Effects of flow regime on the young stages of salmonid fishes - Summary and Conclusions based on results for 1981-1985.

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FRESHWATER BIOLOGICAL ASSOCIATION

PROJECT 73

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Effects of flow regime on the young stages of salmonid fishes - Summary and Conclusions based on results for 1981-1985.

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CONTENTS

SUMMARY

1. The report brings together the results of physical and biological studies made during 1981-85.

2. Future research needs are listed and the practical relevance of this research area is briefly discussed.

INTRODUCTION

The main British salmonid species spawn in clean gravel in streams and rivers, many of them in the upland areas of Britain. The earliest stages of the life cycle (eggs and alevins) spend some months within the gravel of the river bed. During this period their survival rate can be strongly influenced by flow regime and by related phenomena such as movement of coarse river bed material, changes in water level and the deposition of silt. It is also likely that the survival and/or rate of downstream dispersal of free-swimming young stages will be influenced by flow regime.

In recent years human influence upon the flow regimes of upland water courses and upon the sediment inputs to them has increased. This largely reflects an increase in the rate of change of upland land use through such activities as impoundment, water transfer, forestry, land drainage and land improvement.

In order to conserve and, if possible, enhance the populations of salmonid fishes (which are an important commercial and sporting resource) deeper understanding of the interrelationships between survival of young salmonids and flow-related phenomena is needed. The acquisition of appropriate information is the main aim of the present project.

During a previous contract term (1977 to 1981) the study was of an exploratory nature and was wide ranging. During the present term (1981 to 1985) attention has been concentrated on a limited number of themes which were considered to be of greatest importance.

The detailed results of the project are available to customers as a series of offprints of primary publications, photocopies of manuscripts of papers "in preparation" or "in press" and unpublished reports to customers. These documents are listed in Appendix 1. In addition to accounts of work done during the 1981-1985 contract term, Appendix 1 lists offprints of some papers presented as manuscripts at the close of the previous contract term. A copy of the summary report on the contract term 1977-1981 (Crisp, 1981) is included in Appendix 1 as background to the present report. That report listed eleven possible subject areas for more intensive future study (Appendix 2) and all but four of these have received attention during the contract term.

The work during 1981-1985 has contained the following main elements:

1. Methodological and other background work which was essential to further progress.
2. Studies on silt movement and the infilling of gravel voids by fine sediments, together with initial studies on the relationship between intragravel oxygen supply rate and the survival of intragravel stages of salmonids (See Appendix 2, items 1, 2* & 7*).
3. Studies in the general field of egg washout. These included investigations of the physical background to gravel bed disruption, examination of the physical characteristics of sites chosen for redds, dimensions of redds and burial depth of eggs relative to the size of the fish constructing the redd and a series of smaller studies on other aspects of egg washout. (See Appendix 2, items 4*, 6* & 8*).

4. Further experiments on young free-swimming salmonids in Grassholme channels.(See Appendix 2, item 11*).

An important feature of the work has been in the combination of physical and biological aspects. Some elements have demanded, and received, joint inputs from the outset. In other elements, perhaps the majority, it has been expedient for the physical and biological investigations to start from different points and converge towards a common end. One of the purposes of the present report is to draw these threads together as far as possible. This, inevitably, leads to a somewhat simplified summary but any more detailed information required by the reader will be found in the papers listed in Appendix 1.

RESEARCH RESULTS

1. Methodological and background studies.

a. Freeze coring:

This technique for the acquisition of relatively undisturbed cores of gravel from the beds of streams, based on apparatus described by Walkotten (1973, 1976), was further developed (Carling, 1981) during the first contract term. During the current term it has been widely exploited for the investigation of gravel composition and for determining the burial depths of eggs.

b. Intragravel flow and dissolved oxygen concentration.

Apparatus for intragravel flow was described by Turnpenny & Williams (1982) but its use in Teesdale presented practical problems, particularly in calibration. These have been overcome (Carling & Boole, in prep.). The apparatus can now be used to measure seepage velocity

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* = Five topics identified as being of the highest priority in Appendix 2.

in gravels and, in conjunction with dissolved oxygen measurements, to estimate the oxygen supply rate to eggs in the field (Carling, 1985b).

c. Suspended sediment concentration.

Tests were made of two different methods of taking streamwater samples for the estimation of suspended sediment concentration (Carling 1984a).

d. Artificial eggs.

Artificial **trout** eggs were developed by Ottaway (1981). These had a number of potential applications in the study of egg washout and egg drift but it was necessary first to test their performance relative to real eggs. As far as possible, such tests have now been made (Crisp, 1984) and the general conclusion is that their physical characteristics and their performance during drifting are, with one or two **provisos**, similar to those of real salmonid eggs.

e. Grassholme channels.

