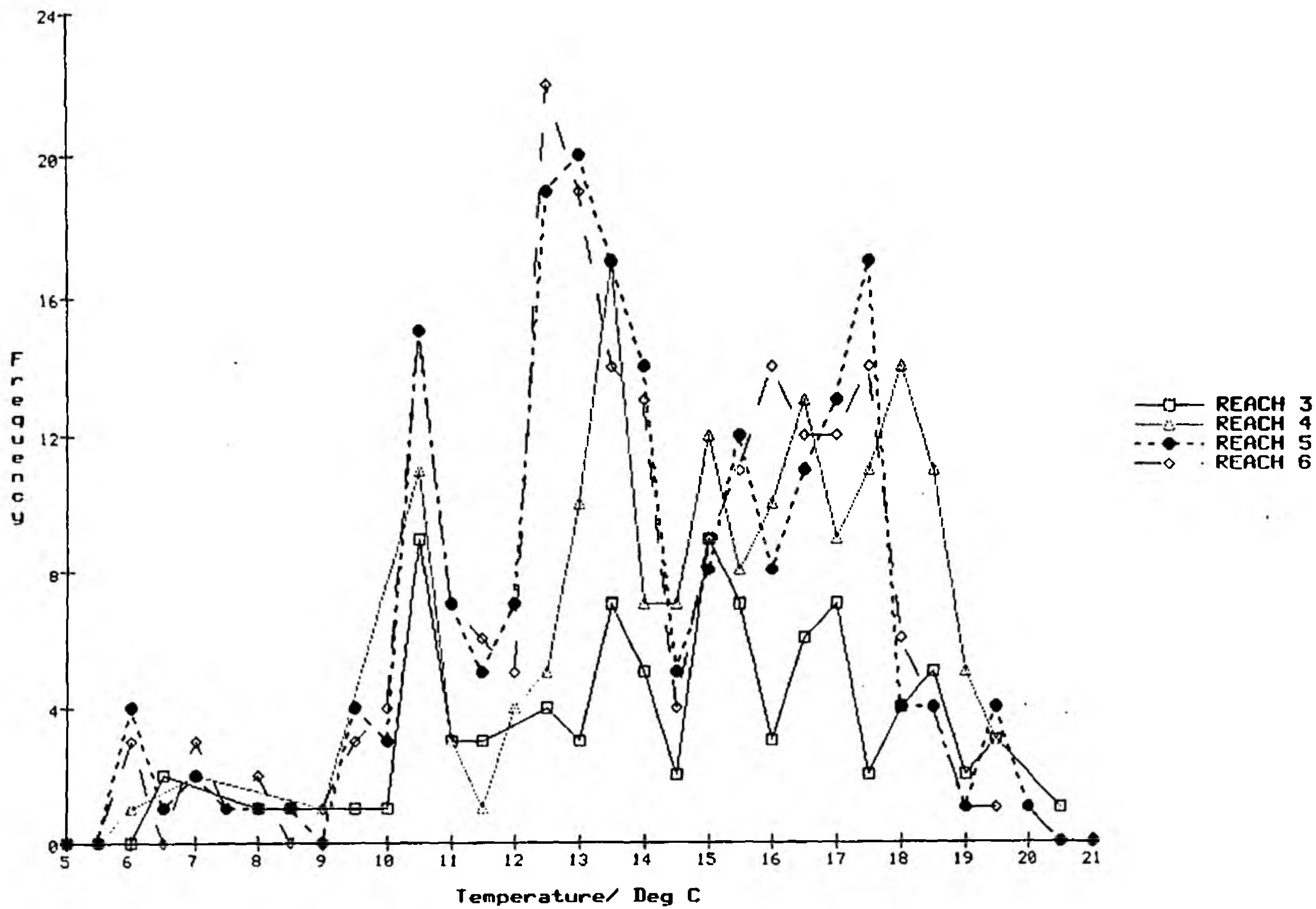


Fig. 21. Flow Distributions, Upstream Entry, by Reach, Dee Estuary.

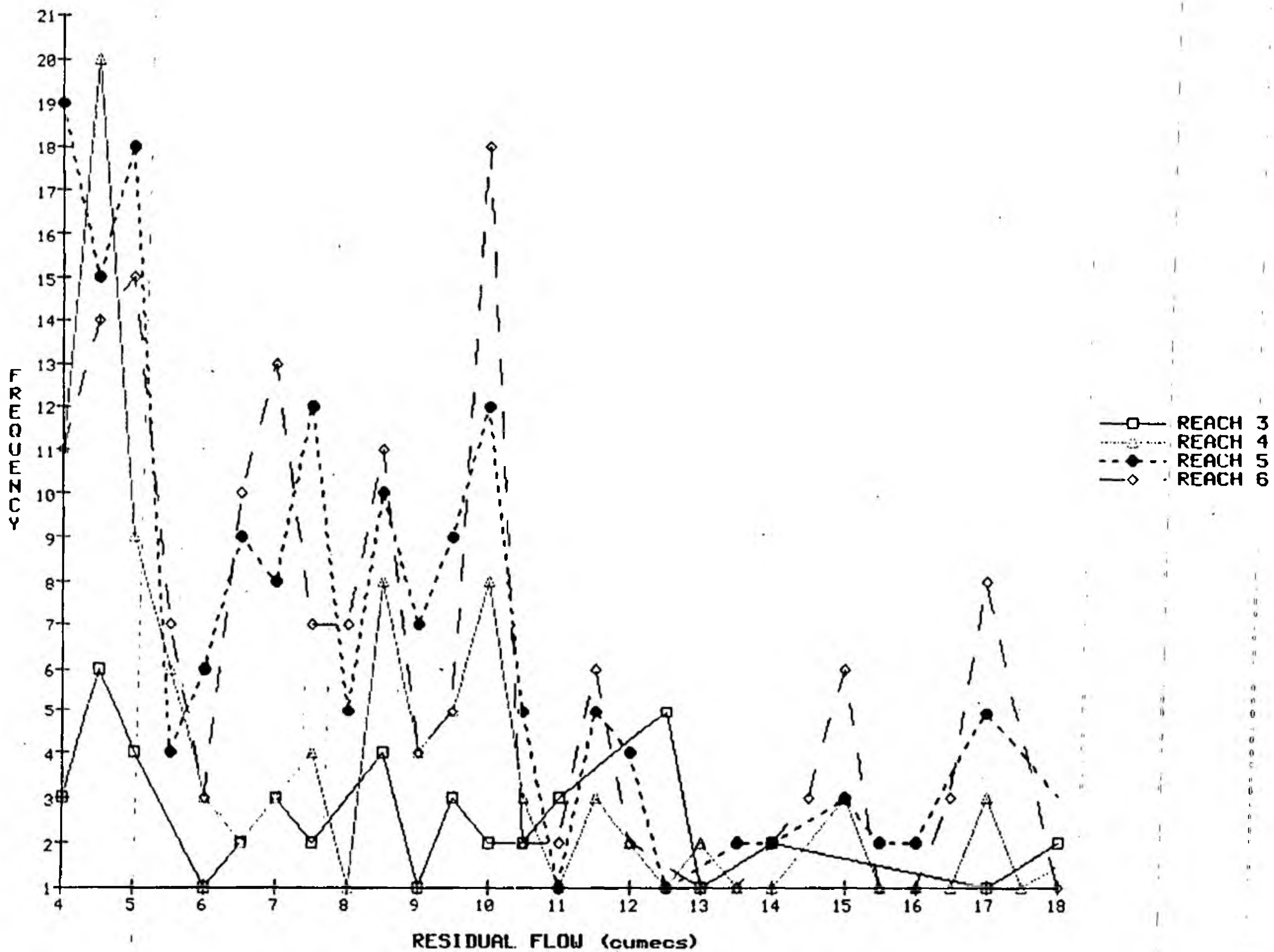


Fig. 22. Day of Week of arrival at Chester Weir for those salmon tagged at Connah's Quay either during or after the netting season.

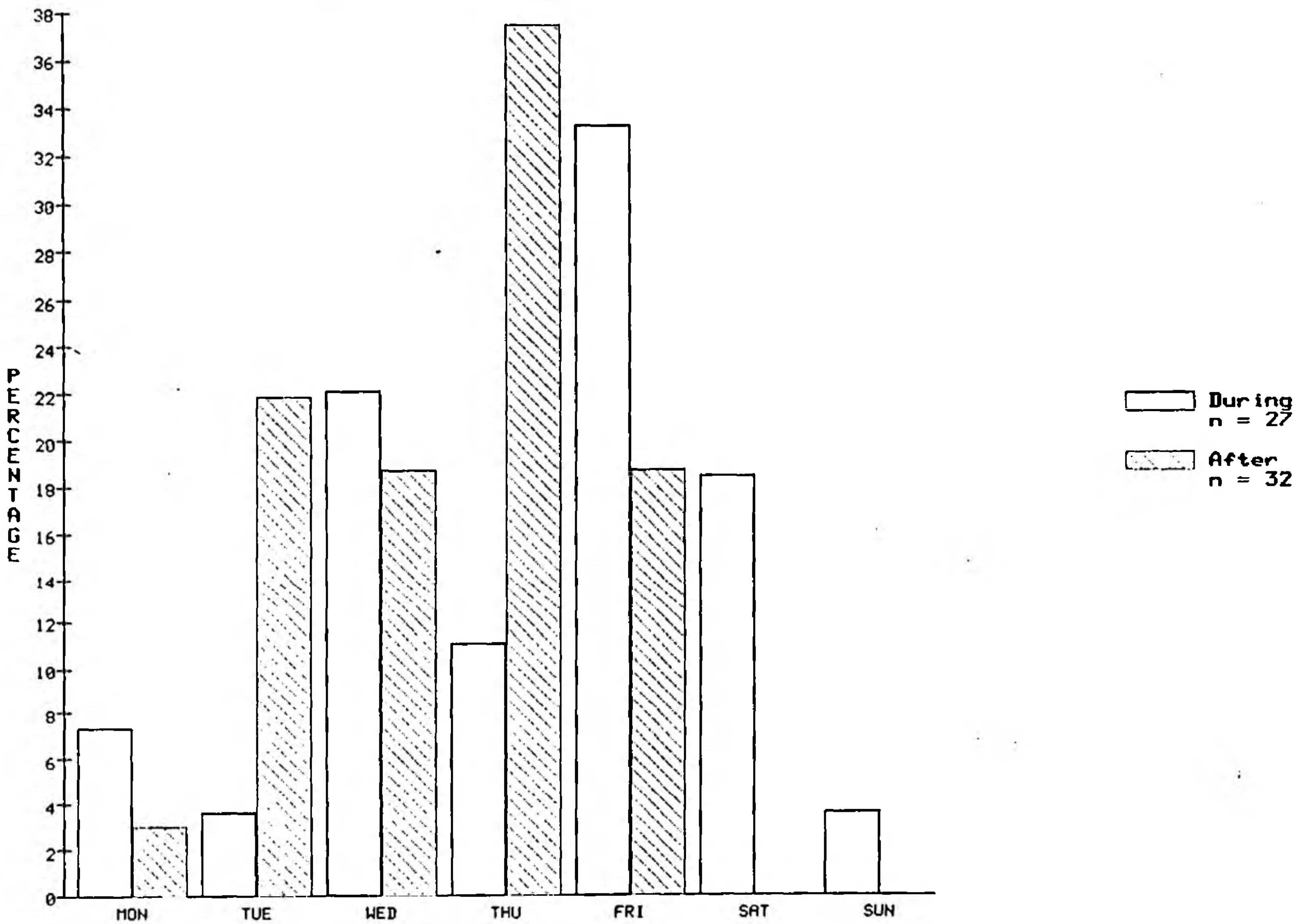


Fig. 23. Proportion of salmon tagged during the net season which successfully reached Chester Weir, related to day of tagging.

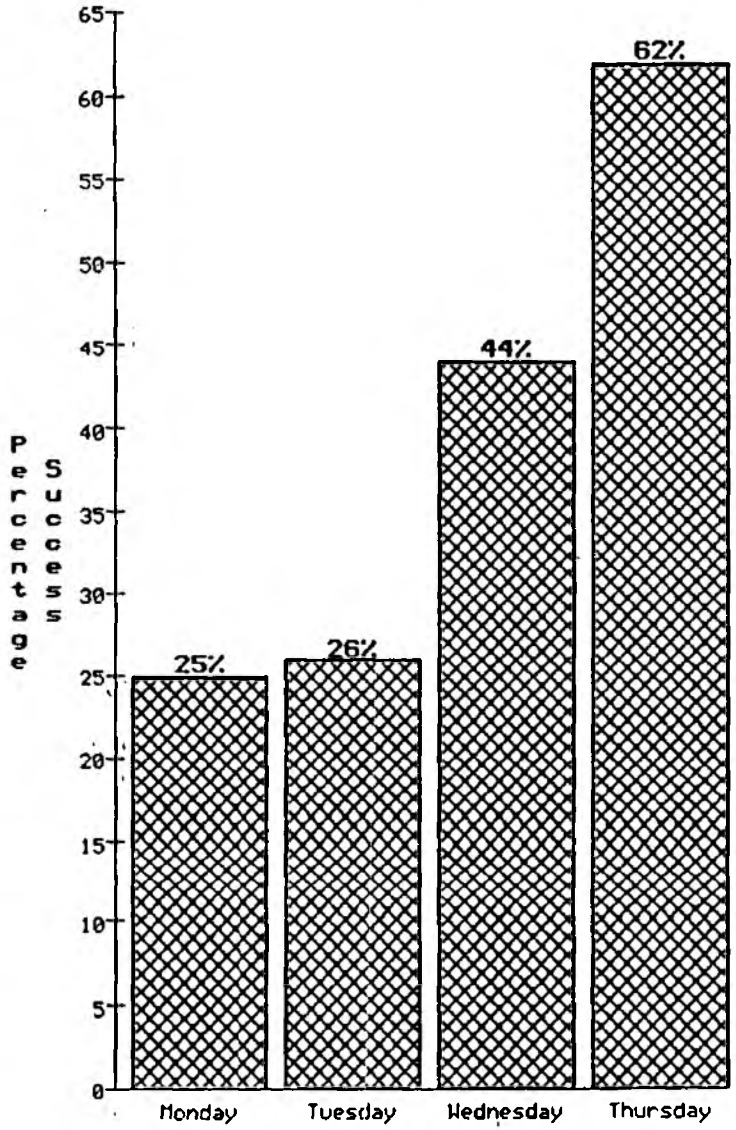


Fig. 24. Timing of Arrivals at Chester Weir, "r"= 0.189, p<0.05.

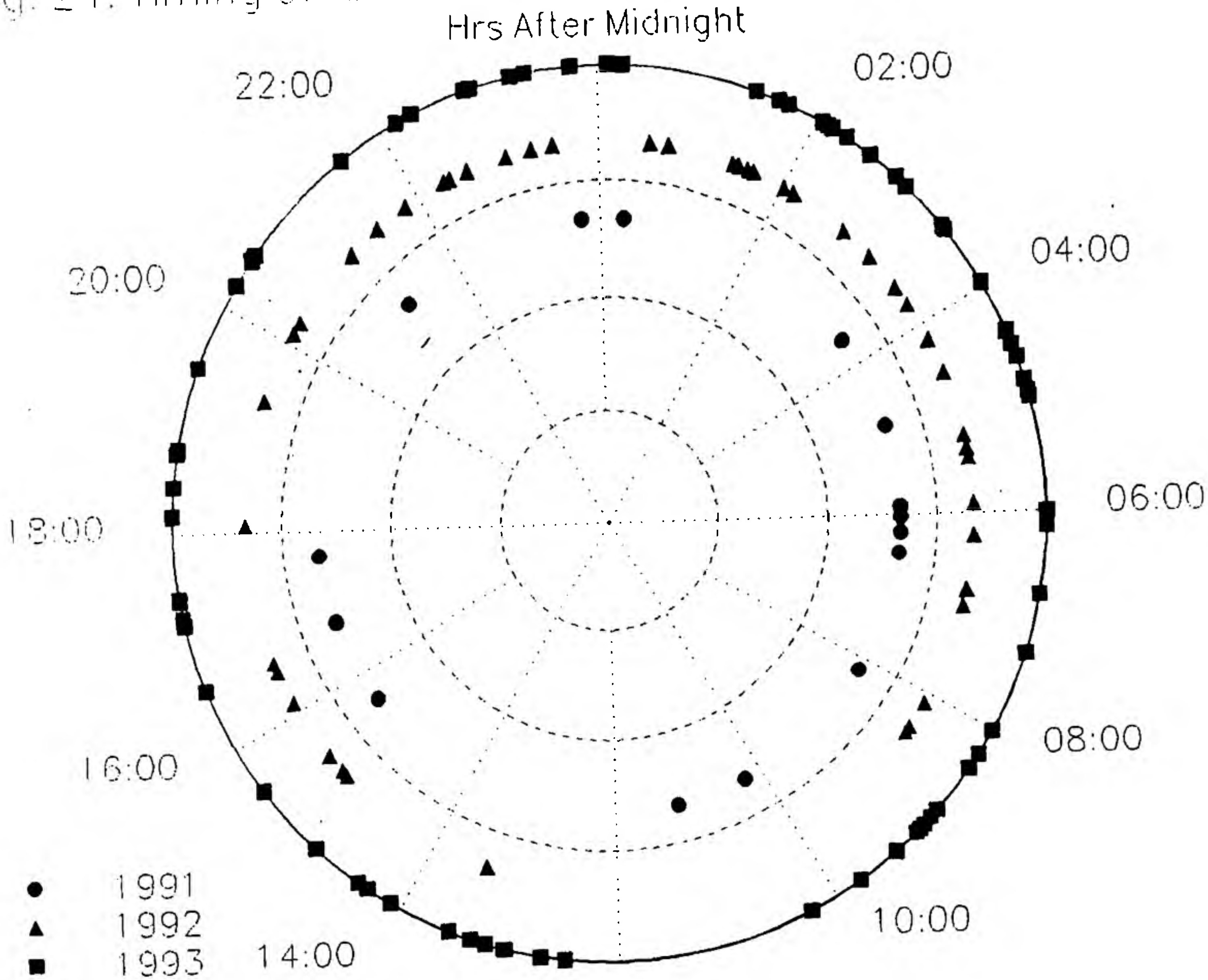


Fig.25. Distribution of Arrivals in the Inner Estuary Related to the State of Tide, peak time= 01:13h after HW, "r"=0.47, p<0.01 .

