Swimming Speeds in Fish: Phase 1

R&D Technical Report W2-026/TR1

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Statement of Use
This Technical Report describes a study to assess the swimming capability of a number of fish species and to determine the minimum effective swimming depth. This report contains the information concerning the experimental procedures involved and the results from these. This document is supported by an associated Literature Review and a Microsoft Excel spreadsheet (Swimit). These will mainly be of interest to Fisheries staff and those involved with the design of in-river engineering works that may have an impact on fish populations.

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Glossary

Burst swimming speed

The maximum swimming speed that can be maintained by a fish for ≥ 20 seconds.

Maximum swimming speed

The theoretical maximum swimming speed that a fish is capable of achieving. Maximum speed can be determined through muscle twitch experiments.

Prolonged swimming speed	The maximum swimming speed which can be maintained for between 20 seconds and 200 minutes.
Sustained swimming speed	The maximum swimming speed which can be maintained for in excess of 200 minutes.
Critical swimming speed	Is an approximation of the final velocity attained before exhaustion, in tests where the speed is increased by incremental amounts at fixed time intervals.
Exhaustion	The point at which a fish in a swimming speed trial can no longer maintain its position against the flow and is subsequently carried downstream and caught against the screen. Exhaustion in this context therefore contains a behavioural component, and may not necessarily correspond to physiological exhaustion.
Fish length	Fish length was recorded as standard length throughout.
Stride length	The distance that the fish moves forward for one complete tailbeat cycle.

Notation

s.l. = Standard length

bl s^{-1} = body lengths per second

EXECUTIVE SUMMARY

Background/Need

There is a growing body of evidence that fish migrate extensively around river systems on both daily and seasonal bases. The financial investment in fish passes to facilitate these migrations is considerable, as is the cost of screens to prevent entrainment of fish at water intakes. Effective design of these structures requires robust data on the swimming performance of river fishes under a wide range of conditions. Fish utilise two main types of muscle for propulsion, referred to as red muscle and white muscle. Red muscle only contracts in the presence of oxygen, and is used for endurance swimming, for example maintaining position in the flow of a river or moving around a stillwater. White muscle contracts strongly in the absence of oxygen, and is used for burst swimming, for example to escape from predators, or when leaping. The burst and sustained swimming performance of fish also governs their ability to ascend weirs and fish passes, and to resist entrainment into water intakes. Swimming performance varies between species, between individuals of the same species, and according to size and water temperature. Other factors such as water depth could also have an impact, particularly when the depth is the same or less than the body depth of the fish. The theoretical maximum speed at which a fish can swim is a function of the distance covered during one complete tailbeat cycle (the stride length) and the number of tailbeat cycles that can be generated in a given time.

Main objectives/Aims

This project aimed to collect robust data and to develop computer models to describe the swimming performance of selected British freshwater fish species for future application to fish pass and water intake design. The species of interest were:

brown trout	(*Salmo trutta* L.)
chub	(*Leuciscus cephalus* (L.))
dace	(*Leuciscus leuciscus* (L.))
roach	(*Rutilus rutilus* (L.))
elver	(*Anguilla anguilla* (L.))

The data from which the models were constructed was collected from a number of sources. A literature review was carried out in order to identify the extent of current knowledge on the swimming performance of the species of interest. Swimming speed experiments were conducted in order to measure the swimming performance of the five selected species. To ensure a broad coverage, fish of different sizes were tested, at a representative range of temperatures. The tests aimed to fill in the gaps in the published data, and were designed to discover the limits of both burst and sustained endurance swimming. Further experiments, designed to assess the impact of slopes and thin films of water on the burst swimming ability of fish were also carried out. In addition, muscle twitch experiments were conducted to determine the maximum number of tailbeat cycles that can be produced in a given time, from which the theoretical maximum swimming speed can be calculated.