Preliminary experiments with young salmonids in Grassholme channels were described by Ottaway & Clarke (1981) and Ottaway & Forrest (1983). The results of both these experiments were of considerable interest, but their interpretation raised important questions relating to channel management, experimental design and statistical analysis of the results. Therefore, in order to establish a firmer base for the interpretation of future experiments, an extensive programme of background work was undertaken. The main elements were:

i. Empirical calibration observations relating to the management of flows in the channels, variations in depth and velocity between channels and within channels, and the repeatability of channel settings. Statistical analysis of the results clearly indicated that the channel system had a number of imperfections but that, as hoped, the main source of variation in depth and velocity between channels could be attributed to the channel settings (Crisp & Hurley, 1984).

ii. Development of an acceptable experimental design and of suitable statistical methods to analyse the results (Hurley, in prep.).

iii. Development of improved methods for the collection of fish leaving the downstream ends of the channels and for removing and enumerating residual fish at the close of each experiment (Crisp, 1983).

These essential methodological exercises were a heavy drain on resources during the first half of the contract term.

2. Silt transport and deposition and the survival of the intragravel stages of salmonids.

Studies on the structure, composition and bulk properties of stream gravels (Carling & Reader, 1982) are the main starting point for consideration of the processes of silt movement and deposition and also of the process of gravel bed disruption (see next section). This work provided a conceptual basis on which to view coarse sediment deposits. The streambed is regarded as a framework of large clasts (stones) infilled by a matrix of fine material. Processes of movement of bed material occur at two levels. First, winnowing movement of the matrix (finer materials) at lower flows. Second, substantial reworking of both matrix and framework at higher flows.

Sediment supply and transport were studied in two natural upland streams and in the lowland reaches of the regulated River Tees. The studies in the two upland streams (Carling, 1983) were concerned with particles down to 0.45 μm diameter. Concentration at baseflow was c. 3.0 mg l^{-1} but arithmetic mean values over the whole observed discharge range were 30 & 22 mg l^{-1}

and ranges were 818-0.8 and 408-1.0 mg l^{-1} in Carl Beck and Great Eggleshope Beck respectively. Sediment supply could be related to discharge via rating curves. However, during the course of individual spates the relation of sediment concentration to discharge was more accurately represented by "rating loops". Total transport in 1980 was 24.77 tonnes km^{-2} of catchment $year^{-1}$ in Carl Beck and 12.09 tonnes $km^{-2}year^{-1}$ in Great Eggleshope Beck. The organic content of the sediment varied from 33 to <1.0 mg l^{-1}, with a mean of 4.8 mg l^{-1}(i.e. c. 20% of the total). Analysis of data from the River Tees at Broken Scar (Carling & Douglas, 1984) showed that the total load carried (c. 15.8 tonnes $km^{-2}year^{-1}$) was similar before and after construction of Cow Green reservoir and that sediment transport was supply-limited, at least up to an annual cumulative discharge of 6×10^8 m^3year^{-1}. These two studies on sediment transport defined the typical suspended sediment concentrations and transport rates which can occur. They also indicated that, although concentration could be approximately related to discharge, the main factor limiting concentration and transport was the rate of supply of fine sediment to the stream. Sediment inputs can be classified as temporally periodic or aperiodic and as spatially diffuse or point-source in origin. Periodic point source inputs are amenable to control, especially if their origin is anthropogenic. Spectral analysis of 11 years' turbidity records from the R. Tees (Carling & Douglas, 1985) showed that there were no periodic inputs (other than the seasonal cycle which led to more turbid waters in winter) and, hence, that most of the catchment behaved in a natural or semi-natural manner. Autocorrelations of turbidity levels with previous levels showed no significant autocorrelations for periods of more than c. 4 days.

The deposition of fine materials in gravel beds was studied in an experimental channel and a variable gradient flume (Carling, 1984b) and then in a natural stream channel (Carling & McCahon, in prep.). Using fine and coarse sands under controlled conditions it was found that the mean rate of deposition Δ_b^1 (g m^{-2} min^{-1}) was not correlated with any hydraulic parameters but was correlated with initial concentration of sand (C_o mg l^{-1}) and the calculated relationship was $\Delta_b^1 = 0.6\ C_o$ ($r^2 = 0.99$). Deposition rate decreased exponentially with distance downstream from a point source. The results indicate that open-work gravels will rapidly become silted in flows with low concentrations of suspended solids but turbulent resuspension may prevent deposition in a surface layer of thickness c. 1 mean grain size. Natural silt deposition in a portion of natural stream varied spatially with the local pattern of water velocity which, in turn, regulated the local supply rate. Infilling was chiefly by particles of 4 mm diameter and less. The results confirmed the general conclusions from the controlled experiments and showed that salmonid redds cut in these gravels would resilt in 2 to 3 days, following a small freshet with a maximum suspended sediment concentration of 80 mg l^{-1} and a maximum deposition rate of c. 10 kg $m^{-2}week^{-1}$. The methodology developed opens up the possibility of making controlled experiments to relate the rate or degree of silting of gravel beds (e.g. in experimental channels) to changes in intragravel flow.