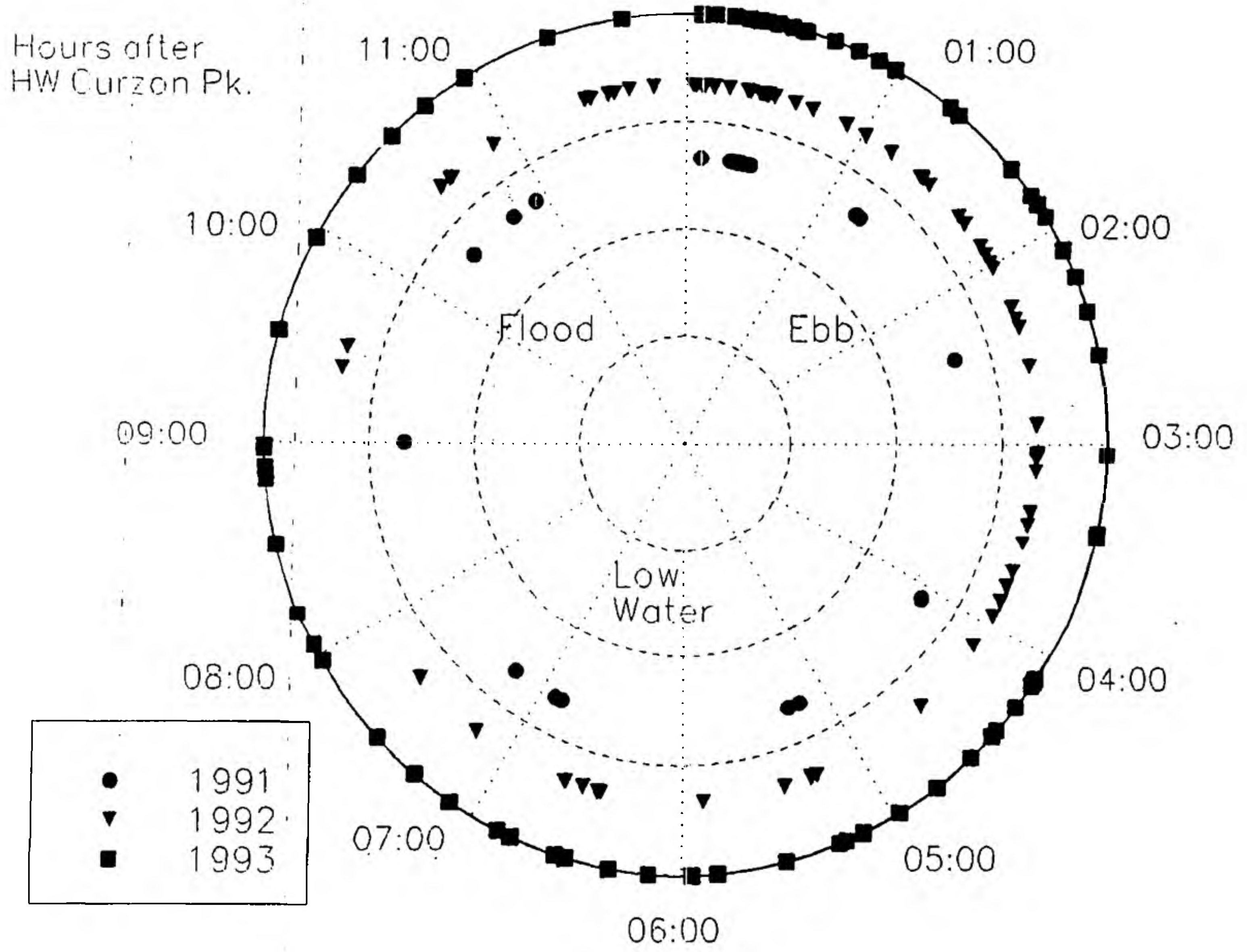


Fig. 26. Arrival of salmon in the vicinity of Chester Weir related to State of Tide, weighted average time 02:44h after HW, "r"= 0.327, p< 0.01.

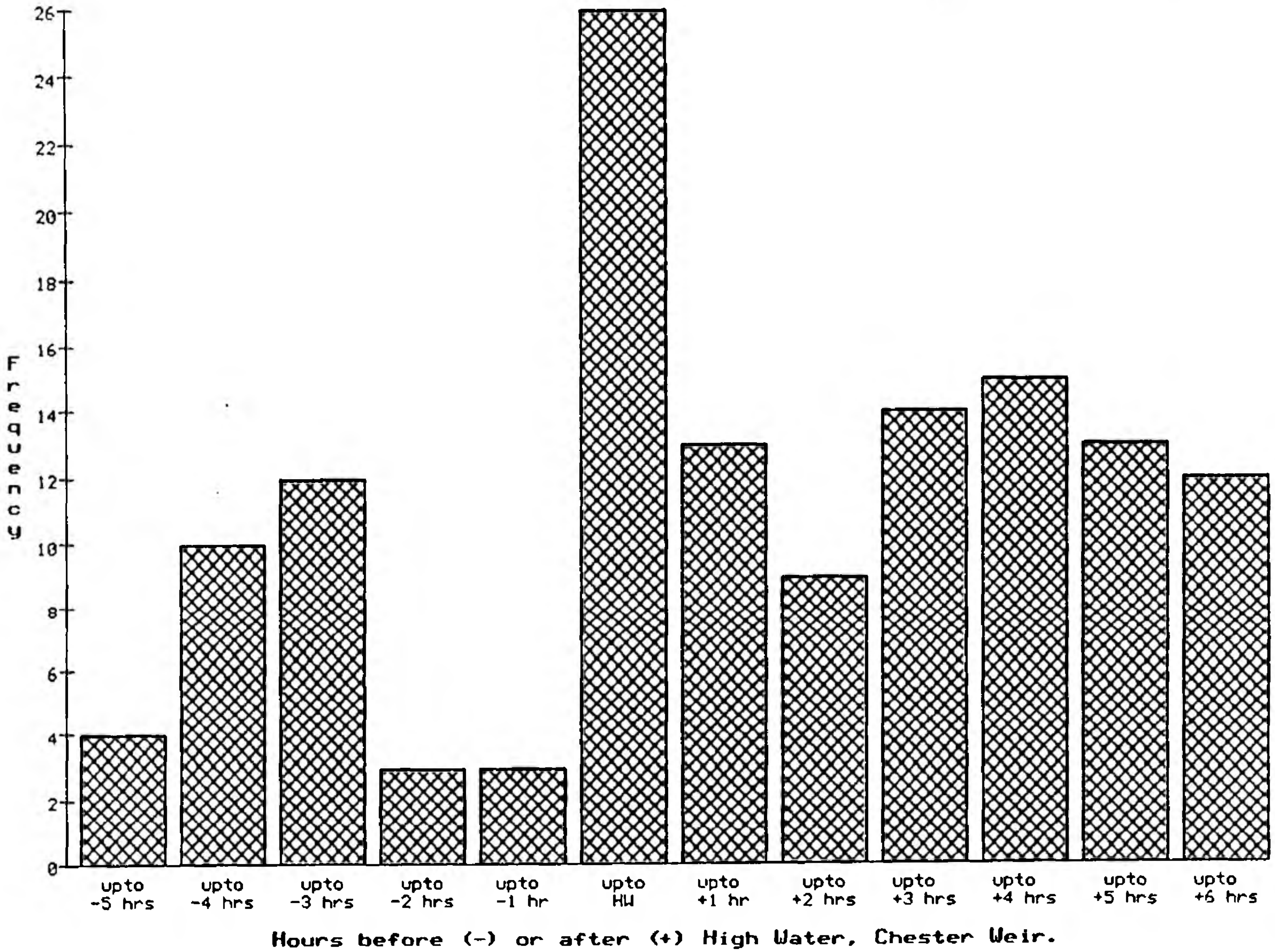
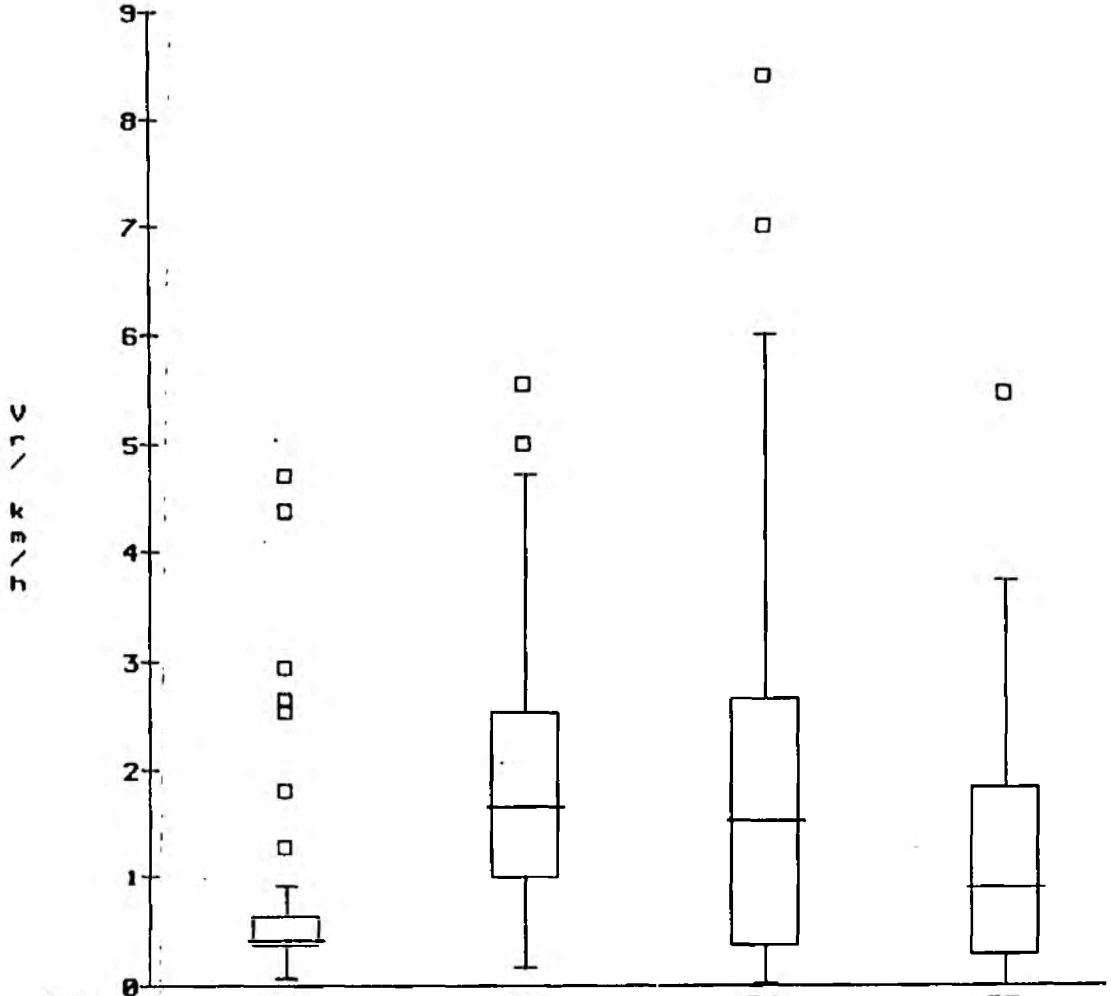


Fig. 27. Distribution of salmon net ground speeds (Vr) by reach tagged salmon, Dee Estuary 1991-93.



Reach	R2	R3	R4	R5
# Pts	57	69	160	189
Mean	0.72732	1.926738	1.796188	1.166065
IQR	0.278554	1.542247	2.314569	1.56044

Fig. 28. Salmon, number 2C2F108, showing atypical vacillation during flood tide assisted net upstream migration and subsequent displacement from the middle estuary. It was recaptured in the outer estuary and the behaviour suggests it may have strayed into the wrong estuary.

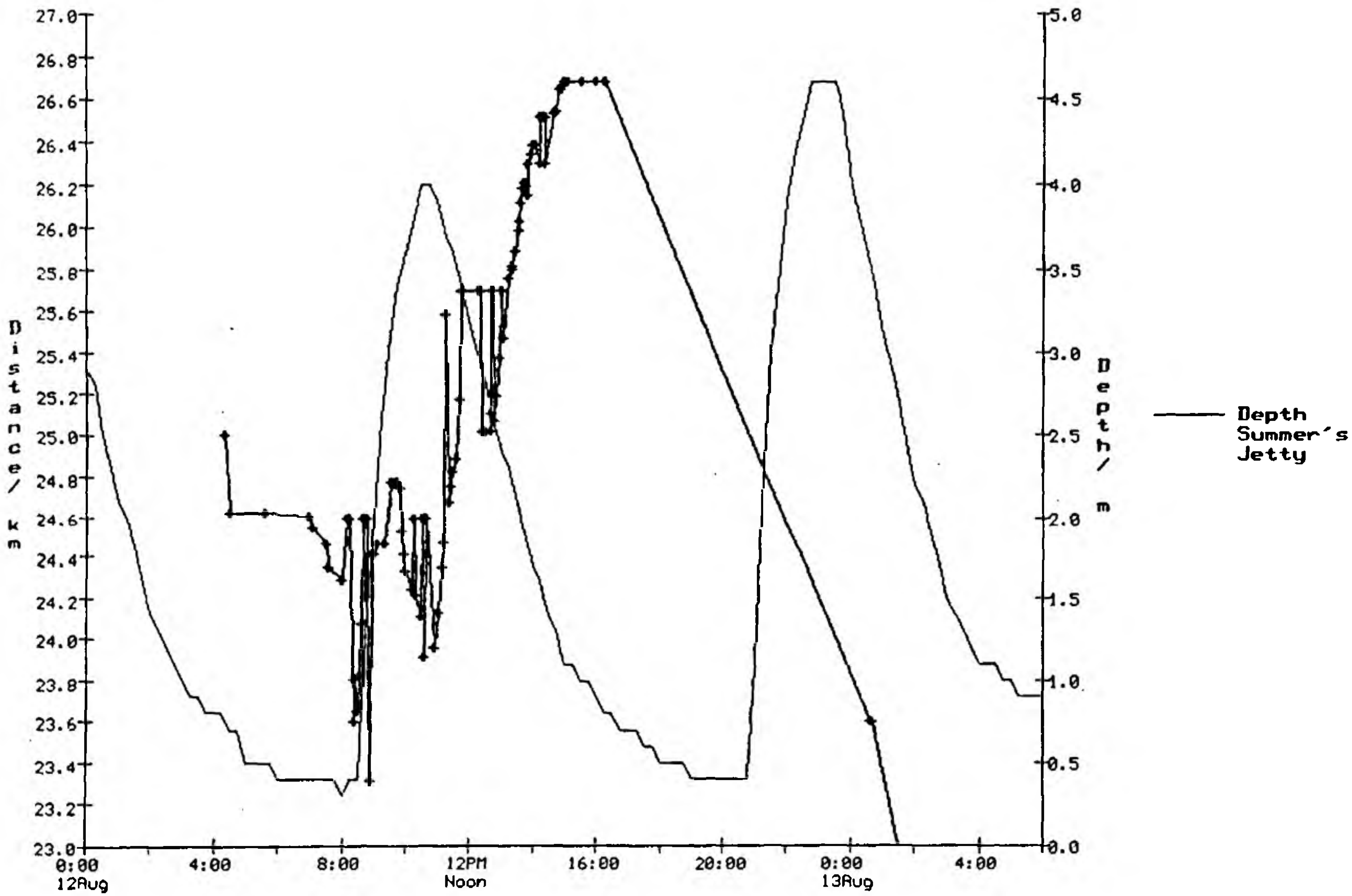


Fig. 29. Movements of Tagged salmon, C2F913.

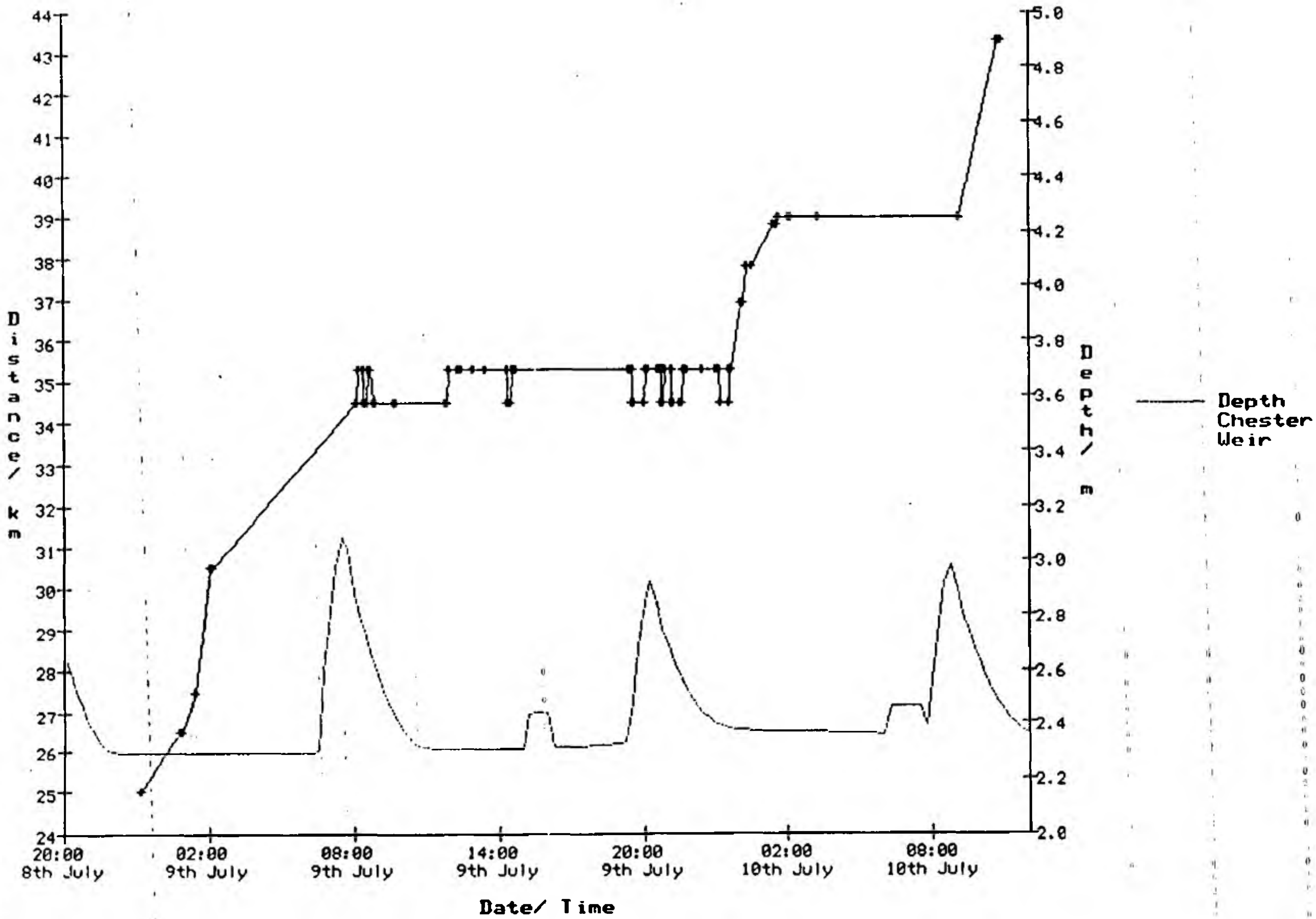


Fig. 30. Middle estuary ground speed (Vr) and mean tide height during estuarine migration, R Dee 1991-93.

