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DEVELOPMENT OF A "WEIR-LESS" ELECTRODE ARRAY FOR A RESISTIVITY FISH COUNTER: RESULTS OF FIELD TRIALS IN 1993

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ABSTRACT

The versatility of resistivity fish counters is presently restricted by the need to mount the detector (an array of electrodes) on a man-made structure. This report describes progress in 1993 in developing a flexible electrode array attached directly to the river bed. The prototype array consisted of three tensioned steel cables laid in parallel across the stream channel. The array, connected to a microprocessor-based counter (Aquantic 1700A), was tested in the Water of Tanar and the Girnock Burn, both tributaries of the Aberdeenshire Dee. At the latter site, actual fish movements were observed with a time-lapse video system, to assess the accuracy of the counter with the prototype electrode array. In the range of river flows in which most salmon movements were observed, 92% of fish swimming upstream were registered correctly, similar to the accuracy achieved in previous trials with slack cable electrodes. The accuracy of the downstream count was greater in 1993 than 1992 (69% compared with 57%), but remained substantially lower than that of the upstream count. Since salmon swam repeatedly up- and downstream, this discrepancy resulted in an inflated estimate of the net upstream count. At low river levels, the accuracy of the counter was lower, but few fish movements were recorded at these times. A systematic difference in the accuracy of up- and downstream counts limits the ability of a fish counter to quantify salmon runs in situations where fish swim repeatedly up- and downstream. More accurate assessment of the passage of downstream-moving fish might be achieved by modifying their swimming behaviour. Possible methods of influencing swimming behaviour are discussed. Considerations in using this type of system in larger rivers are also addressed.

INTRODUCTION

Resistivity fish counters are widely used for monitoring numbers of anadromous salmonids ascending rivers. The information they provide is used for a variety of purposes. For example, counts of Atlantic salmon (*Salmo salar* L.) are used to assess long term trends in stock abundance (Mann *et al.*, 1983; Moores and Ash, 1984; Dunkley, 1991), to investigate environmental influences on upstream migration (Hellawell *et al.*, 1974; Jensen *et al.*, 1986; Alabaster, 1990; Welton *et al.*, 1990), to inform management of water resource use (Cragg-Hine, 1989) and fishing activities (Beaumont *et al.*, 1991; Potter and Dunkley, 1993), and to evaluate the effects of removal or amelioration of obstructions to migration (Holden, 1988).

Resistivity counters operate by detecting the fluctuation in conductivity between pairs of electrodes produced when the river water over them is displaced by a fish's body (Lethlean, 1953). The sensor, an array of parallel stainless steel strip electrodes, is normally mounted on a man-made structure to create a non-turbulent, swift flow of water over the electrode array. These conditions minimise the occurrence of spurious signals and encourage fish to move through the counting zone close to the electrodes without lingering, at least when moving upstream (Hellawell *et al.*, 1974; Dunkley and Shearer, 1989). Most resistivity counters have been mounted on existing fish passes, industrial weirs or flow-gauging structures, but Crump weirs have been built specifically to support fish counters at a few locations (Dunkley and Shelton, 1991; Appendix I).

In managing stocks of migratory salmonids, it is often desirable to monitor fish movements at several locations in a river system, such as at the entrances to different areas of the fishery or to different spawning tributaries. Requirements for short-term monitoring of fish movements may also arise that do not justify investment in a permanent counting facility; for example, evaluation of new measures to ease fish passage. At present, the application of fish counters is limited by the availability of suitable structures on which to mount them, and in the absence of these, by the difficulties associated with building a dedicated weir. Planning consent may not be granted readily for Crump weirs, the costs of construction are high and the structure may be subject to property tax. A resistivity counter with an electrode array mounted directly on the river bed would be cheaper to install, more versatile and less obtrusive than weir-mounted versions, creating the potential for more counters to be operated simultaneously and for individual counters to be moved to different sites as necessary.

In recent years, microprocessor-based counters have been developed for weir-mounted electrode arrays that utilise sophisticated self-calibration and signal processing procedures, resulting in substantial improvements in accuracy over older models (Holden, 1988). It is possible that these improvements enable microprocessor-controlled counters to cope with the sub-optimal conditions of flow and fish swimming behaviour that may be encountered in a natural river channel. Nevertheless, without an artificial structure to create uniform flow conditions, site selection is likely to be critical to the success of a weir-less counter.

In 1991 and 1992, Smith *et al.* (1993) investigated the feasibility of using the "Logie" counter (Aquantic Ltd) with an electrode array attached directly to the river bed. Flexible electrodes were used to facilitate installation of the electrode array on uneven surfaces and transportation of the counter between sites. An electrode array of three steel cables was installed in the Girnock Burn, a tributary of the Aberdeenshire Dee, to monitor the spawning run of Atlantic salmon. The electrodes were anchored at each end to the river bed and pulled taut by hand, but river flow-induced drag caused them to sag downstream. As a result, the electrodes were not straight or parallel. Nevertheless, more than 90% of fish swimming upstream were detected accurately. However, less than 60% of downstream-moving fish were registered correctly by the counter and false counts were caused by fish moving over the electrode array without crossing it completely. The most serious problem was non-detection of fish moving downstream. An obvious improvement that could be made to the counter was in the geometry of the electrode array and it was suggested that tensioning the cables to hold them straight and parallel might improve the counter's performance (Smith *et al.*, 1993).

The aims of the present study were to assess the practicability of using tensioning devices to improve the geometry of a steel cable electrode array and to assess the effect on counter performance of this modification. Devices to tension the cable electrodes were tested in the Water of Tanar. The performance of a "Logie" counter with the modified cable electrode array was assessed in the Girnock Burn, at the same site used previously.