Test fish were collected from the wild wherever possible (see Appendices 3 & 4), with 89% of the fish used being of wild origin. All fish were held in the outdoor stock tanks for at least one week prior to testing. The swimming tests were conducted in purpose built apparatus at Fawley Aquatic Research Laboratories. A large (8 m long) flume tank was used to examine the endurance swimming of fish over a 200 minute period. Flow around the flume was generated by a paddle wheel, and swimming fish were monitored using overhead lighting and closed-circuit TV cameras. Burst swimming performance was tested in a high-speed tunnel, where flow was generated by a large pump. Speed through the tunnel was increased gradually until the fish could no longer maintain their position.

Results

Little suitable data was gathered from the literature. Consequently, swimming speed tests had to be wide-ranging, and covered a representative range of sizes for all five species, within three temperature categories. In all, the swimming performance of over 5000 fish was tested, and a computer program (SWIMIT) was developed from the data. The program can be used to estimate the passage rate for fish of a particular size and species over a given structure, where the water velocity and temperature are known. Similarly, the proportion of fish which could swim fast enough to avoid being entrained into a water intake can also be determined, again providing water temperature and velocity are known.

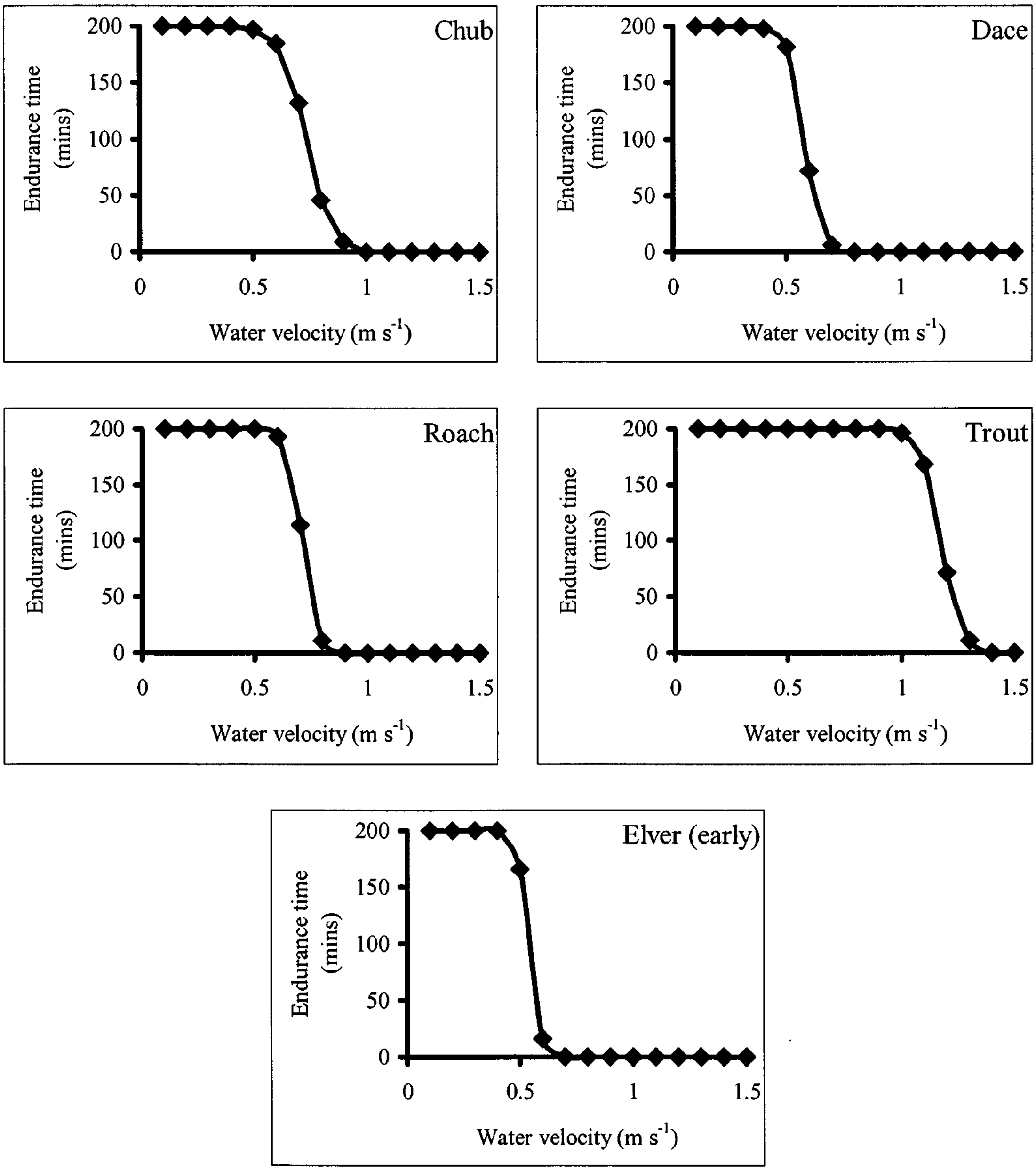


Figure ES1. Median endurance times of 15cm fish at 10°C for each of the 5 species.

Examples of the data that can be generated via the SWIMIT programme are given in Figure ES1. The charts show the predicted endurance time for 15cm specimens of each species, at 10°C, at a range of water velocities.

Conclusions / Recommendations

1. The present study has dealt with a small number of the freshwater fish species found in Britain, and has been limited in size range up to about 30cm fish length. There is regulatory and conservation interest in a much wider range of species, including small epibenthic species such as bullhead (*Cottus gobio* (L.)) and stoneloach (*Barbatula barbatula* (L.)) and other cyprinid and percid species, and migratory species such as lampreys and shads. It is recommended that a prioritised list of these should be drawn up for future testing.