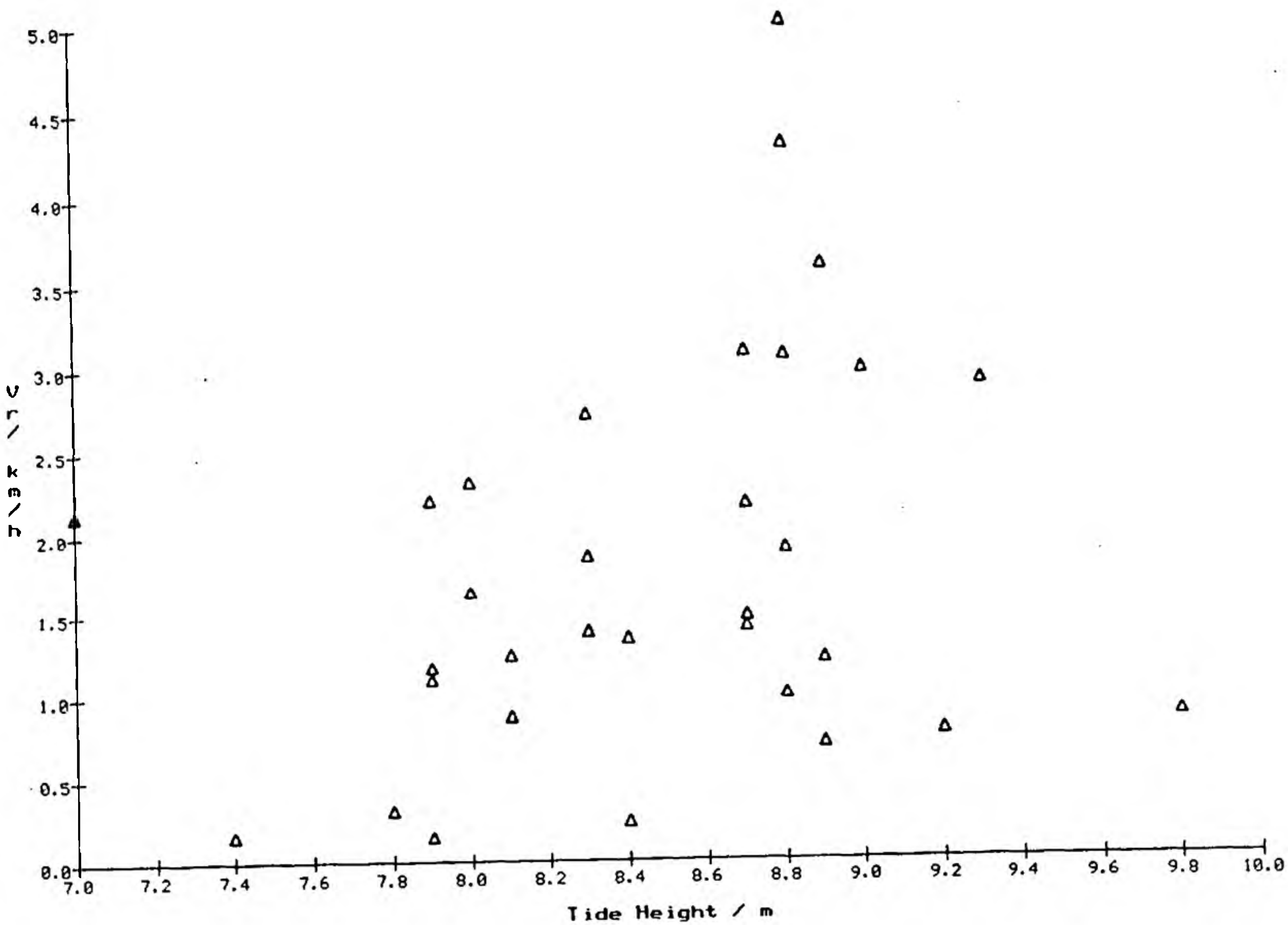


Fig. 31. Movements of Tagged salmon, C2F316, showing rapid response to flood tide and vacillation during net upstream progress at low water.

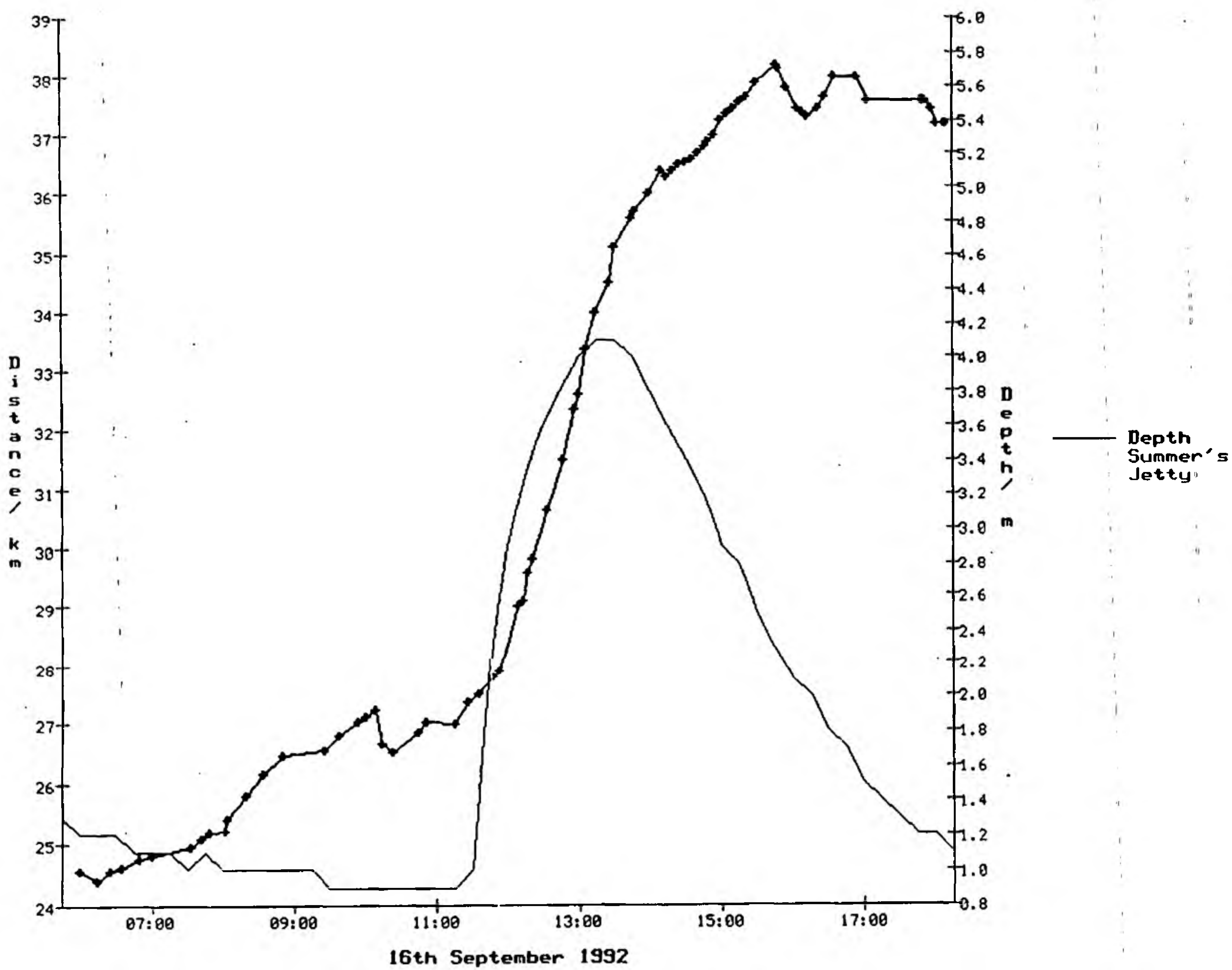


Fig.32. Rate of Migration in the Middle Estuary km/h, in relation to State of Tide.

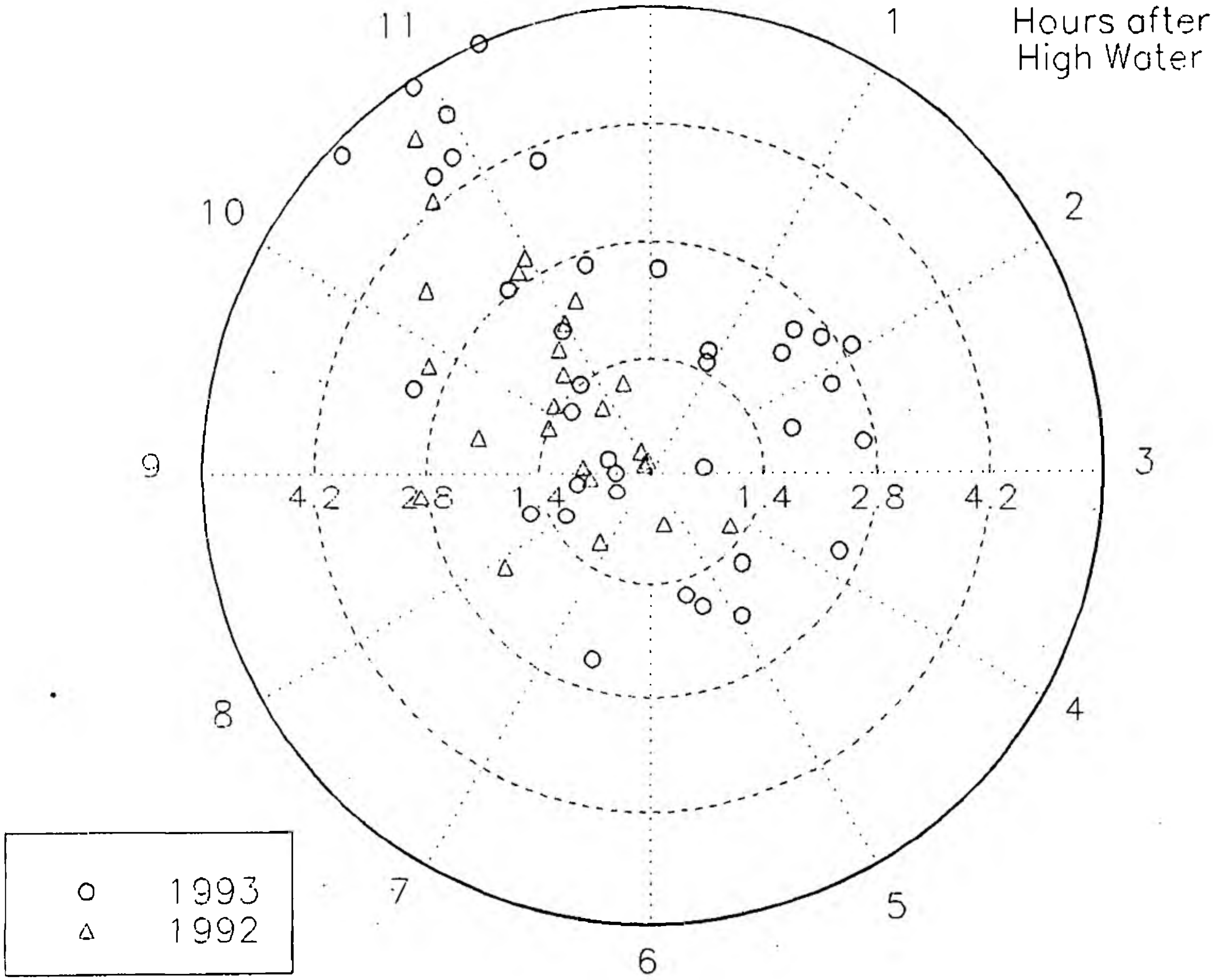


Fig. 33. Distribution of Displacements from R5 into R4, related to State of Tide, Peak Time 02:07h after HW, "r"= 0.539, p< 0.01.

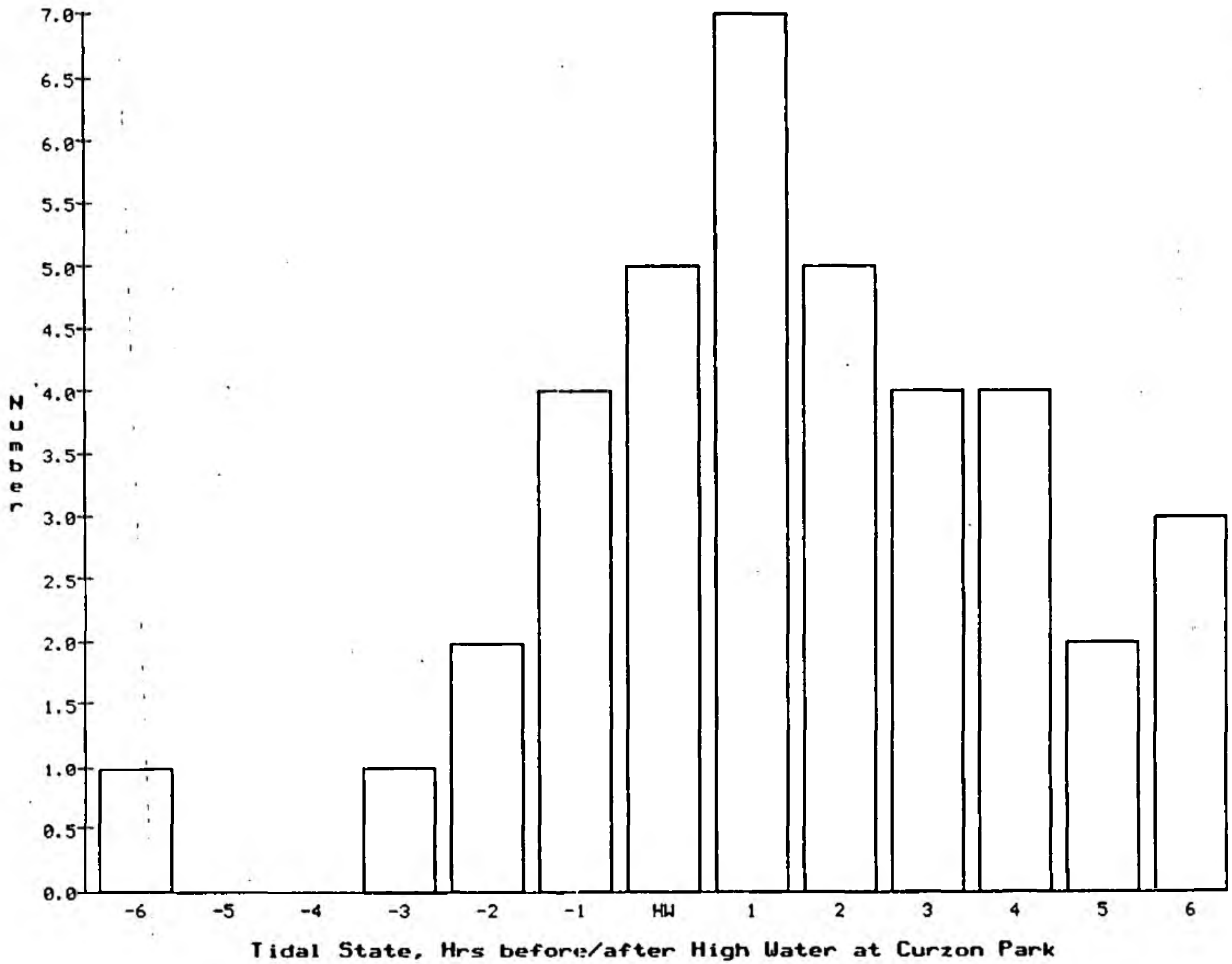


Fig. 34. Probability of Successful Migration through the Middle Dee Estuary related to Max. Temperature prevailing during passage.

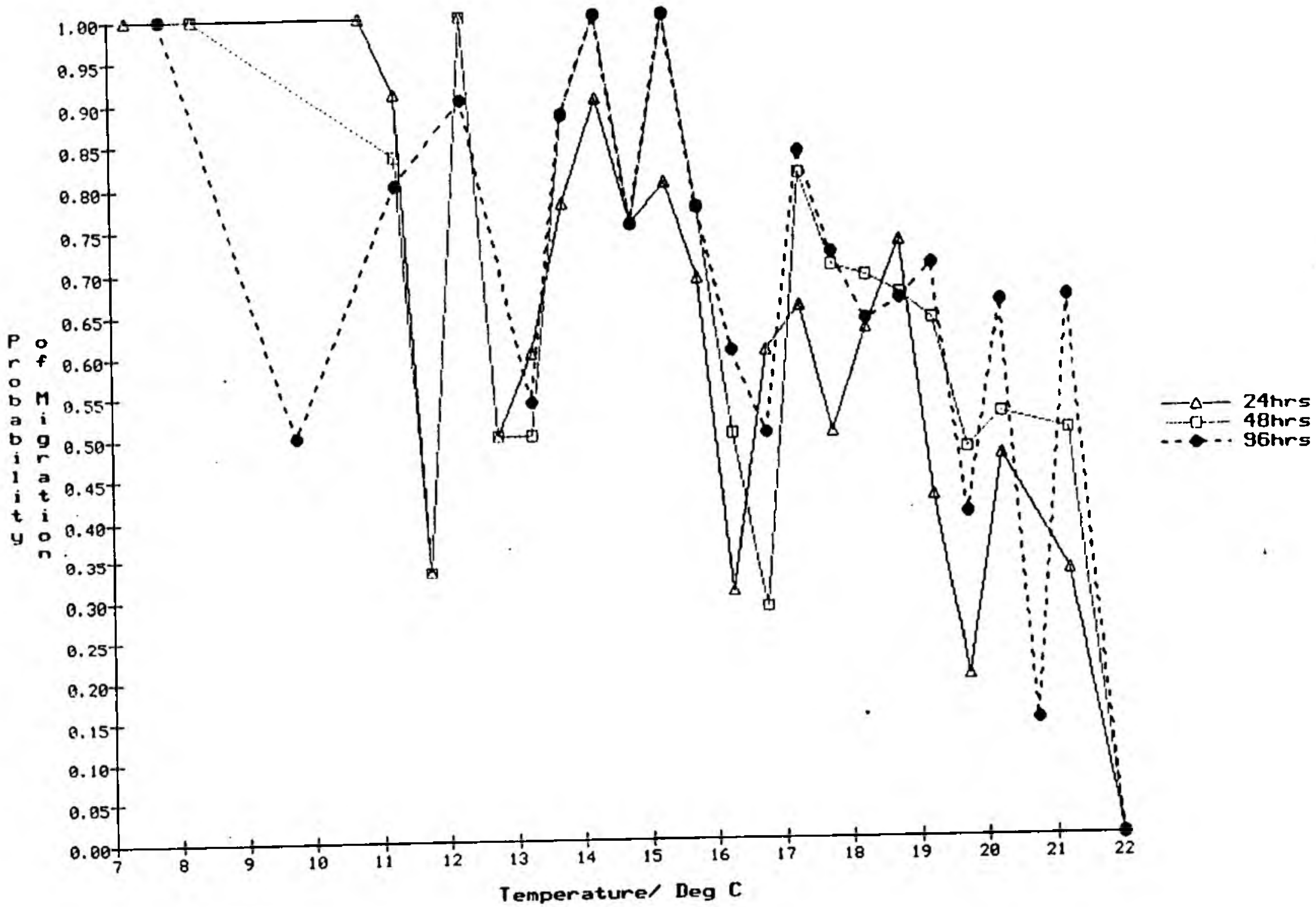


Fig. 35. Probability of not migrating through Middle Dee Estuary within 24 hours related to median available temperature during the 24 hour period and including fitted quadratic line.