Satisfactory methods were developed for field measurement of intragravel seepage velocity and dissolved oxygen concentration in the seepage water. So far, however, it has only been possible to apply them on a limited scale, in conjunction with studies on the survival of eyed ova buried in boxes within gravel beds (Carling, 1985b). Within gravel beds in Teesdale and in Black Brows Beck (Lake District) intragravel velocities varied from < 1.0 to $> 1,000$ cm hr^{-1} and the lowest velocities occurred at heavily silted sites. At any given site, intragravel velocity generally increased with stream stage. However, after the gravels had been disturbed by spates, no clear relationship could be discerned. Interstitial dissolved oxygen concentrations varied from 5 to 13 mg l^{-1} and the values were equal to or less than those in the stream water, whilst oxygen fluxes varied from 1×10^{-2} to 2×10^{-1} mg cm^{-2} hr^{-1}. Under these conditions the survival of trout (Salmo trutta L.)and salmon (S. salar L.)embryos from eyeing to hatching varied from 0 to 100%. No precise quantification of the relationship between intragravel flow and oxygen concentration (or oxygen flux) and egg survival can be obtained from the results. It can, however, be tentatively concluded that critical oxygen fluxes lie within the range $>2.3 \times 10^{-2}$ to $<8.9 \times 10^{-2}$ mg cm^{-2} hr^{-1}. Within this range survival is variable, above this range it is high, and below this range it is low.

3. Gravel movement and egg washout

As there are no accepted methods for predicting the initial motion of individual clasts in coarse-grained streambed mixtures, Carling (1983b) compared field data from Teesdale with published relationships based on laboratory experiments in controlled and simplified conditions. Modifications of Shields' (1936) and Yalin's (1972) relationships could be used in shallow streams with poorly-graded bed materials. The "streampower" concept of Bagnold (1977) was a reasonably good predictor of bedload movements in a broad stream (width/depth >11.0) but the total streampower needed to produce a given transport rate was about one order of magnitude higher than predicted in a narrow stream (width/depth<11.0). In Teesdale streams the depth of disturbance of bed material was generally of the order of one mean grain size. Movement of bed material was shown to be influenced by grain protrusion but not by grain shape. The most useful relationship to emerge relates the size of particles which can just be moved by a given force of the shear stress exerted on the streambed by stream discharge. Particle size (d, mm) is defined as length of the intermediate axis of the three principal axes (i.e. longest, intermediate and shortest) with the axes at right angles to each other. Shear stress (r_o, kg m^{-2}) is γRS, where γ is the specific weight of water, S is water surface slope and R is cross-sectional area of flow divided by the wetted perimeter. For broad channels R approximates to the mean depth. The equation is $d = 18.28\ r_o^{1.58}$ ($r^2 = 0.57$, $P<0.001$). The rate of sediment transport could also usefully be related to the depth of the bed-sediment disturbance. It was evident that only the gravel of the thickness of the disturbed layer contributed fully to bedload movement at bankful discharge. At lower flows only local disturbance and movement occurred (Carling, 1982, Fig. 9).

Further approaches to the problem of predicting gravel movement have been through empirical examinations of the results obtained from the use of scour chains (Carling, 1982) and bedload traps (Carling & Hurley, in prep.). Equations relating mean and maximum depths of scour and deposition(where depth of deposition= $Q^{0.5}$) and percentage of bed area showing scour and deposition (where % area = $Q^{0.17}$) to stream discharge (Q $m^3 s^{-1} m^{-1}$ of stream width) were developed (Carling, 1982). The results also suggest (Carling, 1982; 1983b) that bed material was, typically, disturbed to a depth of one mean grain size. These are useful as very approximate guides but the data are currently being re-evaluated. The data suggest that the percentage of bed area likely to be reworked by scour and/or deposition is about 60% at a threshold discharge of 0.11 $m^3 s^{-1} m^{-1}$ of stream width and that this value rises to c.100% at 2.0 $m^3 s^{-1} m^{-1}$ of bed width. Carling & Hurley (in prep.) examined data collected from bedload traps in two Teesdale streams over a period of six years. Models were developed from Great Eggleshope Beck data to predict the probable frequency of occurrence of bedload movement events and then to predict the magnitude of those events relative to stream discharge. The models were tested on data from Carl Beck and found to be a good fit. These results have potential value for estimating the probability of significant bed scour at different discharges. The possibilities for practical application remain to be fully explored.