2. In view of the good performance of the methods used here, it is recommended that the same methods should be used in future studies. Our experiences with fish condition at high summer temperatures in particular indicate that at least a modest level of temperature control of facilities would be helpful.
3. For species that are particularly sensitive to handling or of high conservation merit, consideration should be given to setting up a portable test facility that can be used on the riverbank. This would eliminate much of the stress associated with handling and transport and would enable the fish to be returned direct to source.
4. It was noted that during endurance swimming tests some fish completed the full 200 minutes, even at the highest velocities. For future studies it would be useful to have a flume facility which offered maximum speeds in excess of 1.4m s^{-1}. A modification to the existing Fawley endurance flume, replacing the paddle wheel with an impeller, would allow much higher water velocities to be generated.

KEY WORDS

Swimming, speed, fish passes, water intakes, weirs, chub, dace, roach, elver, brown trout.

1. INTRODUCTION

1.1 Background

During normal day-to-day life most river fishes use only a small proportion of their available swimming capacity. The excess capacity is used to fulfil specific requirements, for example to escape from predators, to migrate past obstructions and to maintain position during spates. The reproductive migrations of anadromous fish such as the Atlantic salmon (*Salmo salar* L.) are well documented, and there is growing evidence that other species migrate extensively, not just for reproduction, but to fulfil a variety of functions including feeding, refuging and recolonisation following displacement (Lucas *et al.*, 1998). Recent studies have shown that even relatively small riverine fish species like dace (*Leuciscus leuciscus*) are highly mobile, and carry out significant daily and seasonal migrations (Clough & Ladle, 1997; Clough & Beaumont, 1998; Clough *et al.*, 1998).

The activities of man have impacted on riverine fish populations in many ways, not least through physical modifications of natural channels. Some of these, such as the construction of weirs, dams and locks disrupt the natural river continuum and make it more difficult for fish to move around their environment. Such obstacles are likely to influence the distribution and abundance of fish populations within rivers and affect, for example, the rate of recolonisation after a pollution, drought or washout event.