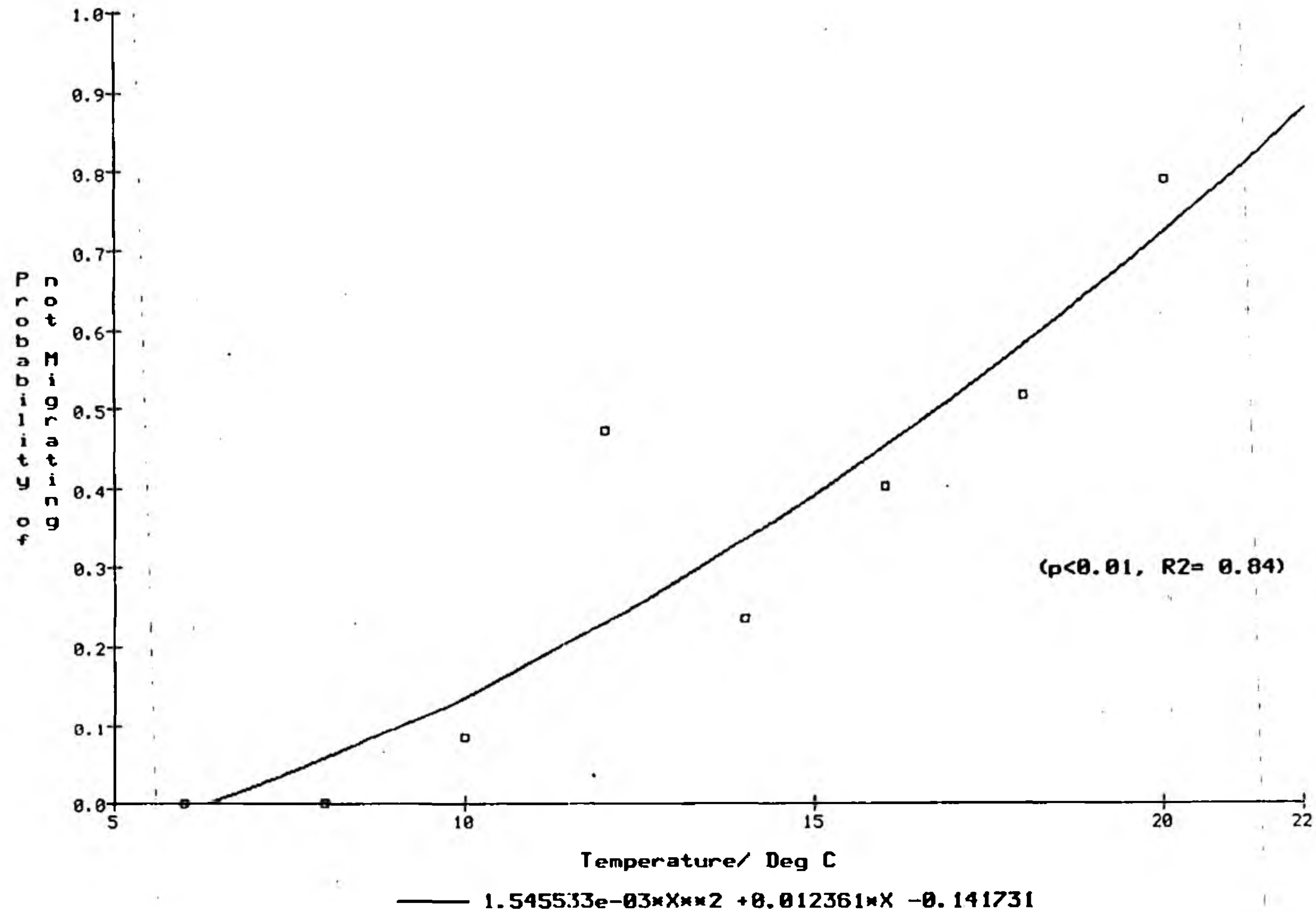


Fig. 36. Cumulative Distribution of Temperatures Prevailing during Upstream Migration over three Time Periods, Dee Estuary 1991-93.

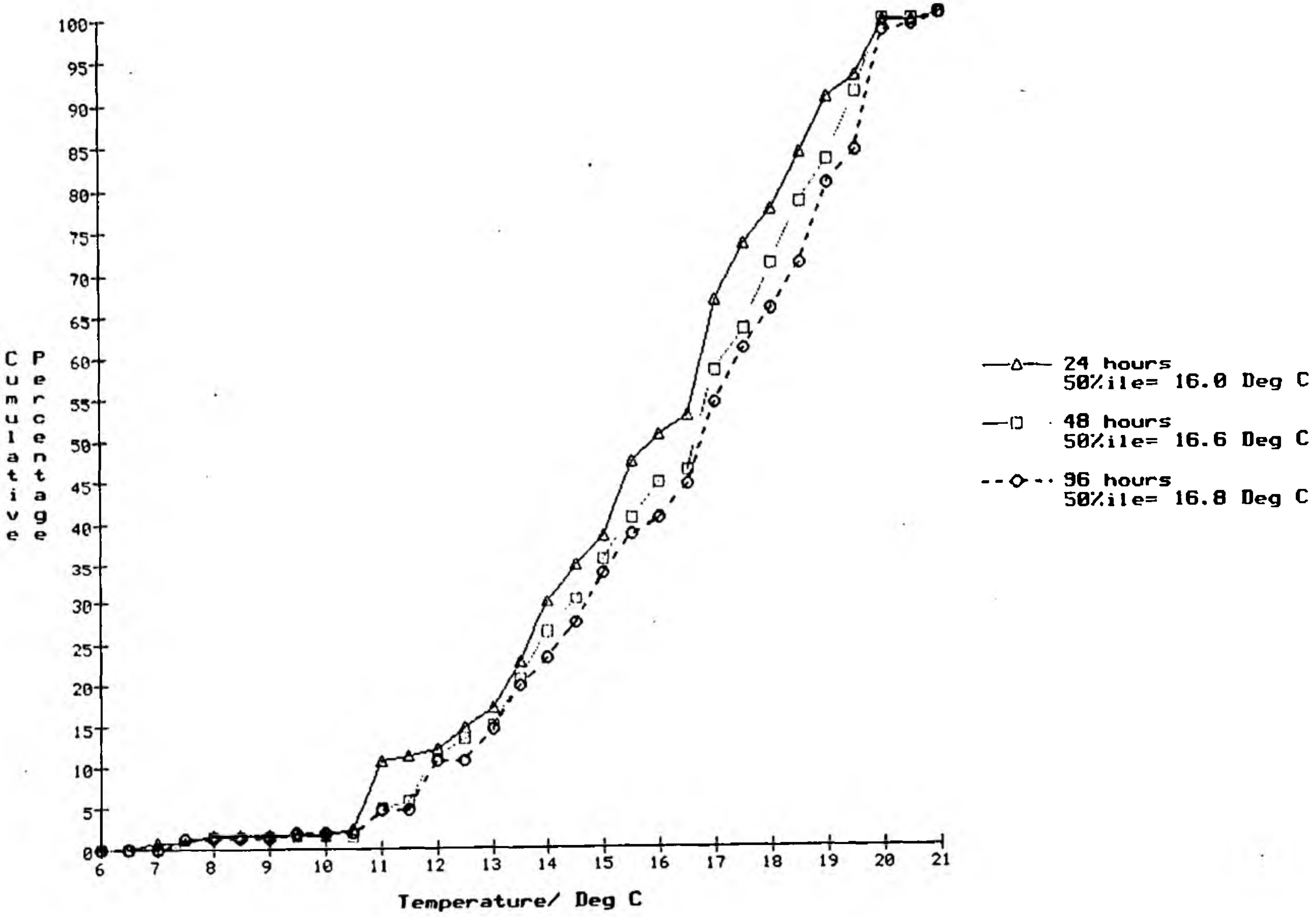


Fig. 37. Probability of Successful Middle Estuary Migration Related to Prevailing Dissolved Oxygen Conditions, Dee Estuary, 1991-93.

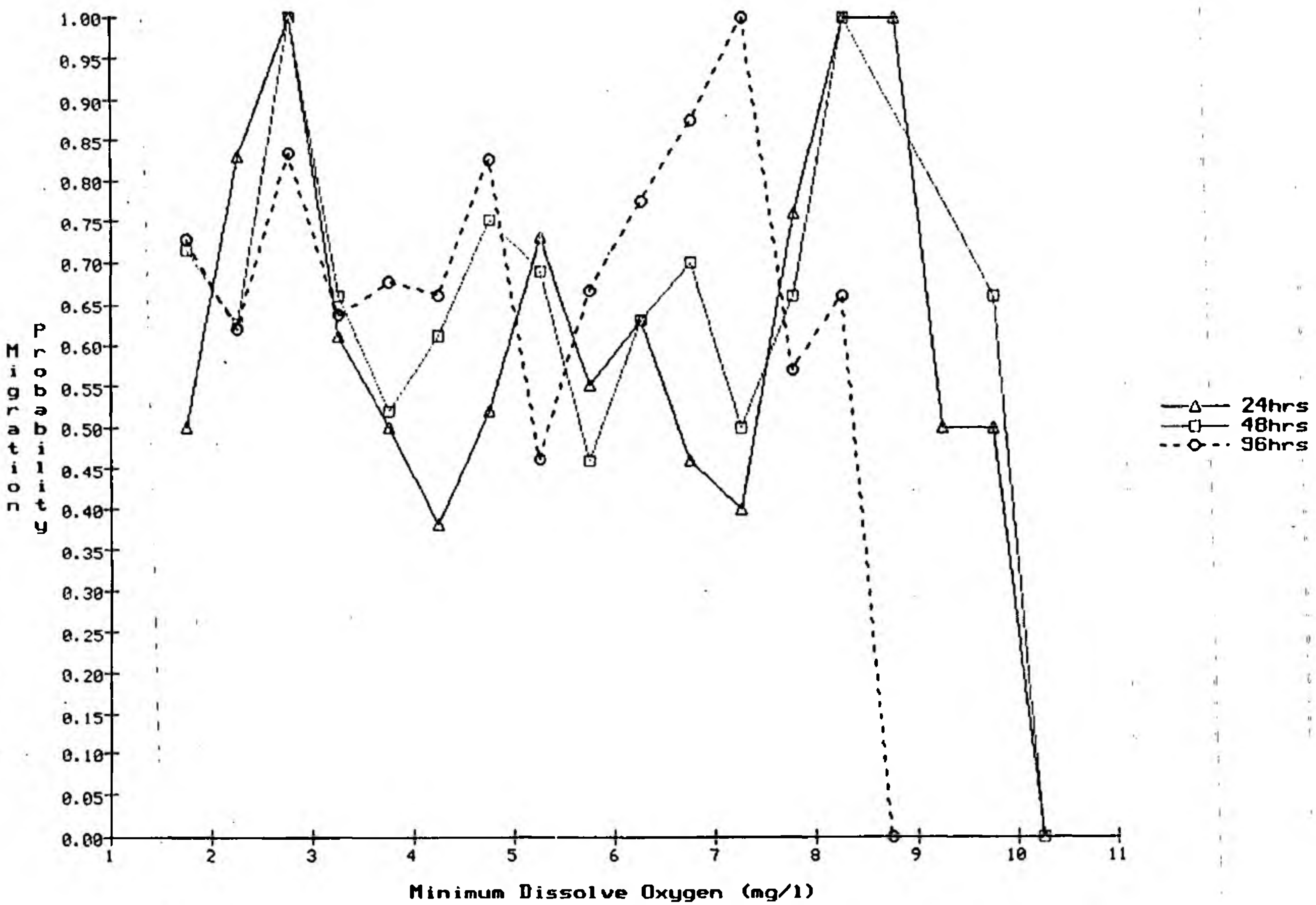


Fig. 38. Cumulative Distribution of Dissolved Oxygen Concentrations Prevailing during Upstream Migration through the Middle Dee Estuary.

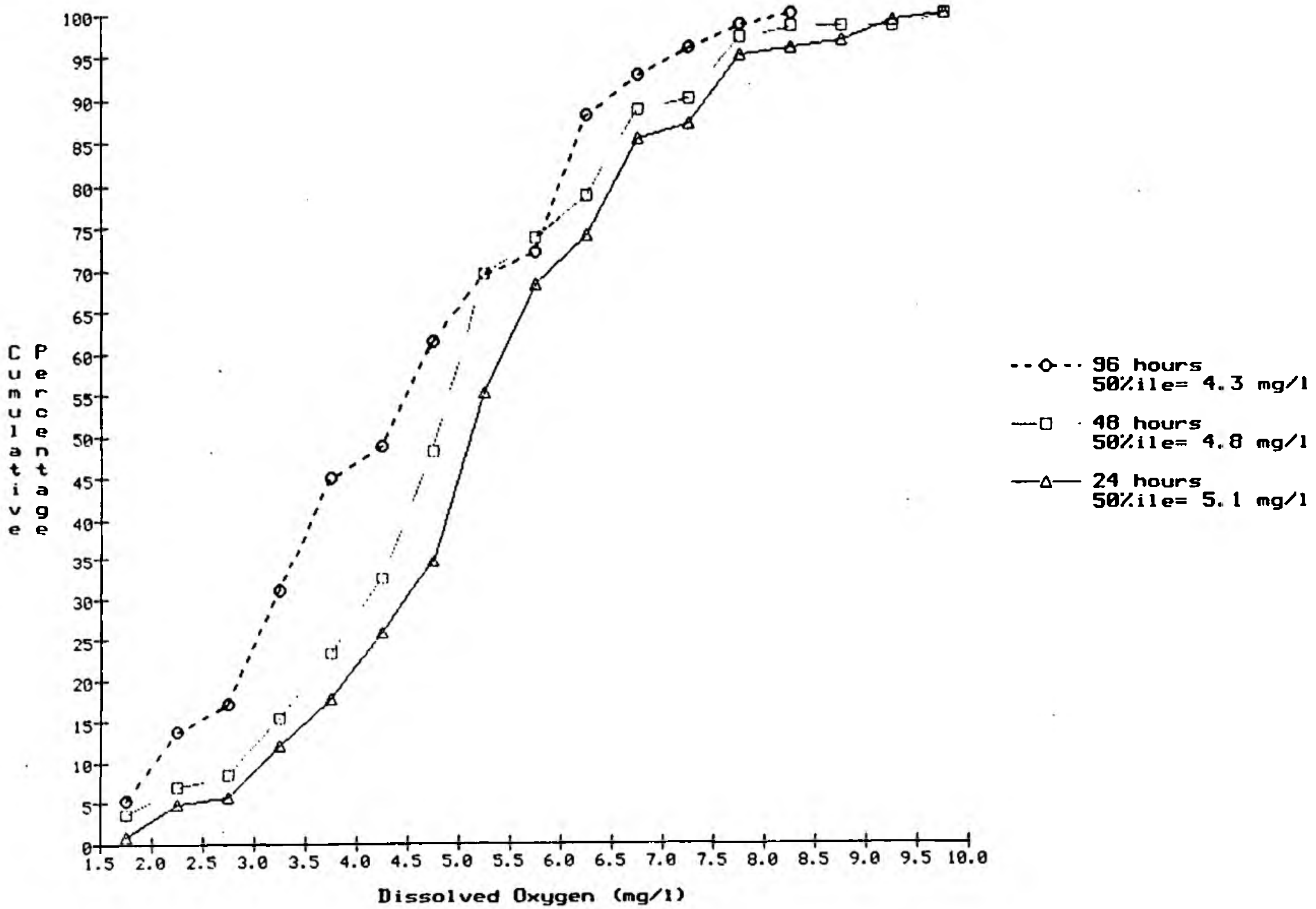


Fig. 39. Middle Dee Estuary Migration Success over three Time Periods
Related to Residual FW Discharge (Flows less than ADF) across Chester Weir.

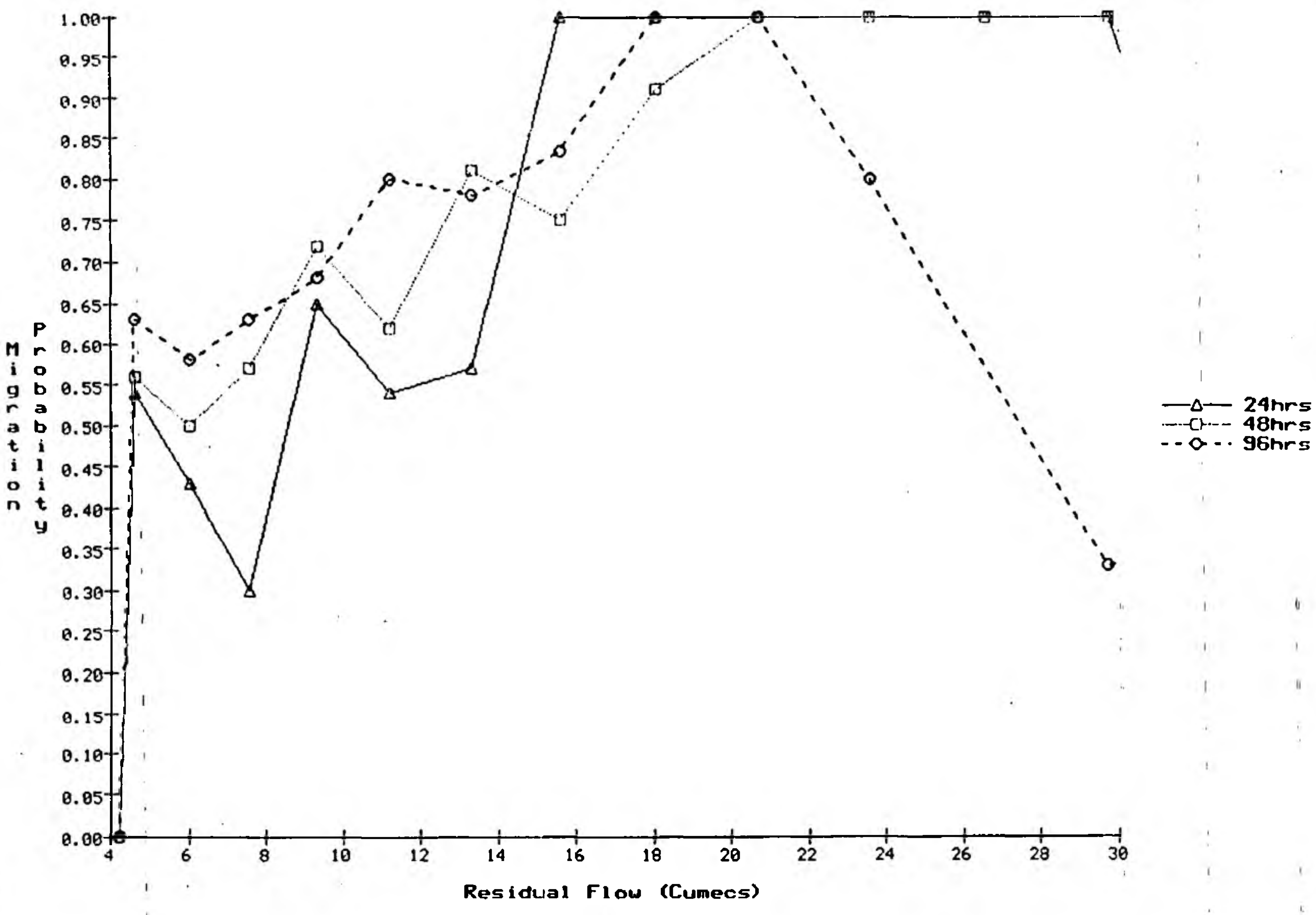


Fig. 40. Cumulative Distribution of Minimum FW Flows Prevailing during Upstream Migration through Middle Dee estuary, over 3 time periods.