The physical studies outlined open the way to prediction of the discharges likely to cause bed movement and the percentage of bed area likely to be at risk. The likely depth of disturbance can be predicted approximately from mean grain size. It is important to note, however, that all of these predictions will have very wide confidence limits. Further application and possible development of the model of Carling & Hurley (in press) may improve these capabilities. The application of such predictions to the washout of salmonid redds also requires detailed information on the choice of redd sites relative to gravel composition, water depth and water velocity; and on the structure of the redd and the depth of egg burial relative to fish size. Preliminary results of such an investigation were described by Crisp & Carling (1985) and the main conclusions were:

i. The burial depths of salmonid eggs in N.E. England and in S.W. Wales can be predicted from a linear regression of mean burial depth upon female length. Gravel composition and water velocity at the redd site have little or no influence on this relationship. The results from Dorset appear anomalous and more data are required. 80% of the eggs lie within ±2 cm of the mean burial depth.

ii. Within limits, the horizontal dimensions of the redd can be predicted from female size and do not appear to be greatly influenced by gravel composition or water velocity.

iii. Data plots suggest that salmonids generally avoid spawning in water which is shallower than their own body depth or whose velocity is less than 20 cm s^{-1}. There may be upper limits on water velocity and gravel composition which are proportional to fish length. More detailed and elaborate statistical analysis of the data is required.

iv. The depth of the redd pot is not a useful predictor of mean egg burial depth.

These various interrelationships require more detailed analysis, but present indications are that some useful, predictive relationships can be developed for practical use.

When the structure of a redd is disrupted by gravel movement some or all of the eggs may be displaced. The evidence (Ottaway, Clarke & Forrest, 1981; Crisp, 1985a) suggests that appreciable washout of redds may occur in flashy upland streams. Some eggs may be damaged during disruption of the redd, some drift downstream (Elliott, 1976; Ottaway et al., 1981) and may be presumed either to be consumed by predators or to be redeposited. It is likely that many of the redeposited eggs will settle in places unsuitable for further development and will die. There is, therefore, some justification for the common assumption that few, if any, eggs displaced from redds will survive. However, there is little quantitative information about the depths within the gravel from which eggs may be displaced, the approximate distance of drift or the effects of the process of drifting upon survival. A series of simple channel and stream experiments upon artificial (Ottaway, 1981) and real eggs was therefore performed to gain tentative answers to some of these questions.

The results can be summarized as:

i. Depth of washout:

The results of Ottaway et al. (1981) from Carl Beck and additional data from Great Eggleshope Beck in 1983-84 (Crisp, 1985) show that, within gravel areas used by spawning trout, washout of eggs buried at 0 - 7 cm was high (80 - 100%), whereas eggs buried at 12 - 15 cm suffered little washout in spates up to 2.6 $m^3 s^{-1}$ in Carl Beck and 7.0 $m^3 s^{-1}$ in Great Eggleshope Beck. At intermediate burial depths the percentage washout was more variable. These results are consistent with the suggestion (Carling, 1983b) that gravel disturbance is generally to a depth of c. 1 mean grain size. However, during similar experiments in Great Eggleshope Beck in 1984-85 discharges of up to 9.0 $m^3 s^{-1}$ occurred and washout was almost complete at 5 cm depth, was high (78 - 100%) at 10 cm depth and was variable (4 - 100%) at 15 cm depth.

Bankful discharge in Great Eggleshope Beck is 5.6 $m^3 s^{-1}$ and mean annual flood (mean recurrence interval 2.33 years) is 6.4 $m^3 s^{-1}$ (Carling & Hurley, in prep.). The most efficient discharge range for movement of bed material was estimated as 5.1 $\pm$ 0.16 $m^3 s^{-1}$ (95% C.L.), where "efficiency" is proportional to competence to move bed material multiplied by frequency and magnitude of occurrence. The patterns of artificial egg washout observed during the 1983-84 and 1984 - 85 field experiments, after peak discharges of 7.0 and 9.0 $m^3 s^{-1}$ respectively, are consistent with these hydraulic considerations.

ii. Distance of drift:

Within an experimental channel, the settling of artificial eggs released at the water surface in c. 12 cm depth of water could be predicted from the empirical equation:

$\log_{10} y = 0.72 \log_{10} x_1 + 0.44 \log_{10} x_2 - 1.28$, where y = distance (m) downstream of point of release, x_1 = mean channel velocity at 0.6 of depth ($cm\ s^{-1}$) and x_2 = percentage of input eggs settled. Predicted distances to final settlement of 50% of the released eggs at channel velocities of 38.7, 53.6 and 68.7 $cm\ s^{-1}$ were 4, 5 and 6 m respectively (Crisp, 1984).