MATERIALS AND METHODS

Study Sites

A prototype electrode array connected to a "Logie" fish counter (1700A, 24 V DC version, software version 5.30, Aquantic Ltd) was tested at two sites in 1993: in the Water of Tanar at Tanarside (23 August–9 September) and in the Girnock Burn at Littlemill (22 October–29 November). These sites were chosen for their relatively shallow, non-turbulent flow of water. Both rivers are tributaries of the Aberdeenshire Dee (Fig. 1). At Littlemill, the accuracy of the counter was assessed by comparing actual fish movements observed with a closed-circuit television (CCTV) system with those registered by the counter, during the spawning run of Atlantic salmon into the Girnock Burn. It was not possible to set up a CCTV system at Tanarside, due to difficulties in accessing mains electricity.

Counter System

At both sites, boulders were arranged on the river bed to create a near-level base for the electrode array (Plates I and II). A "Logie" counter was connected to three 6 m lengths of galvanised steel cable (diameter 14 mm), laid in parallel across the stream bed 0.45 m apart, attached at their ends to steel stakes (48 cm long) driven into the stream bed. In the Water of Tanar it was not possible to drive stakes into the bedrock river bed near one bank, so at that end of the array, the cables were attached to a thick wooden board, which was lashed to nearby boulders. Each cable was held straight by tensioning it with a straining screw (a device consisting of a cylindrical body with eyed bolts at each end which can be screwed in or out by turning the central body: 12.7 mm diameter). At Littlemill, a lightweight, white plastic sheet was laid underneath the electrodes and held in position by steel stakes. This sheet provided a contrasting background against which fish were conspicuous on CCTV.

Digitised signals, representing fluctuations in resistivity between the up- and downstream halves of the electrode array, were transmitted by a serial cable link from the "Logie" counter to a personal computer (T2000SX, Toshiba Corporation) and were stored on magnetic disk for subsequent examination. The magnitude of digitised signals was set to vary between 0 and 127 (arbitrary units of the output from the counter's analogue to digital converter). At intervals, details of the date, time, size and classification of signals logged in the counter's memory were also downloaded to the computer for later analysis.

Closed-Circuit Television System

A camera (National WV-1350E/B with a Computar A1 f8.5 lens) in a weatherproof housing (Molynx WDH) was mounted 6 m above the level of the stream bed on a scaffold tower on one bank, viewing the electrode array at a vertical angle of approximately 40°. At night the scene was illuminated by three far red flood lamps (Molynx Infra-Red Illuminator, 500 W, 50% transmission at 716 nm, 0% at 686 nm) mounted on a frame supported by tensioned cables 2 m above the stream bed, 1 m downstream from the electrode array. The camera was connected to a time-lapse video recorder (Panasonic AG-6720) set to record at a rate of one frame every 0.16 or 0.32 s. Video tapes were viewed in their entirety and the time and character of all fish movements were noted.

Statistical Methods

The significance of differences between proportions was tested with Fisher's exact test. Proportions were compared with theoretical values using the goodness of fit G test (Zar, 1984).

RESULTS

Water of Tanar Trial

Although it was not possible to set up the television system to validate the counter's records at this site, experience was gained in deploying a steel cable electrode array in a larger river than previously. The use of bottle screws to tension the steel cables against river flow-induced drag was successful in holding the cables straight and parallel. This caused the cables to be held above the river bed in some places along their length. However, there was no excessive accumulation of debris or oscillation of the cables, although it should be noted that river flow remained low throughout the 18 day study period.

The baseline signal from the counter showed little fluctuation (Fig. 2). The counter generated 157 signals, 17 registered as upstream fish passages, 15 as downstream fish passages and 125 as unidentified events (signals less than a threshold magnitude and larger signals that did not pass the counter's signal discrimination algorithm). Examples of the signals recorded at Tanarside are illustrated in Figure 2.

Girnock Burn Trial

Fish movements observed with CCTV

Movements of salmon and sea trout over the prototype electrode array were monitored simultaneously with the CCTV system and the counter for a total of 645.87 h. Up- and downstream movements were observed with CCTV from 1 November (Fig. 3) after a period of low river flow. During the study period, river flow was generally lower than the seasonal norm. Water level gauged at a site 600 m upstream exceeded 0.35 m (corresponding approximately with the mean weekly minimum discharge rate for this time of year; Youngson *et al.*, 1983) for only 26% of the time.

Up- and downstream movements occurred at all times of day and night, although activity tended to be greatest 1–4 hours after dusk (Fig. 4). Sunset was at 1628–1556 h (GMT) and sunrise at 0723–0758 h, and overall, daytime constituted 35.5% of the study period. During low river flows, both up- and downstream movements were predominantly nocturnal. When water level was less than 0.35 m, only 20.9% of upstream movements and 18.9% of downstream movements occurred during the day: significantly fewer than would be expected if movements were randomly distributed between day and night (G_1=9.21, P<0.005 and G_1=11.96, P<0.001, respectively). However, during higher flows (water level ≥0.35 m), 50.0% of upstream movements occurred during the day: significantly more than would be likely to result from random occurrence with respect to time of day (G_1=10.07, P<0.005). Downstream movements were more evenly distributed between day and night (42.6% during the day) when river flow was elevated (G_1=2.34, P>0.10).