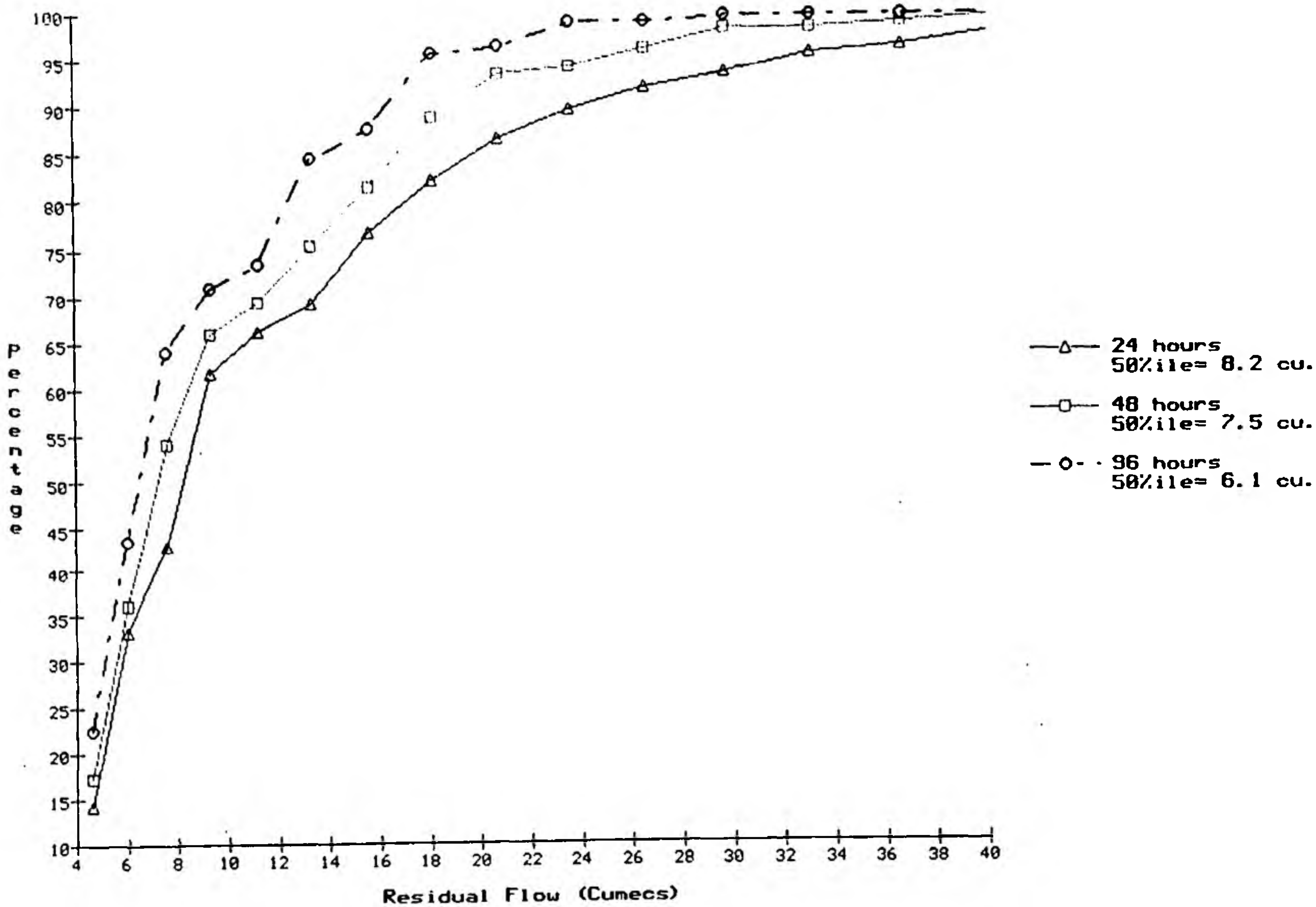


Fig.41 . Distribution of Weir Pool Arrival Times
in Relation to Time of Day.

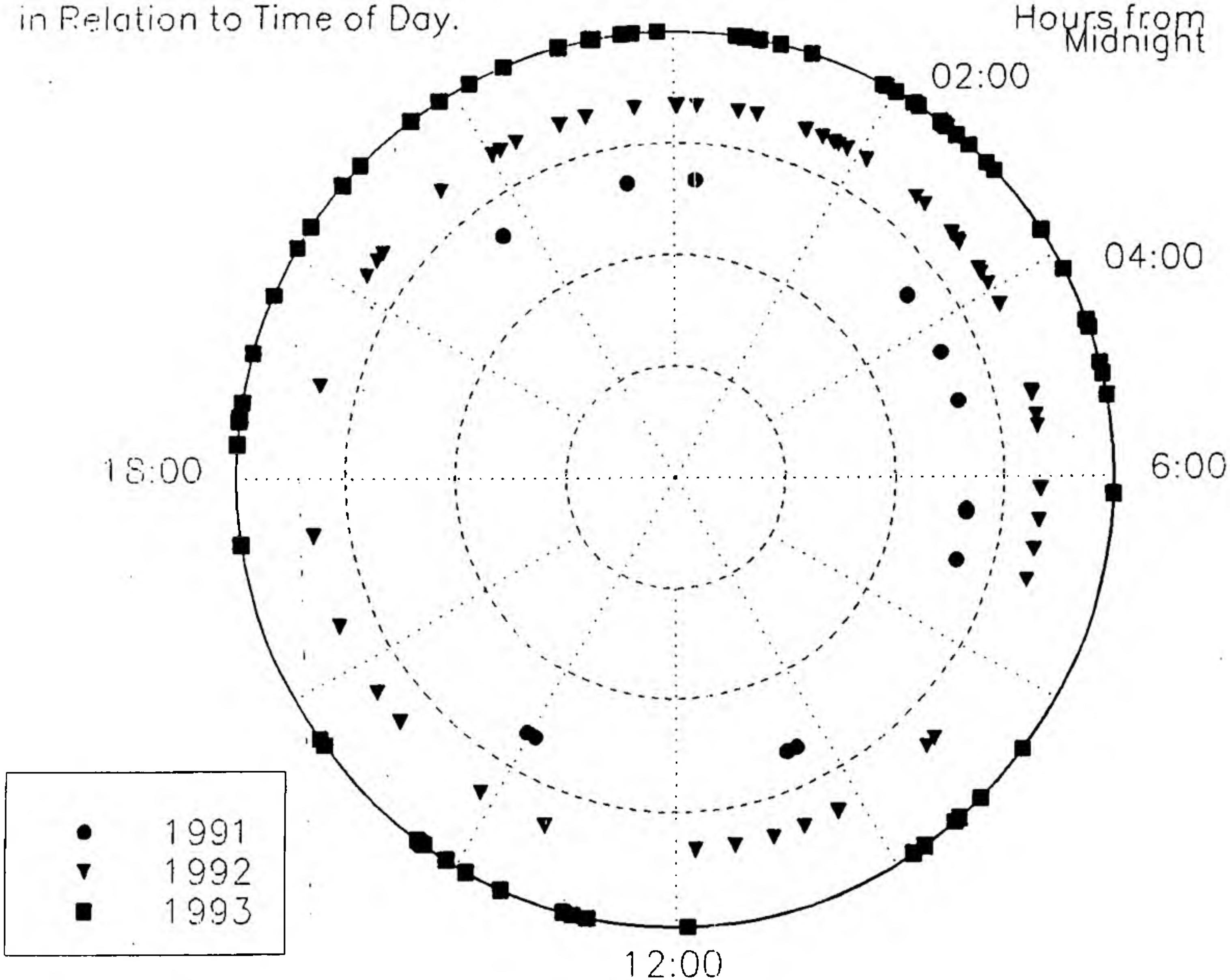


Fig.42. Distribution of Trap Arrival Times in Relation to Time of Day, peak time 02:04h, "r"= 0.385, $p<0.05$.

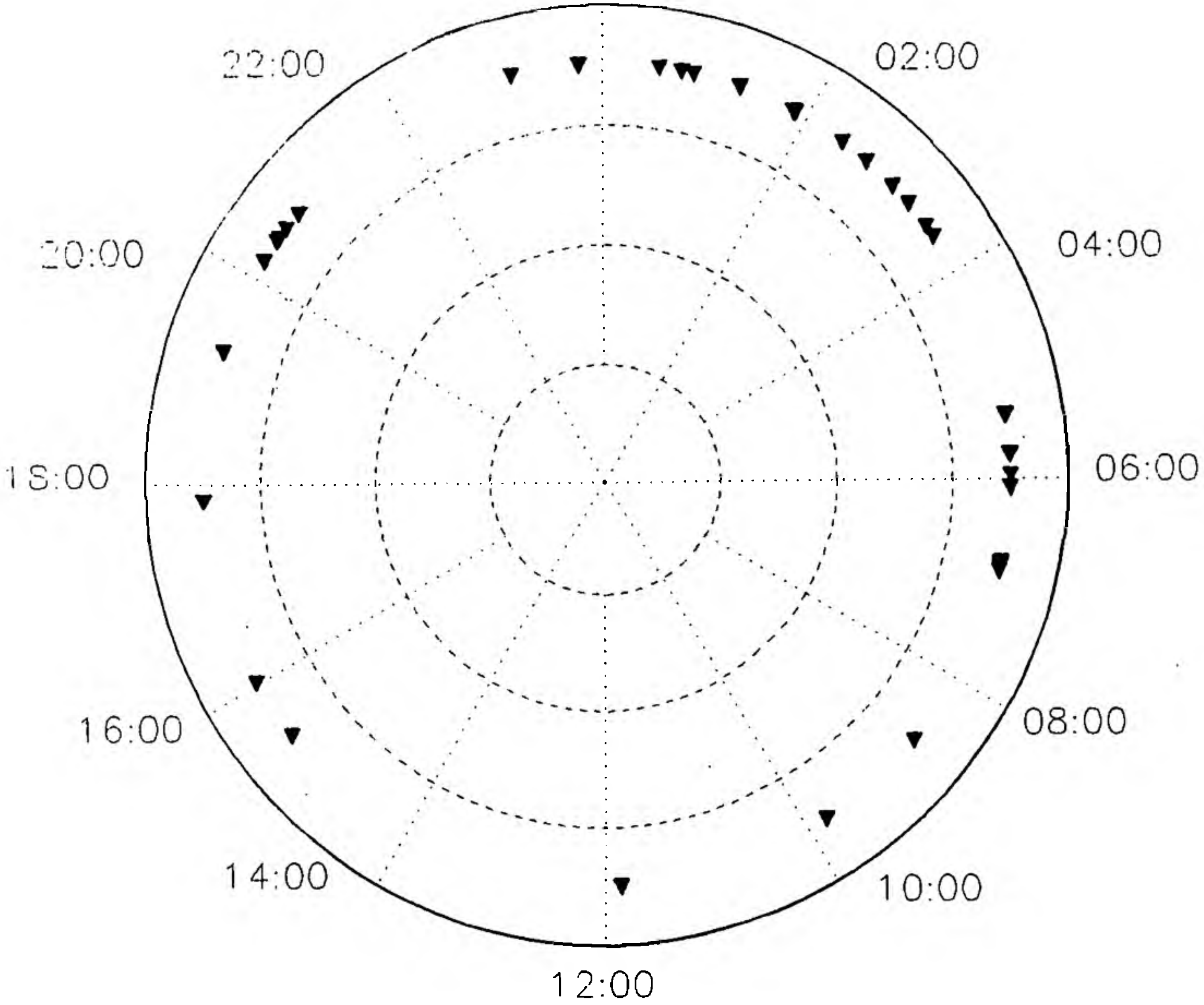


Fig.43. Distribution of Trap Arrival Times in Relation to State of Tide, Random, "r"= 0.1 , p= 0.744.

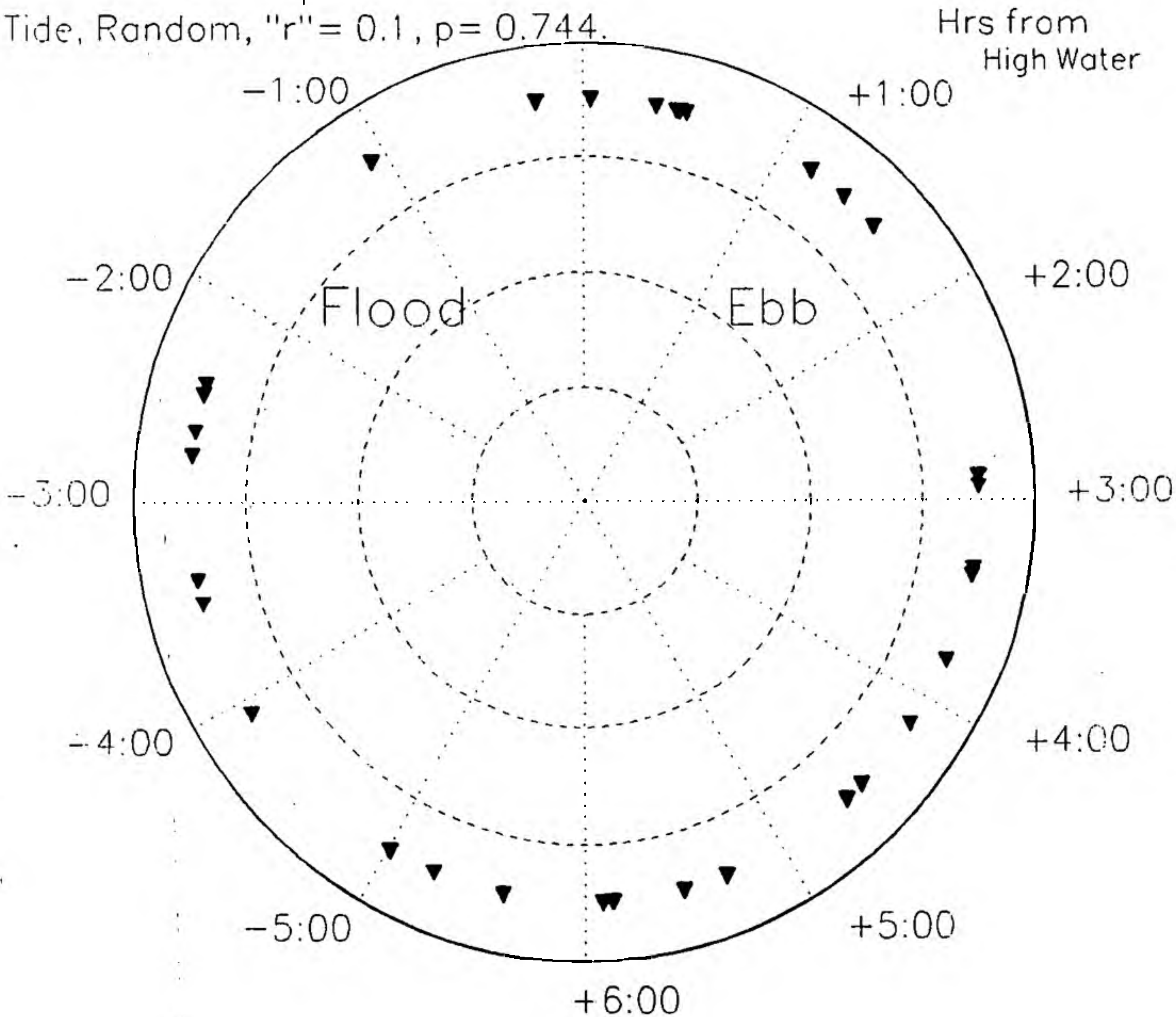


Fig. 44. Differences in Behaviour in Relation to Time of Day (Light ntensity) between Trap Channel Passage, non-random, peak time= 23:43h, r= 0.307, p< 001 and Weir Crest Passage which was random.

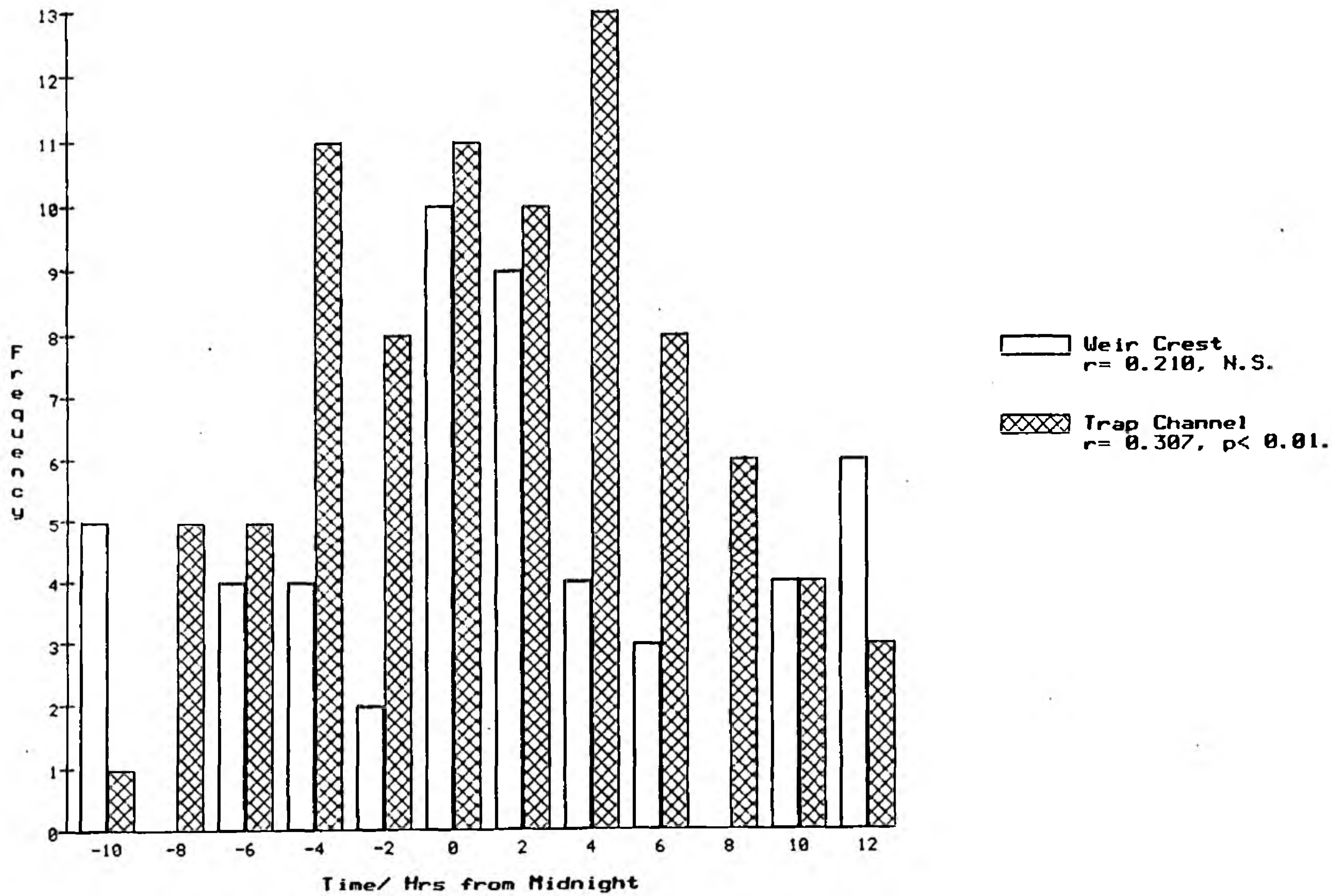


Fig. 45. State of Tide at Weir Crossing, Differences between routes
Trap Channel, "r"=0.029, N.S, Weir Crest, "r"=0.413, p<0.001.