Equations of the same form were found to apply to similar experiments in a natural stream (Crisp & Martin, 1984) but the constants had higher values than for the channels and, thus, median drift distance at any given water velocity was higher in the natural stream than in the experimental channel(e.g. 6 m in the channel and 11 to 19 m in the stream at water velocities of c. 70 $cm\ s^{-1}$). The values of the constants also increased with the time elapsed between release of the eggs and the assessment of percentage settled. This suggests that in the natural stream the concept of "permanent" settlement is not valid and this probably reflects the considerable temporal and spatial variations in velocity which can occur in a natural stream.

Although the results of these experiments do not lead to accurate predictions of drift distances likely to be attained in the field, they do show quite clearly that, in natural spates with mean water velocities of c. 90 $cm\ s^{-1}$ or more, the median distance of egg drift is likely to be measured in tens of metres. The fact that in these experiments the eggs were released at the water surface rather than from the bed of the stream is unlikely to affect this conclusion. In tranquil flows eggs released at the water surface are likely to make their first bed contact within a few metres of the release point and the flow of a natural stream is so turbulent that in shallow water (10-40 cm) the depth of release may be even less important.

iii. Effect of drifting upon survival and hatching time:

In addition to any mechanical shock suffered during the process of disruption of the redd, displaced eggs will suffer some mechanical shock from bed contacts during the process of drifting. There are likely to be between 1 and 4 bed contacts m^{-1} of travel (Crisp, 1984). In two separate experiments brown trout eggs at two stages of development were allowed to drift 10 m in an experimental channel and their survival to hatching was compared with that of control batches. Survival to hatching was >90% in the control batches, could not be shown to differ significantly from the control value in batches drifted at 60-70% development to median hatch, but was only 40-55% in batches drifted at 10-20% development to median hatch. This shows that the mechanical shock imparted by drifting can cause appreciable mortality amongst those developmental stages which are most sensitive. The results also suggested that sublethal mechanical shock, at both 10-20 and 60-70% development to median hatch can modify the date of median hatch by up to one week.

iv. Effect upon survival to hatching of a standard mechanical shock applied at different stages of egg development:

The percentage survival to hatching of trout eggs given a standard shock by impact at a range of different stages of development was examined (Crisp & Robson, 1985). Control batches and eggs shocked before fertilization had survival rates of c. 95%. When a shock of c. 8400 ergs(=840 µJ) egg^{-1} was applied, survival was close to 90% for several hours after fertilization but decreased rapidly thereafter and the lowest value observed was 48% for eggs shocked at 12% development to median hatch. Thereafter survival rate increased until by 60 to 70% development to median hatch it was again close to the control value. Eggs given a shock of c.2500 ergs(=250µJ) egg^{-1} showed a similar survival pattern relative to stage of development but the lowest observed survival was 84% for eggs shocked at 22% development to median hatch. The results of these experiments agree with statements in the literature for eggs of other species of salmonids but suggest that brown trout eggs are less sensitive to mechanical shock than the eggs of coho salmon (Jensen & Alderdice, 1983). The results, again, suggest that sublethal shock at most stages of development can modify the date of median hatch, relative to that of control batches, by one week or more. However, the size and direction of the change appears to be related to stage of development at the time of shocking and possibly also to the mode of shock administration.

4. Channel experiments on relationships between water velocity and the downstream movement of recently emerged salmonid parr.

In three experiments using trout and three using salmon, four different water velocity treatments were applied to each channel. The treatments changed from day to day in a Latin square pattern (Crisp, 1985b; Hurley, in press), and the fish leaving the downstream end of each channel during treatment were counted. Residual fish at the end of the experimental sequence were enumerated and removed from the channels by electrofishing (Crisp, 1983) and the results were analysed for the effects of channel, treatment and fish population density (Hurley, in prep.). Models were developed for the prediction of daily instantaneous rate of downstream movement out of the channels from water velocity and population density. However, the main findings are best described in terms of relative rates of movement out of the channels, where the instantaneous daily rate at the lowest water velocity is given a value of 1 arbitrary unit and the values at other velocities are scaled appropriately. The main findings were:

i. The rate at which trout left the channels was 1.0 units at water velocities of 7.5 cm s^{-1}, lower at 25 cm s^{-1}(0.5 units) and then rose to higher values at 40 cm s^{-1} and 70 cm s^{-1} (1 to 3.5 units). In contrast, the highest rate for salmon was at the lowest water velocity (1.0 units) with much lower rates (0.4 to 0.2 units) in the 25 to 70 cm s^{-1} velocity range.