Counter performance

The accuracy of the counter has been estimated during low water levels (<0.35 m), from 6–7 November and 11–17 November, and during elevated water levels (≥0.35 m), from 8–10 November and brief periods on the 13, 15 and 16 November. Prior to 6 November, the sensitivity of the counter was impaired by a fold in the backing sheet that partially obscured the downstream electrode. Since the backing sheet was required only for CCTV monitoring, this is not a problem that would arise in routine use of this type of counter and data from that initial period are not considered further.

a) Elevated Water Levels

During periods of elevated water levels, when most fish movement was recorded, there was a difference in directionality and speed between up-and downstream-moving fish, as noted at this site in 1992 (Smith *et al.*, 1993). Most fish moved upstream over the electrode array within 1–3 s, on a course approximately perpendicular to the electrodes, while fish passing downstream tended to move more slowly, predominantly tail first, often taking several seconds to pass the electrode array. One fish took 16 s to pass downstream. Downstream-moving fish were often not aligned perpendicularly to the electrodes and frequently paused, turned or veered sideways as they crossed them. These differences in swimming behaviour influenced the size and shape of signals generated by the counter.

The net upstream count registered by the counter (+31) was greater than that observed with CCTV (+6). This discrepancy resulted from greater accuracy for upstream counts than downstream counts. 92.1% of upstream movements were registered correctly by the counter, compared with 68.5% of downstream movements (Table 1).

False counts, representing 3.6% of upstream counts and 7.5% of downstream counts respectively, were caused by fish moving over the electrode array without crossing it completely (Table 1). A common cause of false counts was fish moving downstream over the array and then moving back upstream. This type of activity was detected by the counter on 17 occasions, six of them resulting in false counts (two upstream, four downstream). In addition, two fish that eventually crossed downstream after vacillating over the electrode array, were registered by the counter as upstream-moving fish. During elevated water levels, false counts occurred only when fish were present over the electrode array.

b) Low Water Levels

Relatively few fish movements were recorded by CCTV in low water levels (Fig. 3). Fish were often partially emersed as they crossed the array and seemed more likely to pause over the array or move sideways relative to the current than during higher flows, particularly when moving upstream. The net upstream count registered by the counter during low water levels was the same as that observed with CCTV (+2). However, only 58.3% of upstream movements and 59.1% of downstream movements were registered correctly during low water levels (Table 2). The accuracy of upstream counts was significantly less during low compared with elevated water levels (Fisher's test, $P<0.001$), but the accuracy of downstream counts did not differ significantly between the two categories of water level ($P=0.607$).

False counts were also registered during the period of low water levels due to incomplete or indirect crossings (three false upstream counts, 1 downstream). In addition, one downstream count was registered when no fish were present over the electrode array, possibly due to turbulence and entrained air that occurred when water barely covered the electrodes. The difference in the incidence of false counts between periods of low and elevated water level was not statistically significant (upstream counts, $P=0.099$; downstream counts, $P=0.369$).

c) Comparison with 1992 Trial

The present data, collected at the same site in the Girnock Burn at which an earlier prototype electrode array was tested in 1992, allow comparison of the accuracy of the counter in the two years. In 1992, the steel cable electrodes lay slack on the river bed and bowed downstream, so that they were not evenly spaced or parallel along their length, whereas in 1993, they were tensioned, straight and parallel. Since water level rarely dropped below 0.35 m during the 1992 study period, the results of that trial have been compared with the period of elevated water levels in the 1993 study period.

The user-defined thresholds of signal size for up- and downstream counts were set to 15 units in 1992 and 18 units in 1993. To make the data sets more comparable, the 1992 results have been re-analysed with the threshold signal size set to 18 retrospectively, by considering all up- or downstream counts with a signal size of less than 18 as unidentified events (Table 3). Artificially increasing the threshold in this way made little difference to the reliability of detection of upstream-moving fish in 1992 (91.1% after re-analysis, compared with the original figure of 93.4%) or downstream-moving fish (56.7% vs. 59.6%). The relative incidence of false upstream counts (1.5% vs. 3.1%) and false downstream counts (13.6% vs. 23.7%) were reduced somewhat, principally by eliminating counts due to fluctuations in the baseline signal.

The net upstream count registered by the counter in 1992 was 103, compared with a net upstream movement of 33 observed with CCTV. During elevated water levels in 1993, the equivalent figures were 31 and 6, respectively. The reliability of detection of upstream-moving fish and the relative incidence of false downstream counts did not differ significantly between the 1992 trial (with a threshold of 18 units) and periods of elevated water levels in 1993 (Fisher's test; P=0.496 and P=0.115, respectively). However, the reliability of detection of downstream-moving fish was significantly greater in 1993 than 1992 (68.5% compared with 56.7% of downstream movements; P=0.026). There was also a small, but statistically significant increase in the relative incidence of false upstream counts in 1993 compared with 1992 (3.6% compared with 1.5% of upstream counts; P=0.035).

DISCUSSION

The combination of the Logie counter and an electrode array of tensioned steel cables was capable of detecting fish moving upstream with a high degree of accuracy, similar to that achieved with untensioned cables in 1992 (Smith *et al.*, 1993). The accuracy of the downstream count, however, was greater than in the 1992 trial. This may have been due to the improved geometry and stability of the electrode array, but it should be borne in mind that there may have been other relevant differences between the two study periods, such as those related to river flow prior to and during observations, which may have affected conditions over the electrode array or fish migratory activity and swimming behaviour.

Despite the improvement in the proportion of downstream-moving fish registered correctly by the counter, underestimation of the downstream count remained substantially worse than that of the upstream count. As with other designs of resistivity fish counters, fish were not registered reliably when they paused or turned while crossing the electrode array, or when they passed with the long axis of their bodies misaligned with the direction of river flow, and therefore not perpendicular to the electrodes (Dunkley and Shearer, 1982; Holden, 1988). These swimming characteristics tend to cause fluctuations in conductivity between the electrodes that are too small, or do not conform to the pattern expected of fish, for them to be reliably identified (Dunkley and Shelton, 1991).