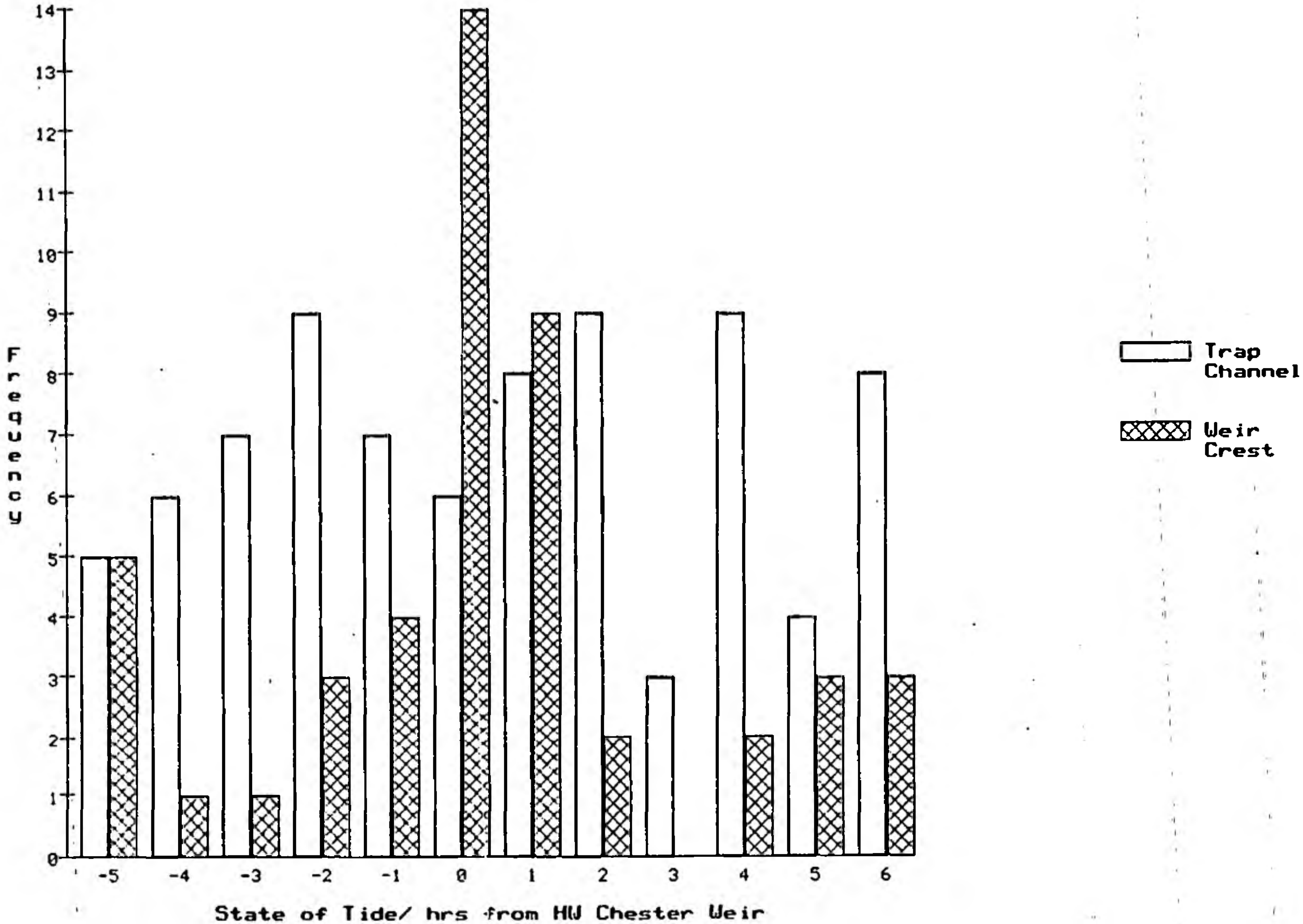


Fig. 46. Probability of Passage via the two Possible Routes related to Water Levels Downstream of the Weir, Weir Crest= 4.33 AOD.

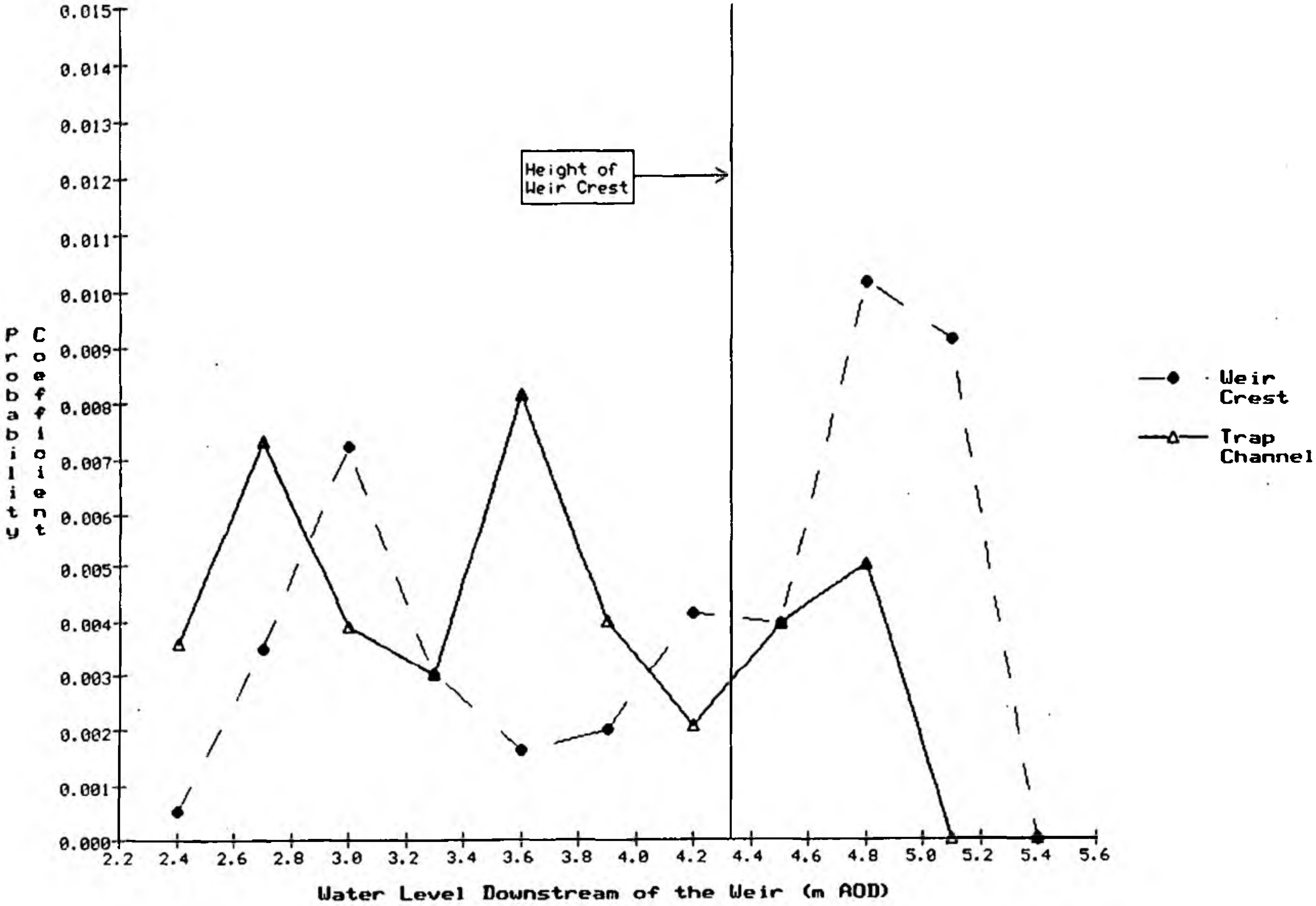


Fig. 47. Comparison of Distribution of FW Flow at Dside Arrival Related to Passage Route, Spearman's Rho = -0.9, Weir Crest vs. Trap Channel.

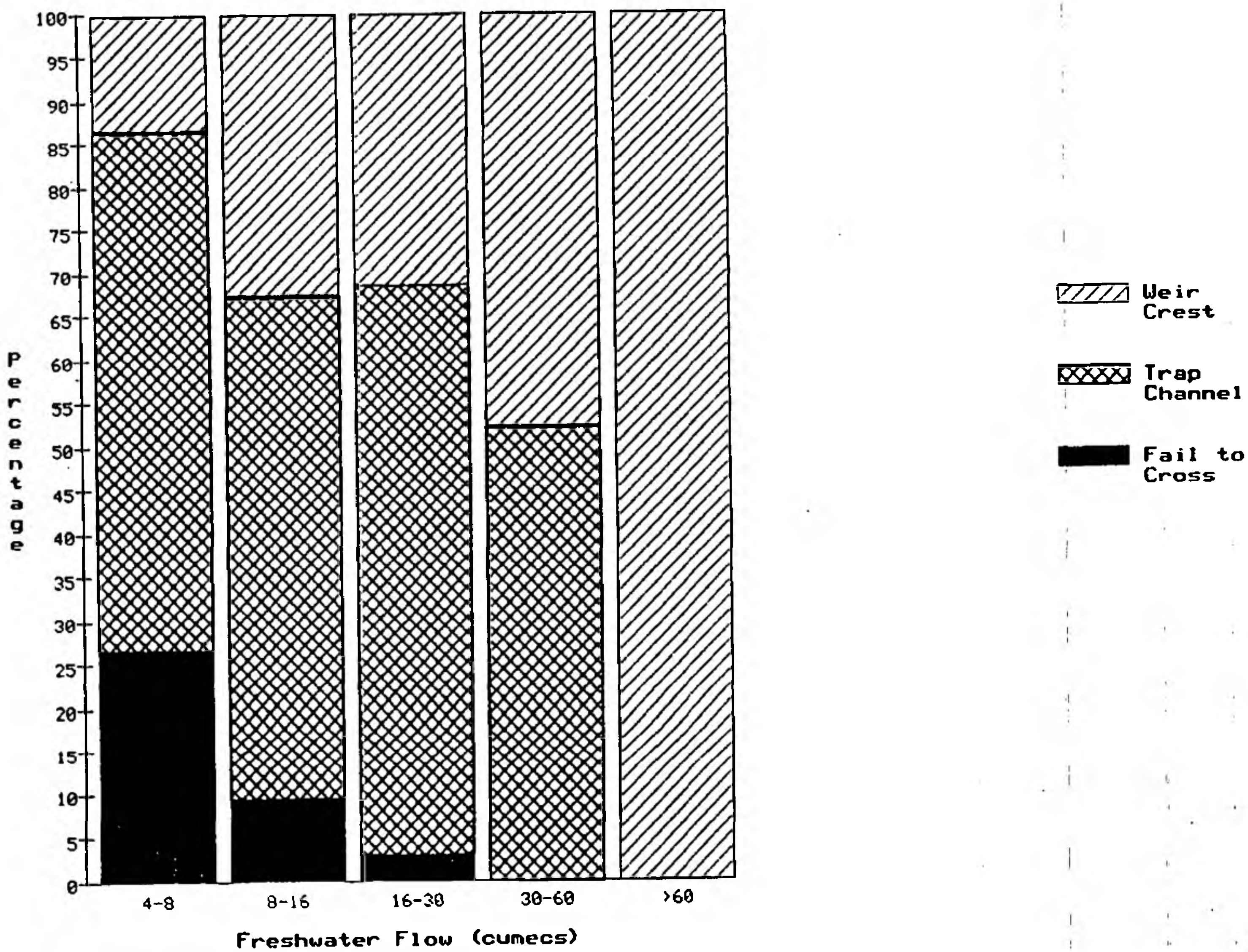


Fig. 48. Impact of Residual FW Flow on the Probability of Weir Crossing by each of the Main Routes, Chester Weir 1991-93.

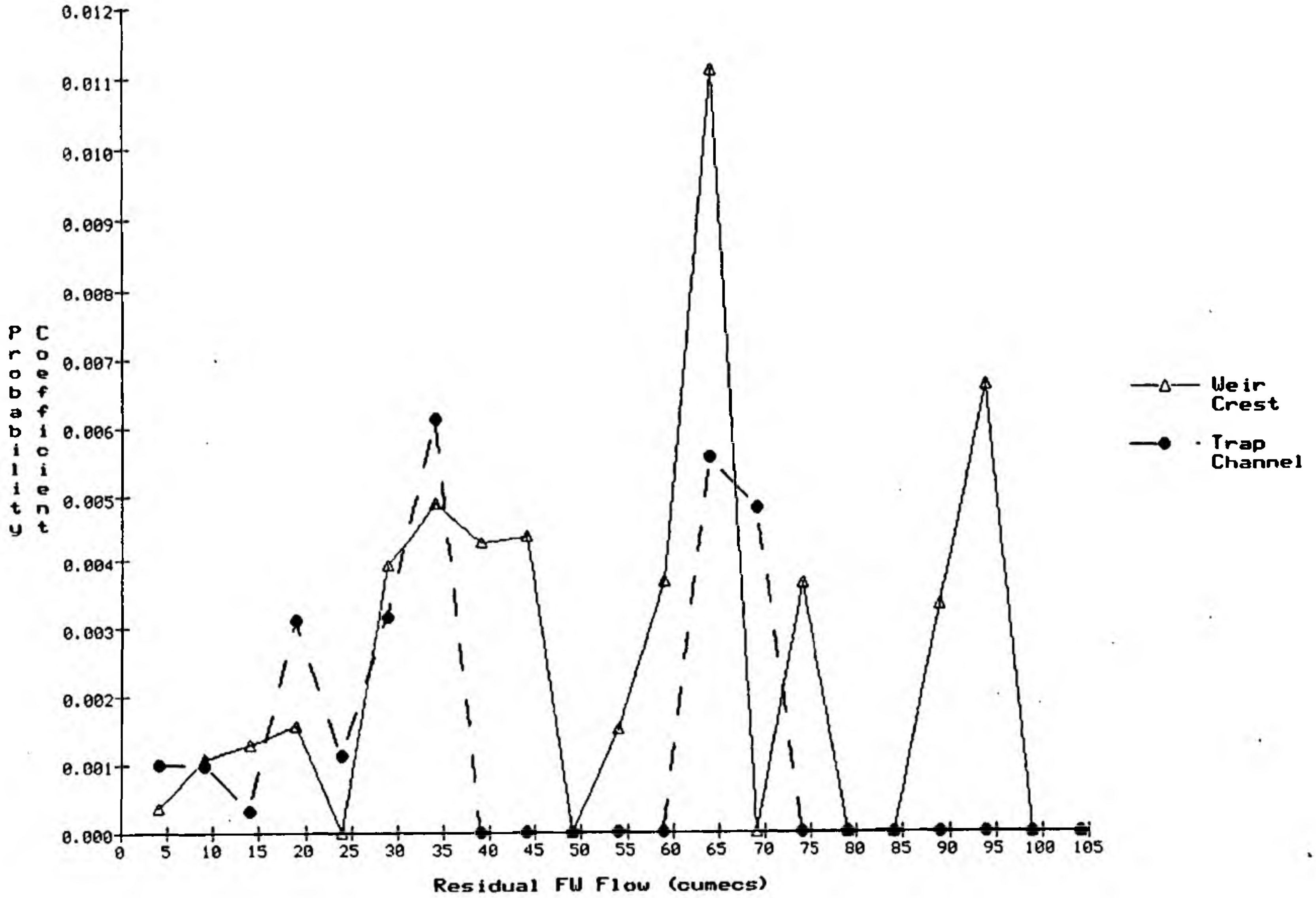


Fig. 49. Relationship between FW Flow and State of Tide for Salmon Ascending Chester Weir across the Weir Crest, 1991-93.

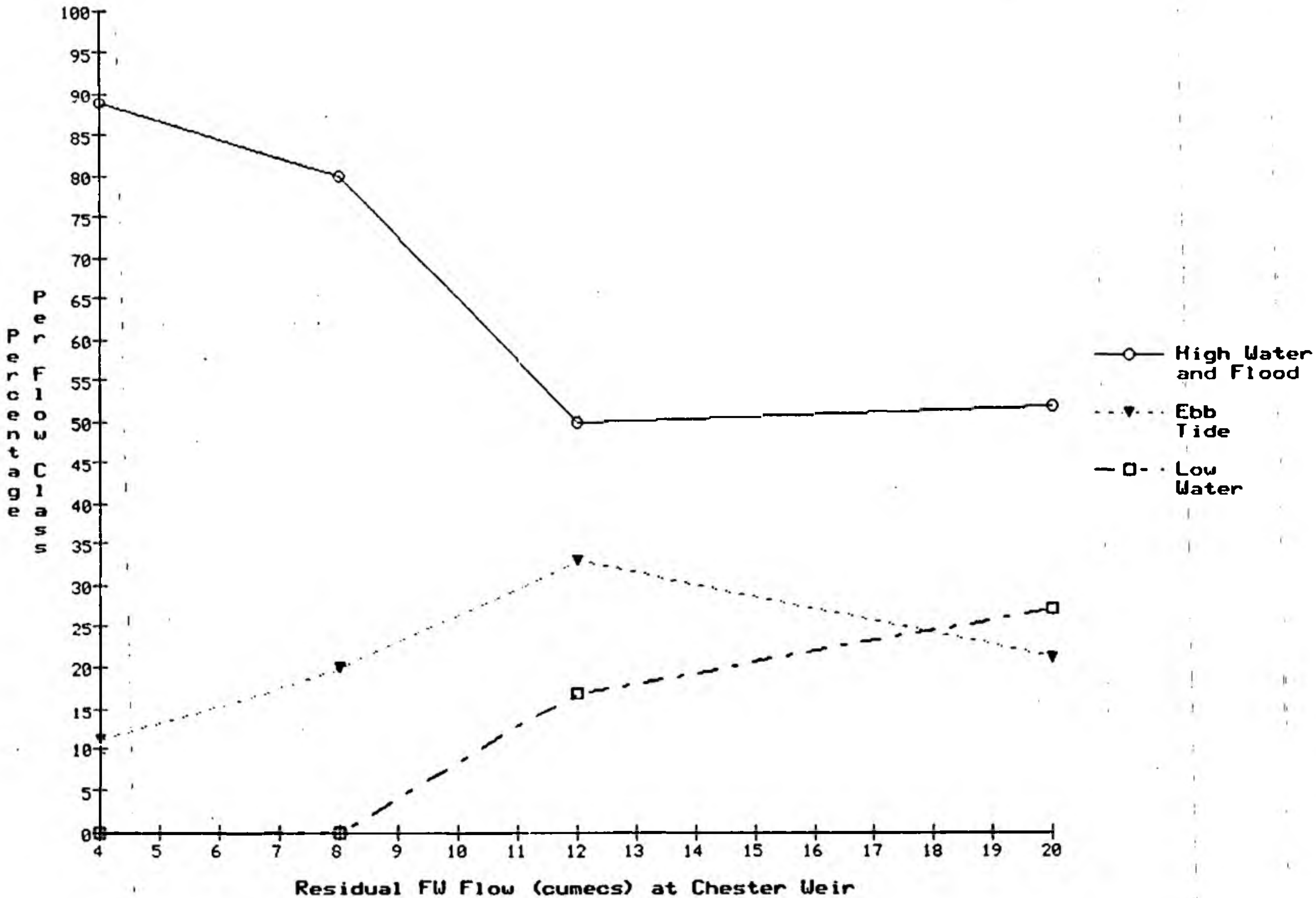


Fig. 50. Relationship between FW Flow and State of Tide, salmon crossing Chester Weir via the Trap Channel, 1991-93.