ii. These general patterns were common to all three experiments within each species and a significant relationship between rate and velocity could be demonstrated in two of the three experiments on each species.

iii. An additional statistically significant relationship between rate and population density was shown in two of the trout experiments but in none of the salmon experiments.

iv. Variation in the intensity of the observed effects between different experimental runs for the same species could imply that the intensity varied with the exact stage of development of the fish. However, it could also be related to some other variable (e.g. water temperature).

Further experiments were made on trout and salmon which were introduced to the channels as yolk-sac fry shortly before the expected time of emergence from the gravel. Each of the four channels was run continuously at one of a range of four different water velocities and the number and stage of development of the fish leaving the downstream end of each channel on each day was recorded. The results showed that few fish of either species left the channels until at or shortly after the swim-up stage. For trout the instantaneous rate of exodus from the channels was low (less than 0.1 day^{-1}) at 8.0 cm s^{-1} but c. 0.2 day^{-1} at velocities of 25, 40 and 70 cm s^{-1}. Swim-up in all four channels was attained during the first week of May. In the channels at the higher velocities the rate of exodus peaked in mid- to late-May and then fell to levels of less than 0.05 day^{-1}. In contrast at 8.0 cm s^{-1} water velocity, the peak rate was lower but did not fall below 0.05 day^{-1} until mid-June. Final population densities and biomasses (late June) were similar in all four channels. This implies that although water velocity influences the rate of exodus, downstream dispersal is not a feature which is tied to a particular stage of development but will continue until an appropriate population density has been attained. Swim-up of the salmon occurred in late May and in every channel the instantaneous rate of exodus rose to values of 0.1-0.4 day^{-1} during early June and then declined to low values by 20 June. Fish in the channel set at 8.0 cm s^{-1} had a higher exodus rate over a more sustained period than those in higher velocity treatments. As a result of this, by 20 June when exodus rates were low in all four channels, the population density in the low velocity channel was 1.8 fish m^{-2}. In the other three channels the population density was 5 to 8 fish m^{-2}. This suggests that young salmon may make very active efforts to avoid low velocities.

Ottaway & Clarke (1981) noted that most salmon leaving the channels did so during the hours of darkness. Further tests in 1984 and 1985 confirmed this finding for both salmon and trout. About 97% of the fish leaving the channels did so by night rather than by day.

Further analysis of the results of these channel experiments is proposed. It is hoped that this will facilitate a more critical assessment of the results of the 1984 and 1985 experiments.

FUTURE RESEARCH NEEDS

1. Siltation and its biological effects

The basic methodology for field studies on the effects of siltation upon intragravel flow and oxygen concentration under field conditions is now available. There is a need for more field data on the effects of depth within the gravel, of stream water depth(discharge) and of siltation upon spatial and temporal variation in intragravel flow and oxygen concentration. There is also scope for detailed physical studies on the mechanisms underlying these interrelationships.

Some continuation of field studies on survival rates in batches of eggs at different values of intragravel flow and oxygen concentration are desirable but it is essential for these to be backed by carefully designed experiments under controlled conditions. These laboratory observations should begin by assessing survival rates in batches of eggs relative to the important physical variables. However, the various interrelationships are complex (Crisp, in manuscript and Fig. 1) and the investigation is likely to lead ultimately to detailed studies on the effects of egg packing within redds, the effects of oxygen depletion caused by previous eggs upon the n^{th} egg in a row and the rate of flux of oxygen across the surface layer of