In the present study, non-ideal swimming behaviour and non-detection by the counter were usually associated with downstream-moving fish. During low river flows, however, the reliability of detection of upstream-moving fish was also low. It seems likely that this was due to the reduced tendency of upstream-moving fish to pass through the counting zone directly and continuously, compared with their ascent in higher flows. Fish appeared to have difficulty in finding a route over the electrode array in low water levels. Nevertheless, the low level of fish activity and net upstream movement during low river flows meant that the greater error in the upstream count in these conditions did not have a significant impact on the accuracy of the counter's estimate of net upstream movement.

In contrast, during moderately elevated water levels, underestimation of downstream movements relative to upstream movements, in combination with the tendency of fish to swim repeatedly up- and downstream over the electrode array, resulted in an inflated estimate of the net upstream count. Repeated ascent and descent within sections of river seems to be a common feature of Atlantic salmon migration (Kristinsson and Alexandersdóttir, 1978; Dunkley and Shearer, 1982; Holden, 1988; Webb, 1989; Clarke and Purvis, 1990; Laughton, 1991), particularly in tributaries during the spawning period (Webb and Hawkins, 1989; Baglinière *et al.*, 1990, 1991). In the present study, the presence of a fish trap and its associated structure a short distance upstream from the electrode array might have hindered upstream migration and exacerbated this tendency. If fish counters are to be used where fish swim repeatedly up- and downstream, the reliability with which they are detected should not differ systematically between the two directions of movement. Alternatively, if the errors in registering fish moving in either direction are relatively constant within the range of flows in which fish are most active and large numbers of fish are likely to be counted, the estimate of net upstream movement might be improved by applying a correction to the up- and downstream counts. The consistency of the counter's accuracy would need to be assessed over a wider range of conditions than prevailed during the present study to determine the validity of applying such a correction.

It is likely that further improvement in the accuracy of downstream counts with a weir-less counter will be possible only if fish moving downstream can be made to align their bodies perpendicularly to the electrodes and move over the array without stopping. A device upstream from the electrode array that caused fish moving downstream tail-first to turn and swim head-first over the array could achieve these objectives. Since fish seemed more likely to swim downstream head-first in daylight than at night, it may be that subdued illumination of the electrode array at night, or the section of river upstream from it, would result in similar behaviour. Another possible solution may be to provide a strongly directional stimulus a short distance upstream from the electrode array to which fish might align their bodies. This could be a visual stimulus, such as a zone of contrasting parallel stripes aligned with, or perpendicular to, the direction of flow, or a tactile stimulus, such as a row of streamers or jets of air across the channel (which may also be associated with acoustic and visual stimuli). Any such device would need to be effective in modifying downstream swimming behaviour under a wide range of river conditions during both day and night, without inhibiting migration in either direction, or impairing the counter's sensitivity.

More complex electrode arrays, with a greater number of electrode pairs, to allow the position of fish over the array to be determined more precisely, might be better able to deal with non-ideal swimming behaviour, but monitoring and interpreting the signals from complex arrays would be likely to require greater computing power in the controlling microprocessor.

There is a need to assess the performance of this type of counter system in higher river flows. Although most fish movements recorded in the Girnock Burn in 1993 occurred during increases in river flow, these increases were comparatively small for the time of year. Higher flows will be associated with greater water depth at any one site, making it possible for fish to swim at a greater height above the electrodes, reducing the change in inter-electrode conductivity that they induce. Since fish moving upstream tend to swim close to the substratum and downstream-moving fish may be distributed throughout the water column (Hellawell *et al.*, 1974; Dunkley and Shearer, 1989), greater water depth may increase the difference in accuracy between up- and downstream counts.

If the accuracy of the downstream count can be improved, the next stage in the development of a river bed-mounted electrode array would be to investigate its use in larger rivers. Larger rivers may also offer more scope for selecting a site where downstream movements of pre-spawning adult salmon are infrequent, thereby mitigating the effects of inaccuracies in the downstream count (Holden, 1988; Dunkley and Shelton, 1991). However, scaling-up river bed-mounted electrode arrays presents a number of problems.

The difficulties in assessing the accuracy of prototype counters are likely to increase with the size of the river. Viewing the counting zone with CCTV in wider rivers may necessitate larger and more elaborate structures on which to mount cameras and lamps, unless the electrode array can be installed next to an appropriate existing structure spanning the river. In addition, water depths, turbulence and turbidity typical of spates in large salmon rivers would tend to obscure the view of the counting zone at a time when frequent fish movements might be expected (Banks, 1969; Milner, 1990).

Regarding operation of the counter itself, spanning wider channels with a river bed-mounted electrode array poses four main problems. First, in larger rivers, there may be fewer sites with adequate hydraulic conditions for fish counting (in terms of current speed, water depth and turbulence) across the entire width of the channel. Second, there will be greater practical difficulties in installing longer electrodes directly on the river bed without requiring a level of construction work that would negate the advantages of a weir-less system. If flexible electrodes are used, greater difficulties may be experienced in tensioning them. River flow induced drag would increase substantially with the increased surface area presented by steel cable electrodes. This would be exacerbated by accumulation of debris. The greater force exerted on the electrodes would require stronger foundations than the stakes used in the present study. Third, bulk resistance between the electrodes of a resistivity counter decreases as electrode length increases (Anon., 1992). This diminishes the change in conductivity produced by a fish's body, thereby reducing the sensitivity of the counter. The recommended maximum length of weir-mounted strip electrodes for the Logie counter is 20 m, depending on the range of river water conductivity (Anon., 1992). Fourth, the wider a counter channel is made, the greater will be the chances of more than one fish crossing the electrode array simultaneously, leading to non-detection of fish.