Ameliorative measures, notably fish passes, designed to reduce the impact of physical barriers on fish migrations, have now been installed on many rivers. The majority of these structures were originally designed to facilitate the passage of the commercially important, and strongly swimming migratory salmonids, e.g. Atlantic salmon and sea trout (*Salmo trutta* L.). It was unclear whether other fish species possessed the swimming ability to ascend existing fish passes. Testing the swimming performance of fish at a range of temperatures makes it possible to determine whether or not the water velocities encountered at a potential obstruction are likely to constitute a barrier to migration, and to provide design criteria for future pass construction, other enhancement, protection and ameliorative measures.

Another potential problem facing river fishes is the risk of entrainment into industrial and potable water intakes and hydro-electric turbines (Solomon, 1992; Turnpenny *et al.*, 1998). Frequently there is an absence of the stimuli that might allow fish to avoid the intake (e.g. visible structural elements or the turbulence generated by screens and trash racks). However, even when suitable stimuli are available, the fish must still be able to swim faster than the intake velocity in order to resist entrainment. By testing the swimming performance of fish at a range of temperatures, maximum acceptable intake velocities can be determined. These need to be based on the particular species and life stages present at a given time of year. Swimming performance data can be used in the future design of water intakes to create hydraulic conditions that minimise the risk to fish stocks from entrainment losses.

1.2 Terms of Reference

The project was to:

1. measure for different size classes of chub, dace, roach, trout and elver, at three water temperatures representative of the seasonal range:

    (a) endurance swimming performance at a range of speeds;

    (b) burst swimming ability.

2. estimate for trout and one of the cyprinid species, the theoretical maximum swimming speed, using the muscle twitch method developed by Wardle (1975),

3. conduct experiments to determine the effects on swimming performance of partial submersion when ascending slopes, and determine the minimum effective swimming depth,

4. produce a computer program that can be used to estimate swimming performance of the species tested for a representative range of fish sizes at different water temperatures.

2. THEORETICAL BACKGROUND

A review of existing scientific literature on fish swimming speed was carried out at the start of this project, with the findings being presented as a separate, stand alone document (Turnpenny *et al.*, 2000). Literature data relating to the project species of interest were limited, and those that were presented varied in experimental methodology.

A number of variables influence the swimming performance within a given species, most notably fish size and water temperature, although dissolved oxygen concentration and pollutant levels can also be important. There is also a degree of inter-individual variation resulting from differences in genetic make-up, health and condition. Important considerations when interpreting published data are the experimental methodologies used to determine swimming performance, and the handling techniques used prior to the test. Some methodologies may not stretch fish sufficiently to yield maximum performance information, and poor handling may cause stress to fish, leading to under-performance in trials. Equally, lack of rigour in fully reporting experimental conditions, especially temperatures, may render otherwise sound data of no value for the present purposes.

To avoid extensive repetition, the salient findings of the review are summarised below.

2.1 The Swimming Muscles

The majority of fish species use two main types of muscle for swimming. Red muscle only contracts when oxygen is available to the cells. Any restriction in oxygen availability limits its rate of performance (Wardle, 1977). White muscle can contract in the absence of oxygen, and becomes exhausted when all the glycogen stored in its cells has been converted to lactic acid. Replacing the glycogen requires oxygen, and can take up to 24 hours (Wardle, 1977). A third muscle type, known as pink muscle, is found in some species, including cyprinids. Pink muscle fibres are recruited into the swimming process after the red fibres and before the white fibres become active.

In the wild, red muscle is used by fish in order to maintain position in the flow, and for daily movements and seasonal migrations within a river system. Red muscle is also likely to be employed by fish in the ascent of low velocity baffled fish passes, and to resist entrainment at water intakes. At burst swimming speeds, energy is almost totally supplied by the white muscle (Wardle, 1980).

White muscle is used during escape from predators or when catching fast-moving prey, and will be employed in order to ascend pool-and-traverse type fish passes, and during leaping. White muscle will also be used in the ascent of baffled fish passes and weir slopes when the velocity exceeds that handled by red and pink muscle contraction alone.