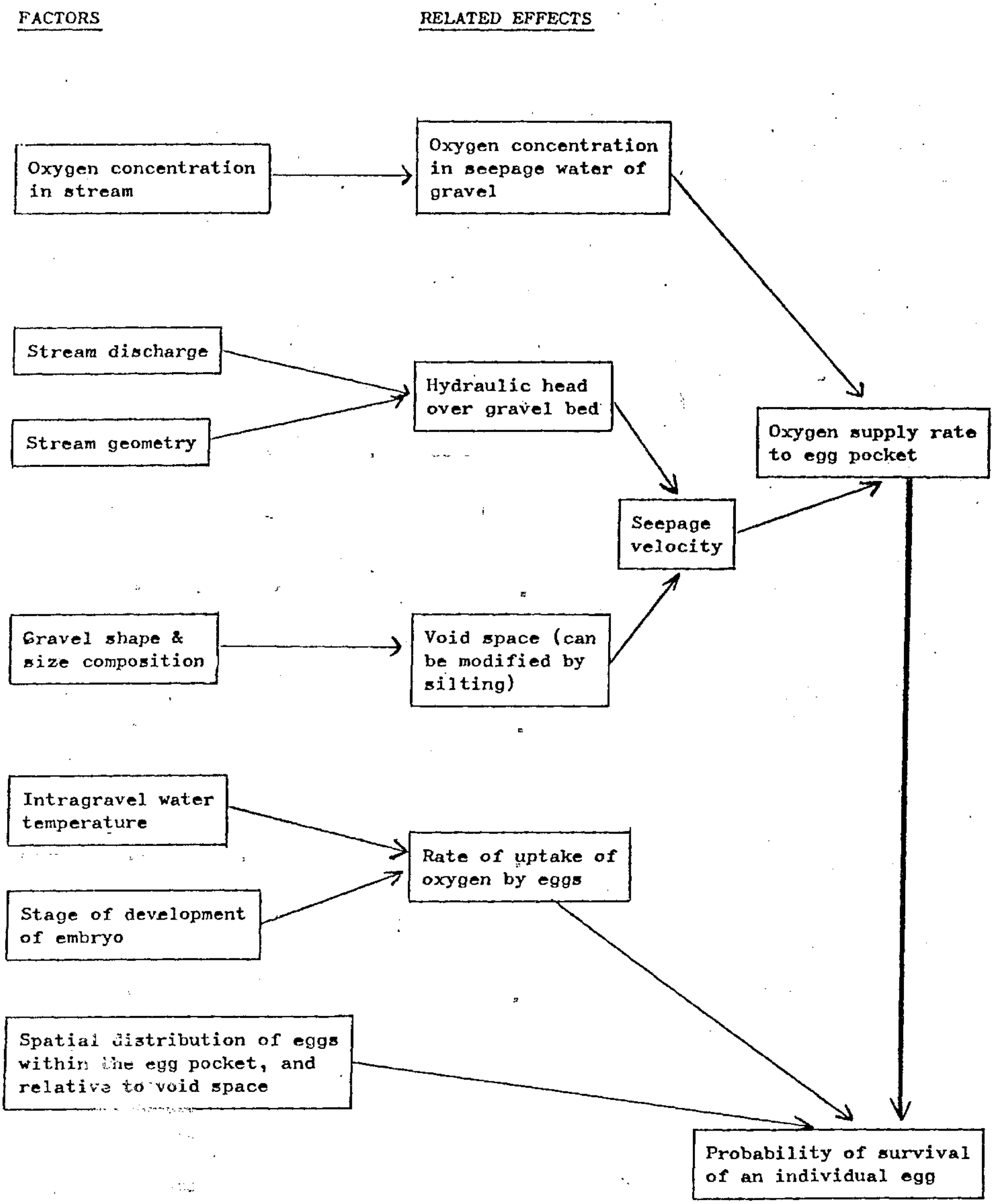

FIG. 1. Simplified scheme to indicate the main factors likely to affect the intragravel environment and the related effects which link them, via oxygen supply rate, to the survival of salmonid eggs. Note that toxic metabolic products are removed from the vicinity of the eggs by intragravel flow. The rate of removal of these metabolites will be determined in a similar way to oxygen supply rate and may influence egg survival.

individual eggs. Work of this type requires a multidisciplinary approach which includes expertise in physics/chemistry, ecology and physiology.

Some workers on Pacific salmon have observed that heavy silt deposition at redd sites can trap alevins within the gravel and that this can lead to appreciable mortality around the time of emergence from the gravel (Koski, 1966, 1975). No studies of this type have been made on British species in British rivers.

Siltation, together with other potential problems such as compaction and exposure of gravel beds, encroachment of terrestrial vegetation, and increased growth of aquatic plants, is primarily a low flow phenomenon. As the problems arising from protracted low flows appear to be a cause of concern within the Water Industry at present, it would be timely for studies on these topics to continue and be expanded.

2. Gravel movement and its biological effects.

Crude models already exist for the prediction of the occurrence, percentage of total stream area and depth of gravel disturbance by spates. It may be that this level of precision is all that can be attained but the models of Carling & Hurley (in prep.) hold out hope of improved predictive capability and should be developed and applied. However, these predictions are generalizations which refer to extensive areas of stream. The discharge needed to wash out any specified redd or group of redds is likely to depend upon local patterns and variations of water velocity and is only likely to be predictable in the light of detailed studies of the relationships between discharge and local water velocities and of the mechanims of gravel movement relative to water velocity on a micro-scale. The feasibility of studies of this type should be considered, though the results would be highly site specific and probably of limited general application. A more fruitful approach might be in extensive empirical studies within spawning riffles, based on observations of scour chains or buried artificial eggs (Crisp, 1985a).