These problems could be overcome to some extent by spanning the channel with several short electrode arrays, electrically isolated from each other, rather than one long array. Counter control units exist that are capable of monitoring several channels simultaneously, to cater for multiple electrode arrays mounted on compound weirs (Holden, 1988). However, the cutwaters separating sections of different height on a compound weir physically constrain fish to move over only one array during a single crossing. If several electrode arrays were simply placed end to end on the river bed, there would be a risk that some fish would pass over more than one array during a single crossing. This might result in individual fish being counted more than once, if they pass the junction of two arrays and cause a characteristic fluctuation in conductivity at each. Alternatively, they may not be counted at all if changes in inter-electrode conductivity take place over more than one array, so that the signal is fragmented between different recording channels of the counter. Some means of preventing individual fish from passing over more than one array, without creating insensitive areas between arrays, would be required with a multiple array mounted on the river bed.

In conclusion, the accuracy of the downstream count needs to be improved and maintained over a range of river flows before the present type of weir-less electrode array could be used for routine counting of salmon. Unmodified, the present system would be likely to overestimate the true net upstream movement by an amount that would depend on the absolute numbers of up- and downstream movements and on the actual error rates, which might vary between sites. The present system could, however, be used to detect times and general levels of migratory activity without quantifying the net upstream movement.

Further experimentation with river bed-mounted electrode arrays requires a site with frequent fish movements up- and downstream over a protracted period, to allow modifications to the system to be made and tested. In general, salmon are only present in small rivers such as the Girnock Burn during a short period at spawning time. Future study sites will therefore need to be in larger rivers in which salmon may begin moving earlier in the year, if prototype counters are to be tested under natural conditions. The present study indicated that salmon or sea trout move within the Water of Tanar in late summer, albeit infrequently in low river flows. The technical difficulties encountered at Tanarside can be overcome and given adequate river conditions this may be a suitable study site in the future, although variability in accuracy between sites should also be examined.

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TABLE 1

Performance of the counter during periods of elevated water levels in the Girnock Burn, November 1993

Event	Number
Movements recorded by CCTV	
Upstream	114
Downstream	108
Net upstream movements	6
Events correctly counted	
Upstream	105
Downstream	74
Other events	35
Upstream movements not counted	
Signal generated	6
No signal generated	3
Downstream movements not counted	
Signal generated	14
No signal generated	18
False upstream counts	
No fish present over electrode array	0
Incomplete crossing	4
Downstream movement	2
False downstream counts	
No fish present over electrode array	0
Incomplete crossing	6
Upstream movement	0

TABLE 2

Performance of the counter during periods of low water levels in the Girnock Burn, November 1993

Event	Number
Movements recorded by CCTV	
Upstream	24
Downstream	22
Net upstream movements	2
Events correctly counted	
Upstream	14
Downstream	13
Other events	46
Upstream movements not counted	
Signal generated	5
No signal generated	4
Downstream movements not counted	
Signal generated	4
No signal generated	4
False upstream counts	
No fish present over electrode array	0
Incomplete crossing	2
Downstream movement	1
False downstream counts	
No fish present over electrode array	1
Incomplete crossing	0
Upstream movement	1

TABLE 3

Performance of the counter during the 1992 trial with threshold signal size for up- and downstream counts set to 15 or 18 units

Event	Threshold setting	
	15 units	18 units
Events correctly registered by counter		
Upstream	283	276
Downstream	161	153
Other events	1312	1342
Upstream movements not registered by counter		
Signal generated	10	17
No signal generated	9	9
Downstream movements not registered by counter		
Signal generated	38	47
No signal generated	69	69
False upstream counts		
No fish present over electrode array	4	0
Incomplete crossing	3	3
Downstream movement	2	1
False downstream counts		
No fish present over electrode array	29	3
Incomplete crossing	20	20
Upstream movement	1	1

Figure 1. Location of the study sites used in 1993:

a) Littlemill, Girnock Burn
b) Tanarside, Water of Tanar

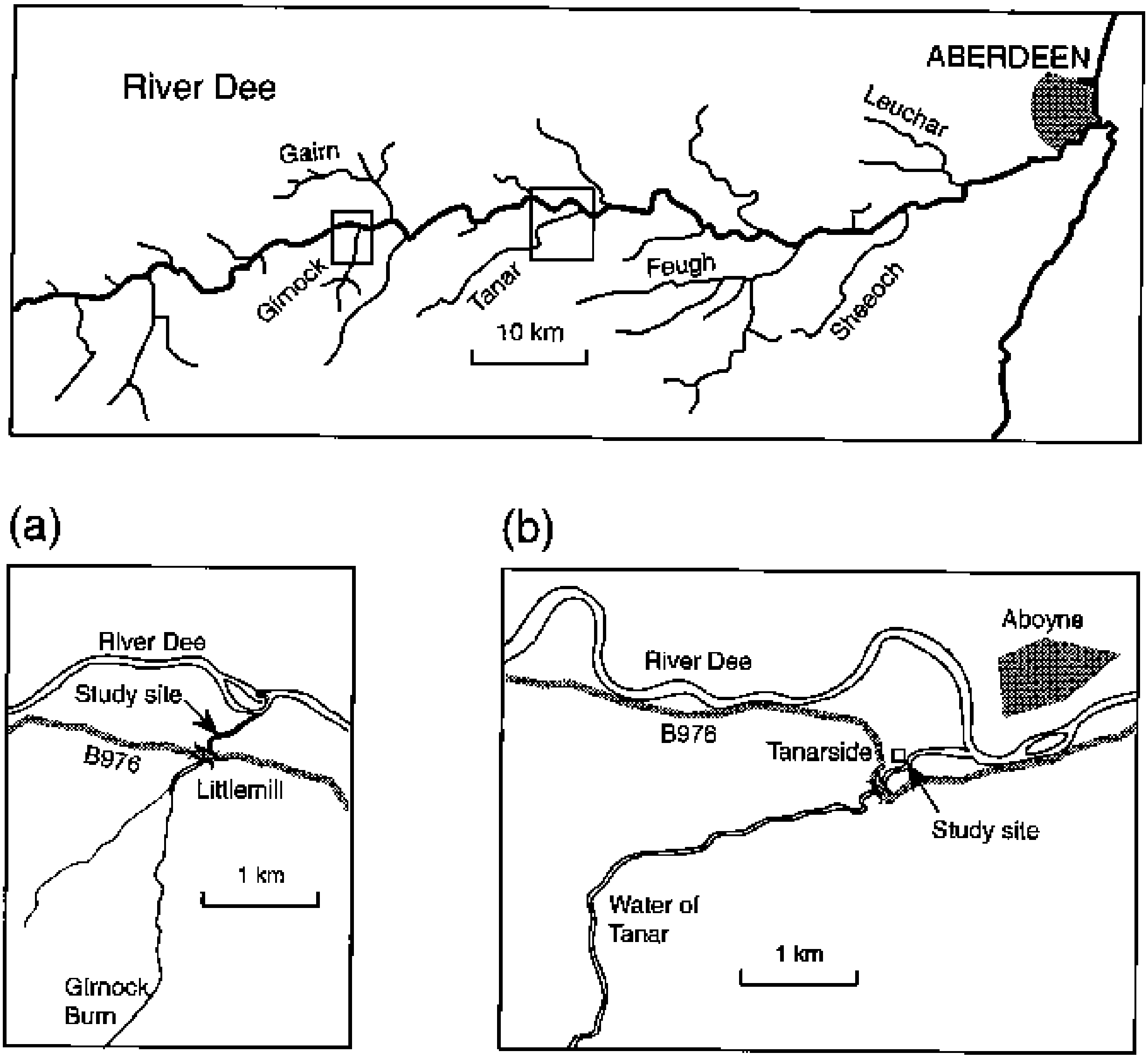

Figure 2. Examples of signals recorded during trials of the cable electrode array in the Water of Tanar in August and September 1993: a) baseline signal, b) upstream count, c) downstream count, d) event probably caused by two fish moving downstream.

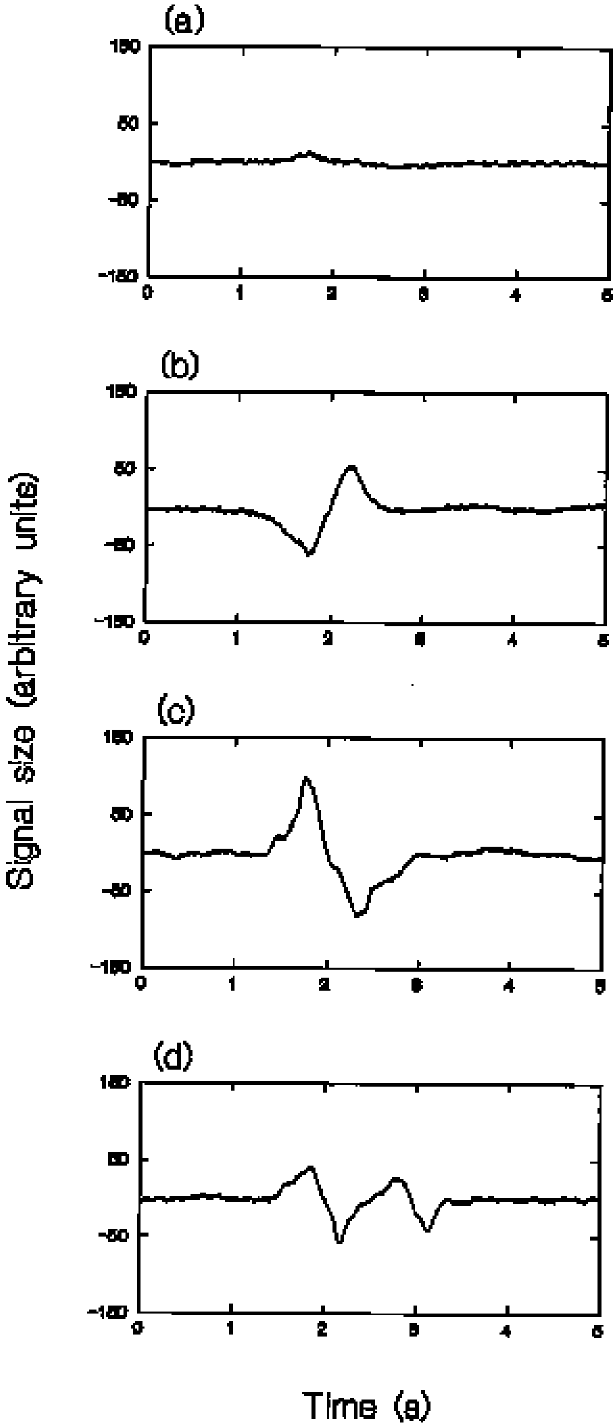

Figure 3. Up- and downstream movements of salmon over the prototype electrode array during the day (□) and night (■) recorded by CCTV in the Girnock Burn, November 1993.