2.2 Power and Drag

A swimming fish must overcome the drag force exerted by the water. This comprises two components: *frictional drag* caused by the passage of water over the body and fin surfaces, and *form drag*, related to the cross sectional area of the fish and the consequent displacement of water as the fish proceeds. Bainbridge (1963) gave the following formula to represent the combined frictional and form drag forces (D_t) acting on a fish:

$$D_t = \tfrac{1}{2}\rho A U^2\, 1.2C_f,$$

where ρ is the density of water (= 1.02 g cm^{-3}), A is the total surface area of the fish, U is the swimming speed and C_f is the coefficient of frictional drag (= 0.00117). For a fish swimming at constant speed (U) the power required (P_r) to overcome the combined drag forces is the product of the velocity and the drag (Bainbridge, 1961):

$$P_r = D_t.U.$$

2.3 Swimming Uphill

The case of a fish ascending a weir or fish pass involves an additional power requirement to overcome the gravitational force. When completely submerged, a fish must raise its own weight in water against gravity. The equation that describes the power required to overcome gravity is:

$$P_g = W_f.H.g/t$$

Where W_f is the total weight of the fish in kg, H is the height of ascent in metres, t is the time of the ascent in seconds and g is the acceleration due to gravity (= 9.81ms^{-2}).

When only partially submerged, a fish must raise the exposed portion of its own weight in air, as well as the submerged portion of its weight in water. The weight of a fish in water is only a small fraction of its weight in air, consequently as the proportion of the fish exposed above the water surface increases, the work required to raise the fish up any given slope also increases.

2.4 Wave Drag

If an object is moving in deep water, far enough from both bottom and surface, the flow around the object is similar to that of a body flying through the air, i.e. it is functioning in a single fluid phase (Hertel, 1966). Swimming at or near the surface creates surface waves. The energy required for the creation and propagation of waves increases the energetic cost of propulsion (Webb *et al.*, 1991). Minimum drag is achieved when the immersion depth of the midline of the object is approximately equal to three times the diameter of the object. From this point, as a swimming body approaches the surface, the resistance increases. Maximum drag, around five times the minimum drag, occurs when the body is immediately below the surface. Resistance decreases sharply as the body breaks the surface, and corresponds to approximately three times minimum drag when a body is half exposed (Hertel, 1969)(Figure 2.4).