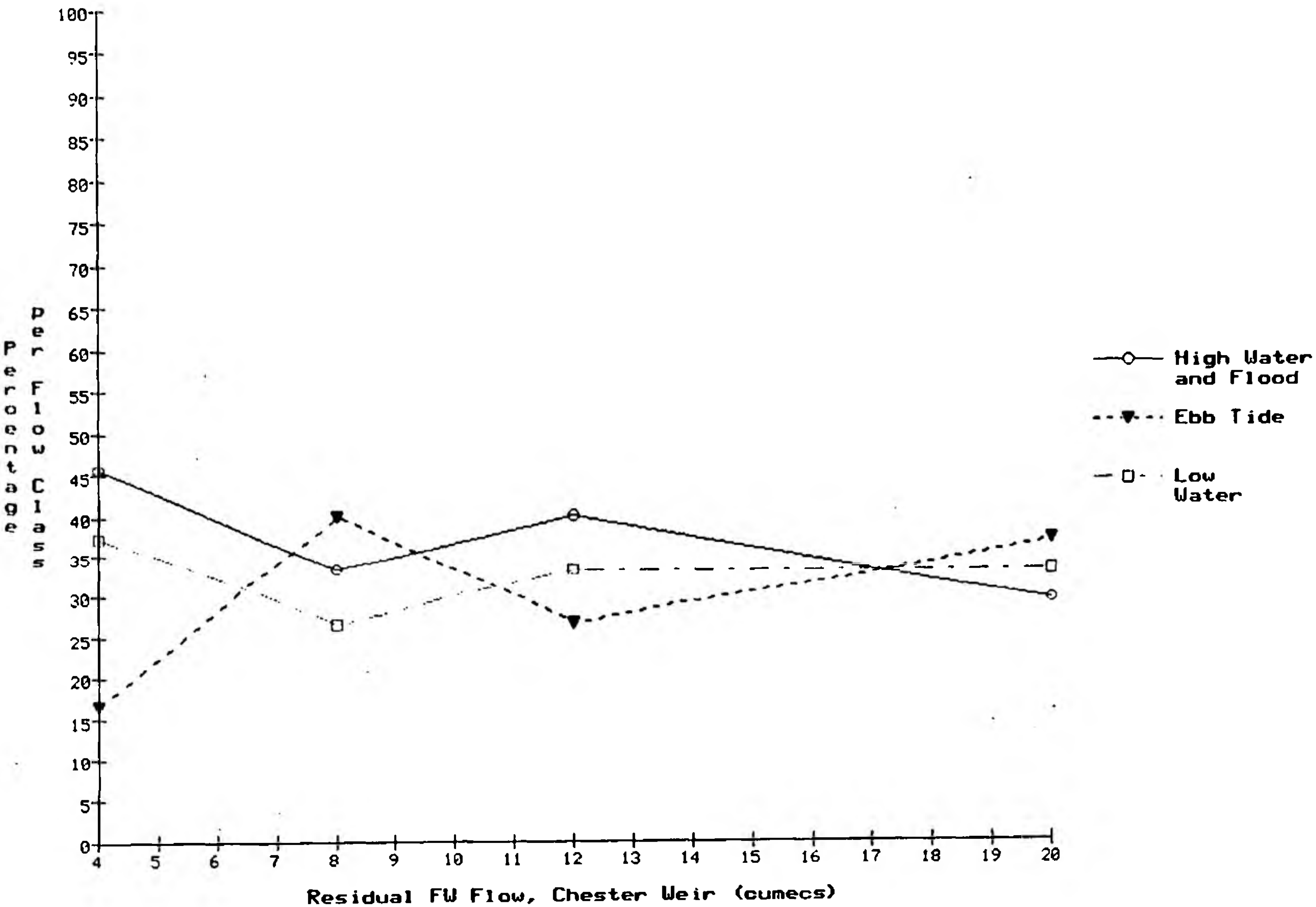


Fig. 51. Delay in the Downstream Vicinity of Chester Weir (square root transformation/ hours) in Relation to Residual Freshwater Flow across the Weir.

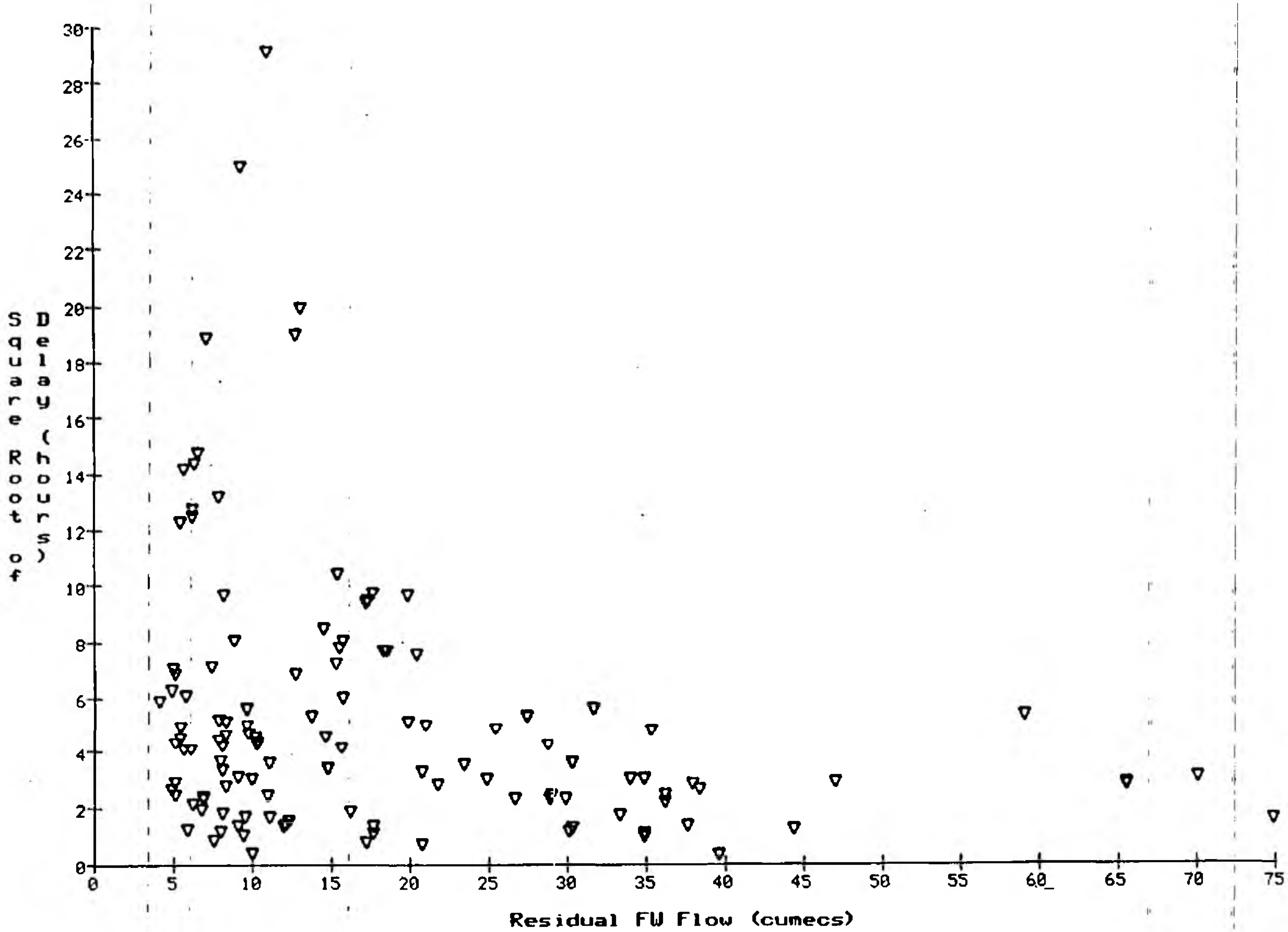


Fig. 52. State of Tide when Tagged Salmon became Displaced from Chester Weir, peak time= 02:24h after HW, "r"= 0.5, p< 0.01.

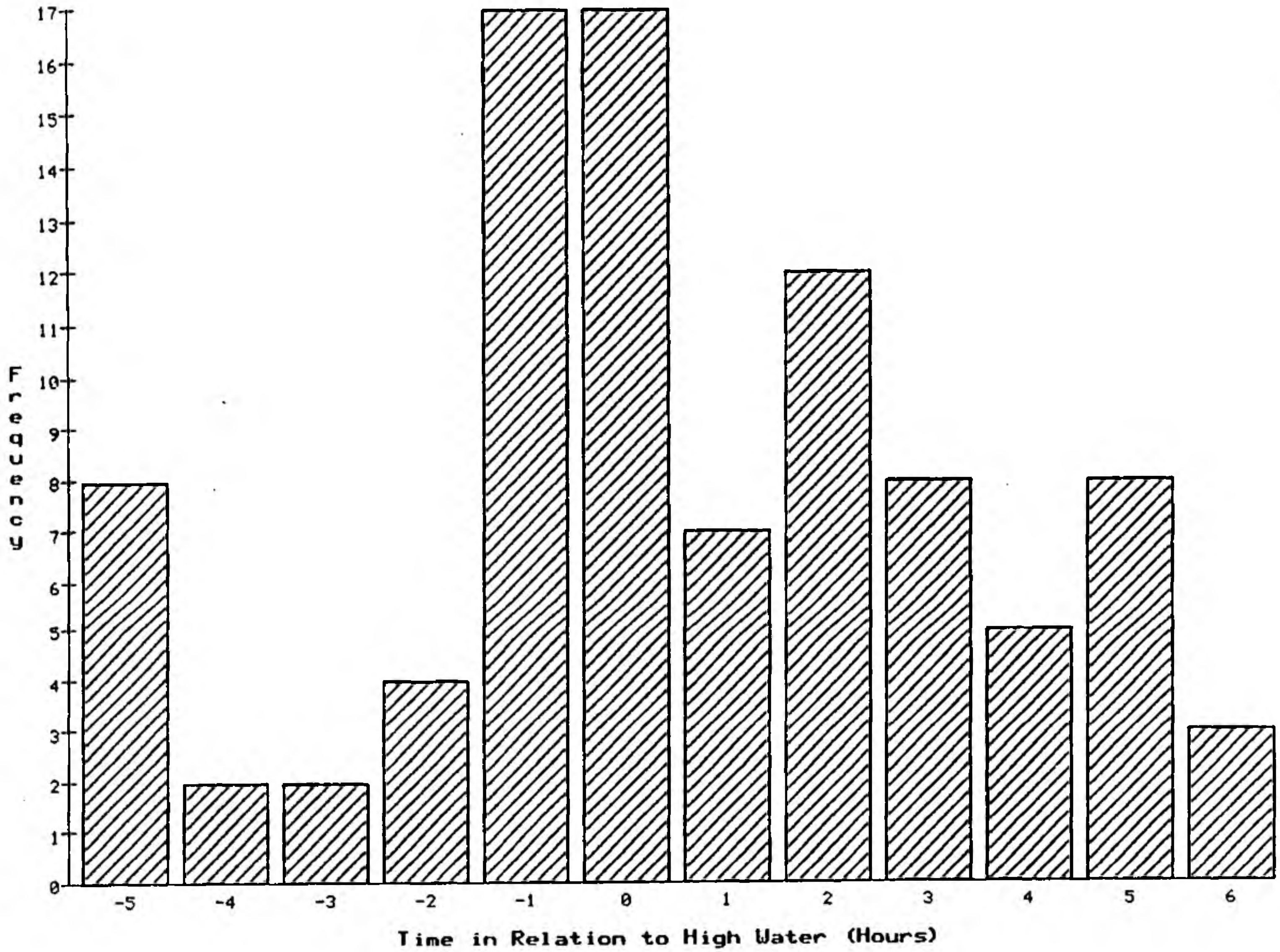


Fig. 53. Timing of Emigration across Chester Weir by Salmon Kelts in Relation to Freshwater Flow (gauged at Eccleston Ferry).

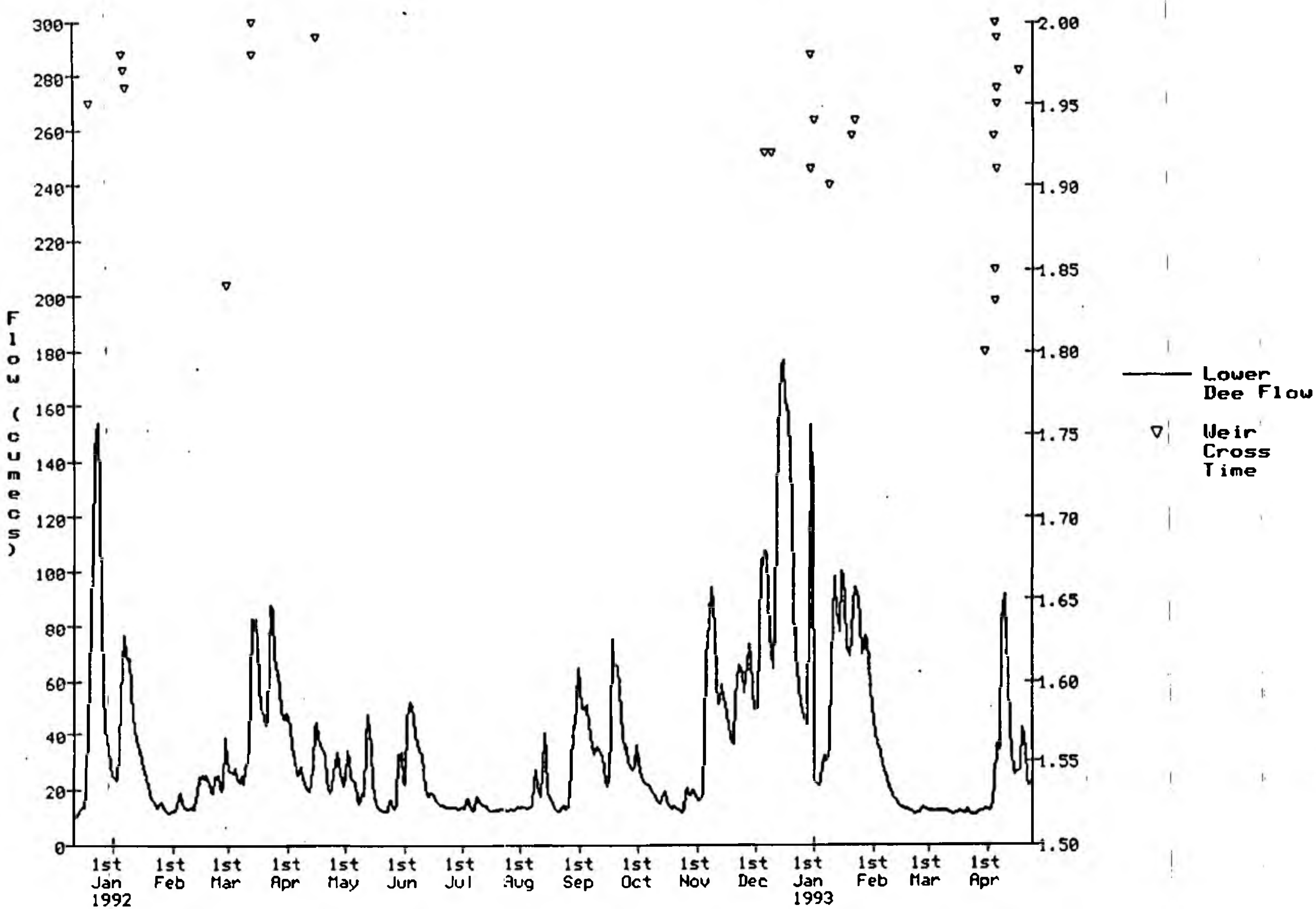


Fig. 54. Kelt Passage Across the Weir

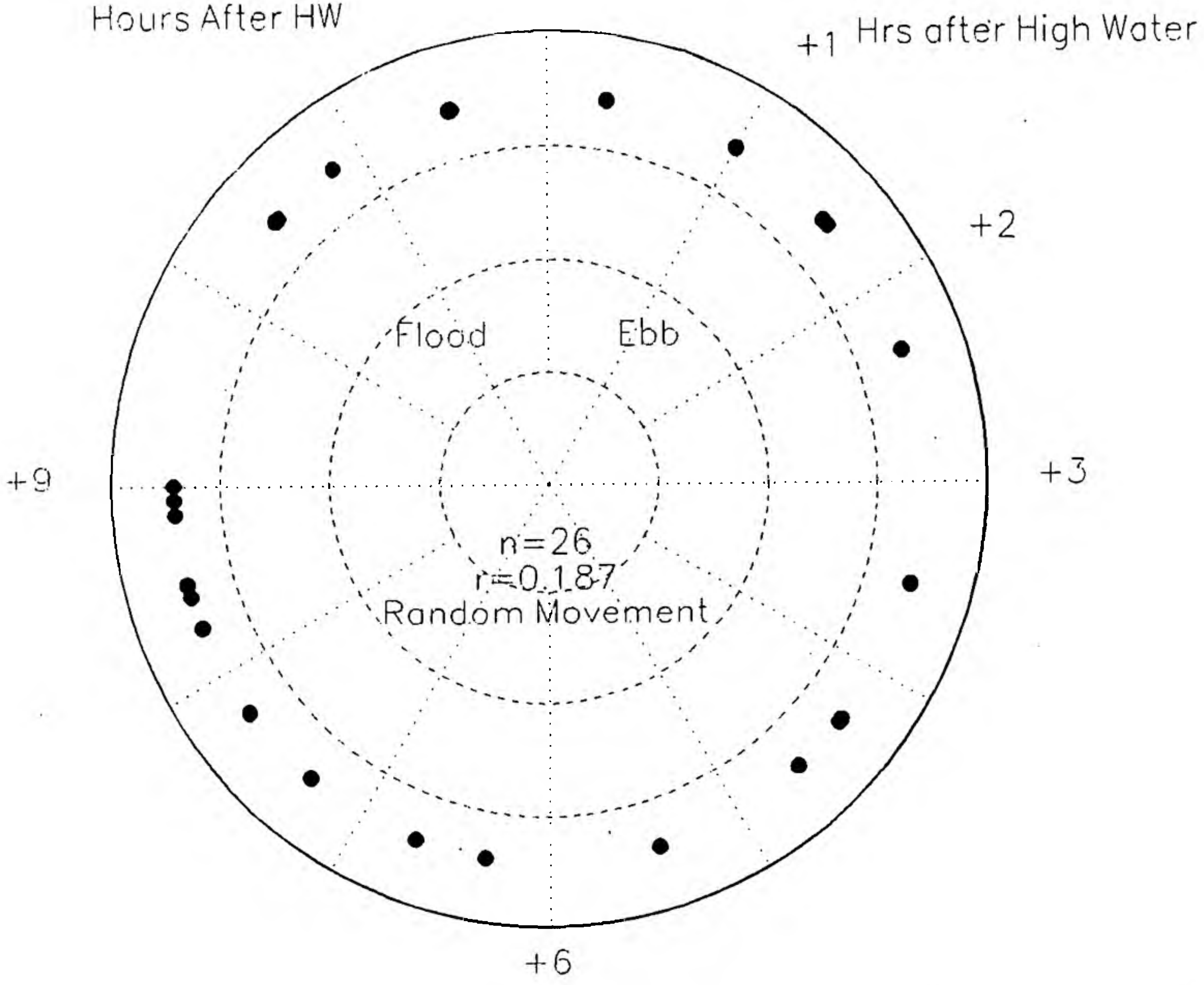
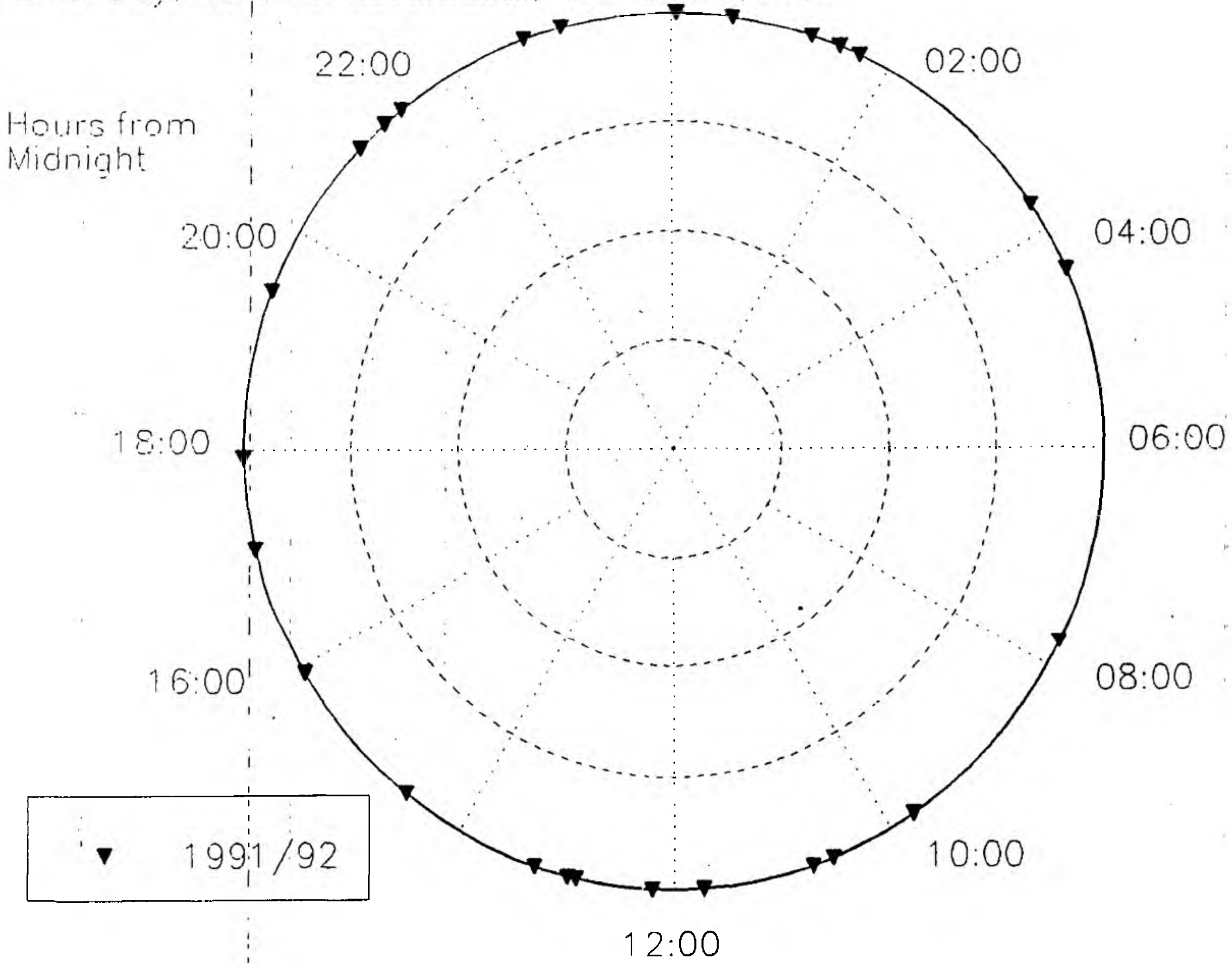