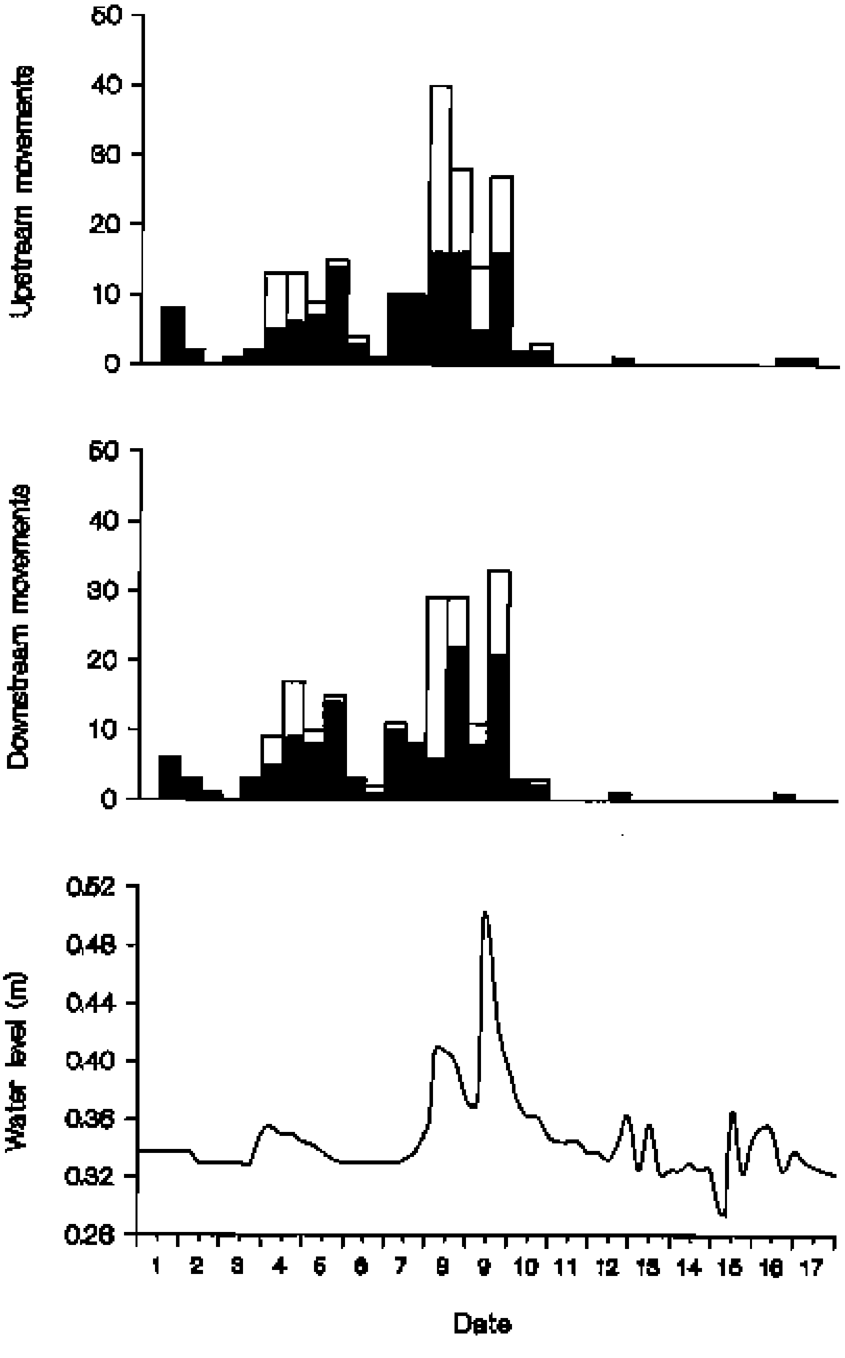

Figure 4. Diurnal variation in salmon movements over the prototype electrode array in the Girnock Burn, November 1993. The average photoperiod during the study is indicated by the bar (black=night; white=day).