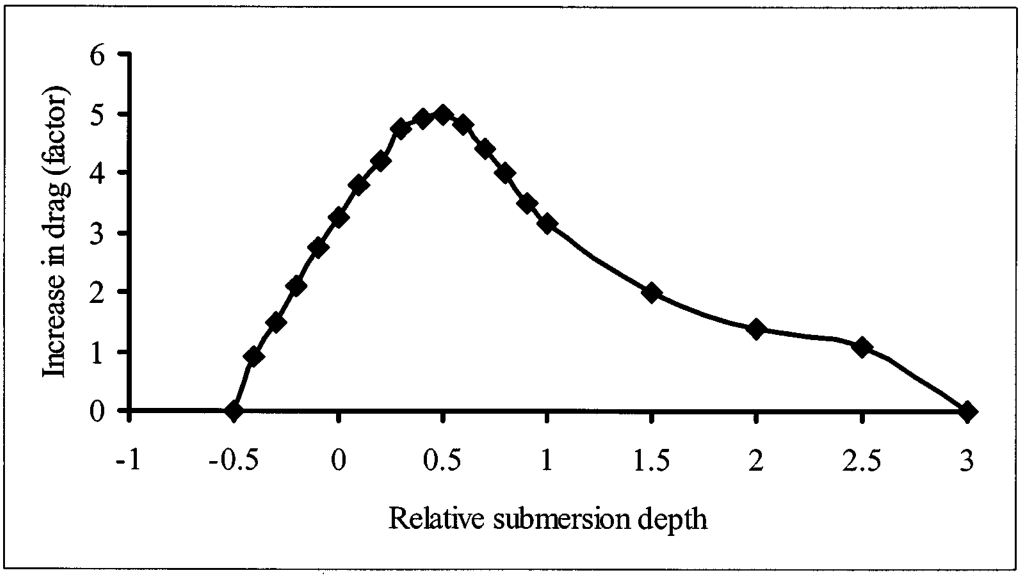


Figure 2.4. **Relationship between relative submersion depth and the increase in drag associated with wave generation. At a relative depth of 0.5 the fish is just submerged, at 0 the fish is half exposed. Recreated from chart data given by Hertel (1969).**

2.5 Power Availability

The power supplied by the swimming muscles is converted to propulsion by the body surface and caudal fin. If the fish is fully submerged, the power available (P_a) is given by:

$P_a = 0.5W_m \times F_p \times e$,

where W_m is the mass of the swimming muscle, F_p is the power factor relating to the unit mass of muscle and e is the propeller efficiency of the body and caudal fin. Bainbridge (1960) demonstrates that the mass of the swimming muscle as a percentage of total body weight rises with increasing fish length (Figure 2.5).

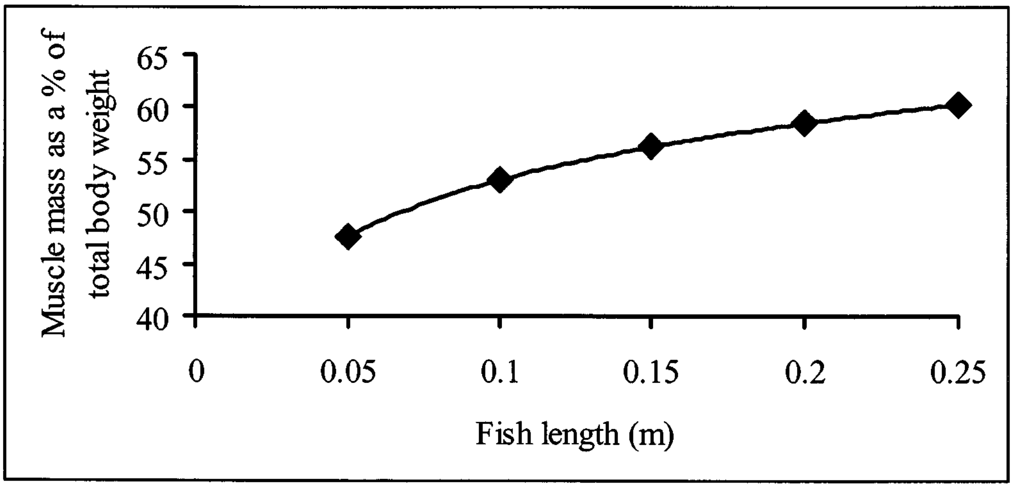


Figure 2.5. **Relationship between fish length and muscle mass as a proportion of total body weight. Recreated from chart data given for dace by Bainbridge (1960).**

Empirically determined values for F_p in cold-water fish white muscle are around 80 W kg^{-1} (Wardle & He, 1988). A value of e of 75% was assumed by Bainbridge (1961), based on a typical value for a well designed marine propeller. As the fish breaks the water surface, part of the tail becomes exposed, and no longer contributes to propulsion. The reduction in useable power is likely to be proportional to the amount of the tail exposed. Consequently a fish which is fifty percent exposed could be expected to deliver half the thrust.