The studies on egg burial depths and spawner lengths have produced valuable information. However, there is an urgent need for more data points from chalk streams. In addition, field data from at least one additional geographical area (e.g. North Wales) would be valuable. It would also be desirable to carry out, as far as possible, some additional studies on the detailed structure of redds and on the detailed spatial distribution of eggs within them.

3. Experiments on young free-swimming salmonids in Grassholme channels.

These channels are probably a unique facility and should be exploited to the utmost before they deteriorate with age. The results of the experiments of 1984 and 1985, although already reported (Crisp, 1985b), await more thorough analysis and interpretation during the winter of 1985-6. When this is done, it will be possible to make detailed proposals for follow-up experiments. Possibilities include:

(a) Studies on mixed species populations, relative to water velocity.

(b) Further exploration of rates of exodus by day and by night and experiments to see whether or not the rates of night exodus can be attained in the daytime as a result of discolouration of the water such as occurs in natural spates.

(c) Studies on the effects of various patterns of velocity fluctuation.

4. General comments

The strategic importance of continuation of this work and the types of programme packages in which it can be contained have already been presented to customers and potential future customers as Project Item Forms and this information will not be repeated here.

Although this work was originally geared to problems arising from impoundment and inter-river transfer and has always been executed with regard to its practical applications, it is also fundamental science which has relevance to a number of other areas of practical interest. These include:

(a) The preservation and enhancement of stocks of salmonid fishes. These are important to sport fisheries in freshwater and to commercial fisheries in freshwater, estuaries and the sea.

(b) The effects of changing land use, especially in the uplands, upon aquatic biota (including salmonid fishes) are a cause of concern There is already some indication that drainage works and afforestation may be affecting salmonids, possibly through changes in patterns and magnitude of siltation and gravel movement. Knowledge of the mechanisms by which these physical factors influence salmonid populations is a pre-requisite of understanding the processes at work and of manipulating the system so as to maximise any beneficial effects and minimise any harmful effects.

(c) Acid inputs are an important political issue. In many of the places where acid inputs are blamed for deterioration of fish populations there is also extensive forestry in progress. The evidence suggests that the presence of coniferous forests aggravates the effects of acid inputs. It is important to know whether this is a result simply of a direct physical effect of the trees (for example by increasing the interception of acid material from the atmosphere) a more complex effect arising through the effects of trees on the underlying soil or an indirect effect arising from the effects of forestry activities in modifying the hydraulic behaviour of the streams draining the forest. The likelihood is that some combination of effects is at work. Studies of the type undertaken in the present project are relevant here because they give information on one of the several types of mechanism which are probably confounded to give the overall effect of forests in aggravating the problem of acid inputs.

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APPENDIX 1.

CONTENTS

1. Background:

Crisp, D.T. (1981) Effects of flow regime on the young stages of salmonid fishes - Conclusions based on results for 1977-1981. F.B.A. Teesdale Unit, unpublished report to customers.

2. Offprints:

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APPENDIX 2. BACKGROUND TO THE WORK OF 1981-1985.

The following list of proposed work for the 1981-1985 contract term was included in the summary report on the 1977-1981 contract term. The aspects which were then considered to be of the highest priority are marked with an asterisk.

1.* Further siltation monitoring in natural streams.

2.* Controlled siltation experiments in channels. Ideally this would require a variable gradient channel. This topic and (1) above are closely interrelated.

3. Continued collection of hydraulic geometry data from natural streams.

4.* Continuation of bedload trapping. This is a rather routine operation, but very few data of this type are available for British upland streams.

5. Collection of hydraulic data from larger rivers such as the Wear, Tyne and Swale. This would facilitate wider application of the results obtained from smaller streams in Teesdale.

6.* Further studies on the structure and dimensions of redds, with special reference to gravel composition and egg burial depth. If possible, the egg burial depth model should be strengthened by the collection of more data from Teesdale/Weardale and extended by the collection of data from a wider variety of river types.

7.* Detailed quantitative studies of the gravel environment, with special reference to oxygen supply rate and embryonic survival.

8.* Quantitative field studies on washout, using both real and artificial eggs.

9. Further development of studies on alevin entrapment and siltation.
10. Development of fish trapping techniques so as to assess downstream movements of young salmonids relative to discharge.
11* Further channel experiments, especially on young fry of trout and salmon.