Fig.55. Kelt Weir Crossing Times in Relation to Time of Day, Random Movements, "r" = 0.119, N.S.



TABLES

Table 1. Automatic Listening Station Details,

Site Code	Site Name	Distance from Zero Pt/ km
E0	SUMMERS	23.5000
E1	NEW SUMMERS (93)	24.2000
E2	CONNAH'S QUAY	25.0000
E3	SHOTTON	26.5000
E4	QUEENSFERRY	27.6000
E5	LOW. SANDYCROFT	30.5000
E6	UPP. SANDYCROFT	33.2000
E7	THOR	34.5000
E8	TILSTONS	36.9000
E9	CURZON PARK	37.8000
ALS Dside	OLD DEE BRIDGE	38.8000
ALS Weir	FISH LADDER	38.9875
ALS Trap	TRAP HOUSE	39.0000

Dee Estuary, 1991-93.

Table 2. Acoustic Buoy Deployments 1991 to 1993

SITE NUMBER	SITE NAME	DISTANCE FROM ZERO POINT	TYPE OF RECEIVER	ORIGINAL DEPLOYMENT	DATE REMOVED	FATE
EB2	LOWER SUMMERS	23.60	OMNI	JUNE 92	NOV 92	OK
EB1	UPPER SUMMERS	23.70	OMNI	JUNE 92	SEP 92	VANDALISED
EB1B	SUMMERS JETTY	24.19	DIRECTIONAL	AUG 93	NOV 93	OK
EB3	WATER INTAKE CQ	24.60	DIRECTIONAL	JULY 92	NOV 93	OK
EB4	UPPER GROYNE I	25.70	OMNI	JUNE 91	SEP 92	TIDAL DAMAGE
EB4A	UPPER GROYNE II	25.85	OMNI	JULY 91	SEP 92	TIDAL DAMAGE
EB5A	LOWER SHOTTON	25.80	DIRECTIONAL	OCT 92	NOV 93	OK
EB5A	SHOTTON	26.30	DIRECTIONAL	JULY 92	NOV 93	OK
EB5	UPP. SHOTTON	26.70	OMNI	JUNE 92	JULY 92	VANDALISED
EB6	QUEENSFERRY BRIDGE	27.50	DIRECTIONAL	JUNE 92	JULY 92	STOLEN
EB6A	SANDYCROFT	28.70	OMNI	JULY 93	NOV 93	OK
EB7	LOW. SANDYCROFT	30.50	OMNI	JUNE 92	JUNE 92	STOLEN
EB8	UPP. SANDYCROFT	33.20	OMNI	JUNE 92	JULY 92	REMOVED TO PREVENT TH
E8	SALTNEY FERRY	33.35	DIRECTIONAL	AUG 93	NOV 93	OK
EB10	THOR	35.30	OMNI	JUNE 91	NOV 93	OK

Table 3. Details of Estuarine Reaches.

REACH	Lower Limit	Upper Limit	Dist from Weir (Km)	% Flood Tide 9.4m	% Flood Tide 7.3m	Tidal Phase Lag 9.4m	Tidal Phase Lag 7.3m	ALS / Buoy Entry	ALS / Buoy Exit	Ave Depth Range
R1	G'Field	Summ Jetty	34.09	42.2	45.4	N/A	N/A	N/A	Summers ALS/Buoy	N/A
R2	Summ Jetty	Shotton RL BR	14.8	18.9	23.2	0:00	0:00	Summers ALS/Buoy	Shotton ALS/Buoy	1.4 1.7 3.8
R3	Shotton RL BR	The Bar	12.47	15.5	14.9	0:32	0:50	Shotton ALS/Buoy	Thor ALS	0.6 1.4 4.9
R4	The Bar	Crane Warf	6.46	12.4	11.7	1:08	1:51	Thor ALS	Tistons ALS	0.5 2.6 3.9
R5	Crane Warf	Old Dee Bridge	2.13	11.0	7.0	1:20	3:04	Tistons ALS	Dside ALS	1.1 1.8 2.3
R6	Old Dee Bridge	Queens Court	0.2	10.1	6.2	1:37	3:34	Dside ALS	QC ALS	0.5 3.0 4.3

Table 4. Fish Tagged By Location 1991 to 1993

Capture Site	Release Site	1991	1992	1993	Total
Trap	Trap	48	60	47	155
Connah's Quay	Connah's Quay	82	82	46 *	210
Curzon Park	Curzon Park	-	20	15	35
Trap	Curzon Park	-	-	6	6
Trap	Outer Estuary	-	-	21	21
Trap	Middle Estuary	-	-	27	27
Connah's Quay	Outer Estuary	-	-	7	7
Total		**130**	**162**	**169**	**461**

* Incl. 2 tags; C2G516, 29KG7 held overnight

Table 5. Fates of Middle Estuary Tagged Salmon, by Year, 1991-93.

Fate Category	Numbers 1991	Percent. 1991	Numbers 1992	Percent. 1992	Numbers 1993	Percent. 1993
Successful FW Entry	17	20.7	36	43.9	27	50.9
Confirmed Regurgitation (estuary	3	3.7	2	2.4	0	0.0
Regurgitated or Found Dead	8	9.8	0	0.0	0	0.0
Confirmed Found Dead	1	1.2	1	1.2	0	0.0
Recaptured by Licensed Netsman	19	23.2	25	30.5	13	24.5
Not Seen Post-Tagging	27	33.0	2	2.4	8	15.1
Confirmed Poached	2	2.4	0	0.0	0	0.0
Suspected Poached	3	3.7	8	9.8	0	0.0
Last Seen Estuary	1	1.2	7	8.5	4	7.6
Detected Other River	1	1.2	1	1.2	1	1.9
Totals	82	100.0	82	100.0	53	100.0

Table 6. Fate by Month, Estuary-Tagged Salmon, 1991-93 pooled.

Category	May/ June No. (%)	July No. (%)	August No. (%)	Sept'br No. (%)	Oct/ Nov No. (%)
Entered Freshwater	6 (67%)	14 (22%)	21 (21%)	37 (65%)	2 (40%)
Confirmed Regurgitatio	0 (0%)	2 (3%)	1 (1%)	1 (2%)	1 (20%)
Dead or Regurgitated	1 (11%)	1 (2%)	4 (5%)	2 (4%)	0 (0%)
Confirmed Found Dead	0 (0%)	0 (0%)	1 (1%)	1 (2%)	0 (0%)
Licensed Net Recaptures	1 (11%)	25 (39%)	31 (38%)	0 (0%)	0 (0%)
Not Seen Post-tagging	1 (11%)	13 (20%)	15 (18%)	7 (12%)	1 (20%)
Confirmed Poached	0 (0%)	1 (2%)	0 (0%)	1 (2%)	0 (0%)
Suspected Poached	0 (0%)	4 (6%)	3 (4%)	4 (7%)	0 (0%)
Disappeared Estuary	0 (0%)	4 (6%)	4 (5%)	3 (5%)	1 (20%)
Detected in Adj Catchmen	0 (0%)	0 (0%)	2 (2%)	1 (2%)	0 (0%)
Total	9 (100%)	64 (100%)	82 (100%)	57 (100%)	5 (100%)

Table 7. Fates of Trap Caught Salmon Tagged and Relocated to Middle or Outer Estuary during 1993, River Dee Study.

Fate Category	Number	Percentage
Successful FW Entry	33	68.8
Confirmed Regurgitation (estuary	4	8.3
Regurgitated or Dead (estuary)	1	2.1
Confirmed found Dead (estuary)	0	0.0
Recaptured by Licensed Netsman	5	10.4
Not Seen Post-Tagging	3	6.3
Confirmed Poached	1	2.1
Suspected Poached	0	0.0
Last Seen Estuary	1	2.1
Detected Other River	0	0.0
Totals	48	100.0

Table 8. Conditions at Reach Entry.

Reach		Temperature °C	Max/Min	Dissolved Oxygen mgl	Max/Min	Flow Cumecs	Max/Min
R2	MEAN	16.09	20.34	9.16	18.07	13.3	94.1
	S.D.	± 2.68	6.98	± 2.66	4.12	± 12.42	4.1
R3	MEAN	15.29	20.88	8.65	16.29	18.1	92.5
	S.D.	± 3.10	6.85	± 2.02	4.12	± 16.23	4.27
R4	MEAN	15.37	20.42	8.45	11.29	14.9	94.2
	S.D.	± 2.76	7.36	± 0.98	5.79	± 13.05	4.2
R5	MEAN	13.86	20.12	8.74	14.29	15.7	94.6
	S.D.	± 2.94	6.09	± 1.37	2.32	± 12.91	4.25
R6	MEAN	13.87	20.01	8.63	12.65	16.5	95.8
	S.D.	± 2.83	6.34	± 1.14	6.03	± 13.25	4.2

Table 9. Duration of Residence in Selected Reaches as a Proportion of Total Estuarine Residence Post-Tagging, Dee Estuary, 1991-93.

	Tagging to Thor 24.8- 34.7 km	Thor to Dside 34.7 - 38.8 km	Dside to Weir Cross 38.8 - 39.0 km
Mean	39.36	27.36	33.28
Std Devn	3.29	3.21	3.51
Maximum	98.60	94.46	94.41
Minimum	2.01	0.29	0.79
Observations	71.00	71.00	71.00

Table 12a) Comparison of Temperatures during Reach Residence and at Displacement.

Reach	Reach Exit Mean Temp.	Reach Res. Mean Temp.	No. of Observns	P (sig)
R2	15.91	15.67	7/7	0.87 (NS)
R3	13.77	13.67	6/5	0.96 (NS)
R4	11.72*	11.10*	5/5	0.74 (NS)
R5	14.56	14.74	26/25	0.78 (NS)

* Median

Table 12b) Comparison of Dissolved Oxygen levels during Reach Residence and at Displacement

Reach	Reach Exit Mean D.O.	Reach Res. Mean D.O.	No. of Observns	P (sig)
R2	8.92	9.52	6/7	0.77 (NS)
R3	6.23	8.26	6/4	0.24 (NS)
R4	8.90	9.28	5/5	0.41 (NS)
R5	8.74	8.78	24/23	0.84 (NS)

Dissolved Oxygen Concentration (mg/l).

Table 12c) Comparison of Residual Freshwater Flow during Reach Residence and at Displacement.

Reach	Reach Exit Mean Flow	Reach Res. Mean Flow	No. of Observns	P (sig)
R2	7.21	7.36	8/8	0.89 (NS)
R3	16.06	22.24	6/4	0.49 (NS)
R4	16.55	16.46	5/5	0.98 (NS)
R5	11.67	12.53	38/36	0.61 (NS)

Freshwater Flow at Chester Weir (cumecs).

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

[illegible]

Table 13. Multiple Regression R2 Values.

	Temperature		Dissolved Oxygen		Flow	
	MAX	MEDIAN	MIN	MEDIAN	MIN	MEDIAN
24	0.192*	0.833**	0.046	0.851**	0.002	0.475**
48	0.063	0.106	0.158	0.816*	0.005	0.496**
96	0.046	0.248	0.305	0.790*	0.012	0.281**

* P<0.05
** P<0.01

Table 14. Fates of Tagged Salmon Reaching Chester Weir by Year.

Fate	1991	1992	1993	TOTAL
NX *	4	7	6	17
TC	7	20	26	53
TR	2	10	20	32
WC	8	20	26	54
TOTAL	21	57	78	156

Table 15. Fates of All Tagged Salmon Reaching Chester Weir by Month (3 years pooled).

Fate	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	TOTAL
WX	-	-	-	13	3	1	-	-	17
TC	1	-	1	12	16	17	6	-	53
TR	3	-	2	8	4	12	3	-	32
WC	3	1	6	5	16	11	8	4	54
TOTAL	7	1	9	38	39	41	17	4	156

Table 16. Comparison of Number of Fish Arriving in the Weir Pools during and outside of Trap Fishing Times.

Year	P	No. Trap Fishing	No. Trap Not Fishing	Chi-Square Calculated	Chi-Square Critical
1991	N.S.	7	6	0.314	3.84
1992	N.S.	28	27	2.770	3.84
1993	P<0.001	48	19	21.950	10.83
Combined	P<0.001	83	52	13.230	10.83

Table 17. Numbers of Tagged Salmon crossing Chester Weir via the Weir Crest at Different Residual Flow Values and Different State of Tide.

Flow	HW Flood (-2 to +2 h)	Ebb Tide (+2 to +6 h)	Low Water (+6 to +10 h)	Total
4 to 8 cumecs	8 (89%)	1 (11%)	0 (0%)	9 (100%)
8 to 12 cumecs	8 (80%)	2 (20%)	0 (0%)	10 (100%)
12 to 20 cumecs	3 (50%)	2 (33%)	1 (17%)	6 (100%)
>20 cumecs	15 (52%)	6 (21%)	8 (27%)	29 (100%)
Total	34 (63%)	11 (20%)	9 (17%)	54 (100%)

Percentage within each flow class given in brackets ().

Table 18. Numbers and Percentages () of salmon crossing Chester Weir via the Trap Channel, Related to both Residual FW Flow and State of Tide.

Residual FW Flow	HW/ Flood (-2 to +2 h)	Ebb (+2 to +6h)	Low Water (+6 to +10h)	Total (%)
4 to 8 cumecs	11 (45.8)	4 (16.7)	9 (37.5)	24 (100)
8 to 12 cumecs	5 (33.3)	6 (40)	4 (26.7)	15 (100)
12 to 20 cumecs	6 (40)	4 (26.7)	5 (33.3)	15 (100)
> 20 cumecs	8 (29.6)	10 (37)	9 (33.3)	27 (100)
Totals	30 (37)	24 (30)	27 (33)	81 (100)

Table 19. Proportions of Tagged Salmon using the two different routes across Chester Weir during periods when Residual FW Flows were less than 22 cumecs, compared with State of Tide, Expected Frequencies in ().

State of Tide	Salmon using Trap Channel	Salmon using Weir Crest	Total
HW/ Flood -2 to +2	20 (25.7)	19 (13.3)	39
Ebb +2 to +6	14 (12.5)	5 (6.5)	19
Low Water +6 to +10	22 (17.8)	5 (9.2)	27
Total	56	29	85

Chi Square= 7.14, df= 2, p< 0.05.

Table 22. Proportions of Salmon showing Oscillatory or Non-Oscillatory Behaviour in the Trap Channel and Related to Trap Status at First Arrival in Fish Ladder, Chester Weir 1991-93.

Behaviour	Numbers Trap Fishing	Percentage	Numbers Trap not Fishing	Percentage
Trap Channel Oscillation	19	54	10	29
No Trap Channel Oscillation	16	46	24	71
Totals	35	100	34	100

Table 23. Weir Crossing Route Preference Related to Trap Status at Fish Ladder Entry, Chester Weir 1991-93.

Trap Status at Weir Pool Arrival	Recaptured in Trap	Trap Channel	Weir Crest	Failed to Cross	Totals
Number Arriving during trap Fishing	11.0	3.0	3.0	2.0	19
Percentage during Fishing	57.9	15.8	15.8	10.5	100
Number Arriving during Trap non Fishing Times	0.0	16.0	1.0	0.0	17
Percentage during Non-fishing	0.0	94.1	5.9	0.0	100

Table 24. Details of Impoundment Residence Amongst Salmon Kelts delayed for substantial periods in the impounded reach behind Chester Weir.

	Tag Number 29CF4	Tag Number 23EE4	Tag Number 23DF4	Tag Number 28EF4
Delay Hours	482:37:00	1039:54:00	431:27:00	122:35:00
Flow, Impoundment Entry/ cumecs	4.11	20.02	4.59	5.61
Weir Crossing Flow/ cumecs	9.15	26.38	5.02	7.99
Median Flow Impoundment	4.93	9.79	4.45	5.66
State of Tide, Weir Crossing	+4:00h	+1:00h	+2:00h	+2:00h
Tide Size/ m Impoundment Entry	7.50	8.00	9.70	7.70
Tide Size/ m Weir Crossing	9.40	7.60	7.80	9.40