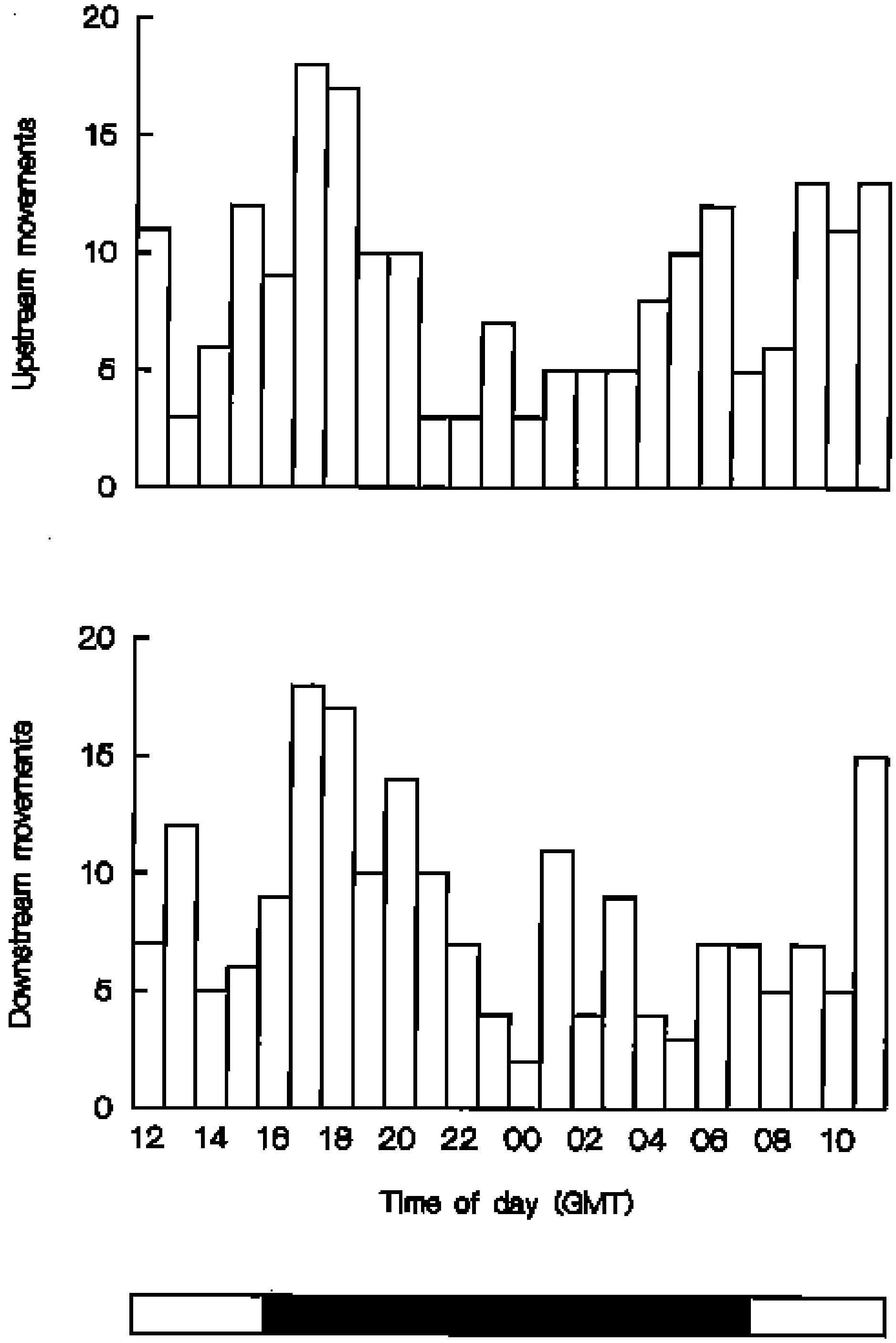

Plate I. The prototype electrode array of tensioned galvanised steel cables in the Water of Tanar.

Plate II. The prototype electrode array in the Girnock Burn, showing the CCTV camera mounted on the scaffold tower, lamps mounted on the suspended steel frame and white backing sheet underneath the electrode array.

APPENDIX I

Automatic fish counters in Scotland

Site (OS grid ref)	River*	Structure	Make/model of counter	No of channels
Operated by SOAFD				
Logie (NO 699640)	North Esk	Crump weir (GRP)†	Aquantic 2100A	3
Inchbare (NO 604662)	Westwater [North Esk]	Crump weir (GRP)†	Aquantic 2100A	3
Whitley Fish Counter, near Banchory Devenick (NJ 918029)	Dee (Grampian)	Crump weir (GRP)†	Aquantic 2100A (2 units)	5
Torrish (NC 979185)	Helmsdale	Concrete weir, GRP insulation	Aquantic 2100A	3
Grimersta, Lewis (NB 215297)	Grimersta	Timber ramp (experimental)	Aquantic 1700A	1
Morsgail, Lewis (NB 139225)	Morsgail	Sluices from Loch Morsgail	Aquantic 2100A	3
Islay (NR 311569)	Laggan	Crump weir (GRP)†	Aquantic 2100A	3
Operated by Scottish Hydro-Electric plc				
Awe barrage (NN 045288)	Awe	Borland lift	H-E Mk X‡	1
Aigas dam (NH 474437)	Beauly	Borland lift	H-E Mk X	1
Beannachran dam (NH 315391)	Farrar [Beauly]	Borland lift	H-E Mk X	1
Torr Achilty dam (NH 447545)	Conon	Borland lift	H-E Mk X	1
Meig dam (NH 376561)	Meig [Conon]	Borland lift	H-E Mk X	1
Invergarry (NH 276021)	Garry [Oich, Ness]	Borland lift	H-E Mk X	1
Mucomir dam (NN 183840)	Lochy	Borland lift	H-E Mk X	1
Morar dam (NM 683922)	Morar	Pool/overfall ladder	H-E Mk X	1
Dundreggan dam (NH 358157)	Moriston [Ness]	Borland lift	H-E Mk X	1
Lairg dam (NC 575069)	Shin	Borland lift	H-E Mk X	2
Shin diversion dam (NC 561051)	Shin	Borland lift	H-E Mk X	1
Pitlochry dam (NN 935577)	Tummel [Tay]	Pool/orifice ladder	H-E Mk X	1
Clunie dam (NN 885609)	Tummel [Tay]	Pool/orifice ladder	H-E Mk X	1
Lochay dam (NN 543351)	Lochay [Tay]	Borland lift	H-E Mk X	1
Stronuich dam (NN 507420)	Lyon [Tay]	Weir	H-E Mk X	1

Site (OS grid ref)	River[*]	Structure	Make/model of counter	No of channels
Operated by Scottish Power plc				
Tongland dam (NX 702420)	Dee (Kirkudbright)	Pool/orifice/ overfall ladder	H-E Mk VIII	1
Loch Doon dam (NS 477015)	Doon	Overfall ladder	H-E Mk VIII	1
Operated by Tay District Salmon Fishery Board				
Westfield, Blairgowrie (NO 176463)	Ericht [Isla, Tay]	Pool/traverse ladder	H-E Mk X	1

[*] Where counters are situated in tributaries, the rivers downstream are named in square brackets. Names in round brackets indicate the geographical location of rivers with non-unique names.

[†] Purpose-built compound Crump weir of glass-reinforced plastic (GRP) deck sections mounted on triangular steel supports fixed to trench sheeting foundations in the river bed.

[‡] Hydro-Electric electronic fish counter. Electrode arrays for these counters are mounted on a GRP flume attached to the fish pass or weir.