3. METHODS

3.1 Swimming Speed Experiments

Experiments were carried out with the cyprinids chub (*Leuciscus cephalus*), dace (*Leuciscus leuciscus*) and roach (*Rutilus rutilus*), with brown trout (*Salmo trutta*) and with elvers (*Anguilla anguilla*). Test fish were retained in 2 m-square stock tanks at Fawley Aquatic Research Laboratories, having been collected from flowing water environments wherever possible. Fish were collected as they were required, usually by electrofishing, and held for at least 1 week prior to testing. Where flowing water fish were unavailable hatchery reared or stillwater stocks were used, but only as a last resort. The source of the fish used in each test is given in Appendix 3. The unheated stock tanks were situated outside, and were consequently subject to natural diel and seasonal temperature fluctuations. Although the tanks were fitted with solid lids to prevent the fish from jumping out, these were not flush fitting and small gaps were left to allow light to penetrate, thus maintaining the natural day/night cycle. The stock fish were fed daily, and the water in the tanks was changed as required, either continuously by partial replacement or intermittently. Food was either pelleted (trout and / or carp pellets) or live (maggots and / or 'pinkies') according to the fish's preference. A low-velocity circulation of water within the tank was provided by internal electric pumps or by air-lift pumps, in order to exercise the fish.

To ensure a wide range of fish lengths and temperatures, tests fish were divided into categories. Test fish were divided into three groups according to length, these being <10 cm, 10-15 cm and >15 cm for cyprinids and trout. Fish from each of these three categories were tested within three different temperature ranges, <11°C, 11-15°C and >15°C for cyprinids, and <9°C, 9-14°C and >14°C for trout. Elvers were tested both early (spring) and late in the season (late summer-autumn), with size therefore being related to age.

3.2 Swimming Test Apparatus

Blaxter (1969) and Beamish (1978) reviewed techniques previously used to test fish swimming speeds. As the aim of the present study was to determine the limits of fish swimming performance, methods that measure spontaneous or voluntary swimming (e.g. telemetry) were not considered. Circular and annular tanks have been used in a number of previous studies (e.g. Hettler, 1977; MacLeod, 1967) but water flow around such flumes is commonly uneven, with variations in water velocity across the radius, and there is an added influence of centripetal force acting on the fish, making results difficult to interpret. Linear systems provide more consistent laminar flow conditions, more like those commonly experienced by wild fishes. Tunnels are particularly good for examining swimming performance, as the lack of an open water surface means that the fish do not generate surface waves (i.e. raise water against gravity) which can increase drag forces (Hertel, 1966 – see section 2.4). In this study, swimming speed tests were carried out in three different sets of apparatus, according to the type of test, and the size and species of fish being tested. Each apparatus provided a linear test and observation area, supplied by a recirculating flow of water. The different apparatus were designed with smooth surfaces throughout, in order to minimise the width of the boundary layer. Measurements carried out in the low-speed flume by Turnpenny & Bamber (1983) showed that the water velocity 5cm from the base was comparable to that of the rest of the water column, and at 2.5cm from the base water velocity was 92% of the maximum velocity. Although the widths of the boundary layers were not measured for each apparatus, it is considered that these were at least as thin as could be found in the wild, and therefore had no significant effect on results.

3.2.1 The high-speed tunnel

The high-speed tunnel was designed and constructed specifically for this project, and was used to test the burst swimming capacity of the cyprinids and brown trout. The maximum achievable velocity was of the order of 3m s^{-1}, depending on the particular set-up. The tunnel itself, designed by Hydroplan Ltd (Wimborne), and constructed by BJ Metalwork (Hythe), was self-contained and consisted of a variable recirculating water system and reservoir (Figure 3.2a). The swimming chamber was 1.5m long x 0.25m x 0.25m, and had a plexiglass viewing panel. An access port for fish introduction was provided at the top, and an instrument port. Water flow was generated by an electronically regulated pump and was controlled by valves with lockable settings. Using these controls, speed could be continuously adjusted to a resolution of ~0.1% of the overall range. The swimming chamber tilted on its base and could be adjusted using a hydraulic jack to give inclinations of the test channel of up to 20° from the horizontal. Water velocity through the flume was measured using a calibrated Streamflo® high-speed probe (Nixon Instrumentation Ltd) and readout unit located in the downstream end of the test section.

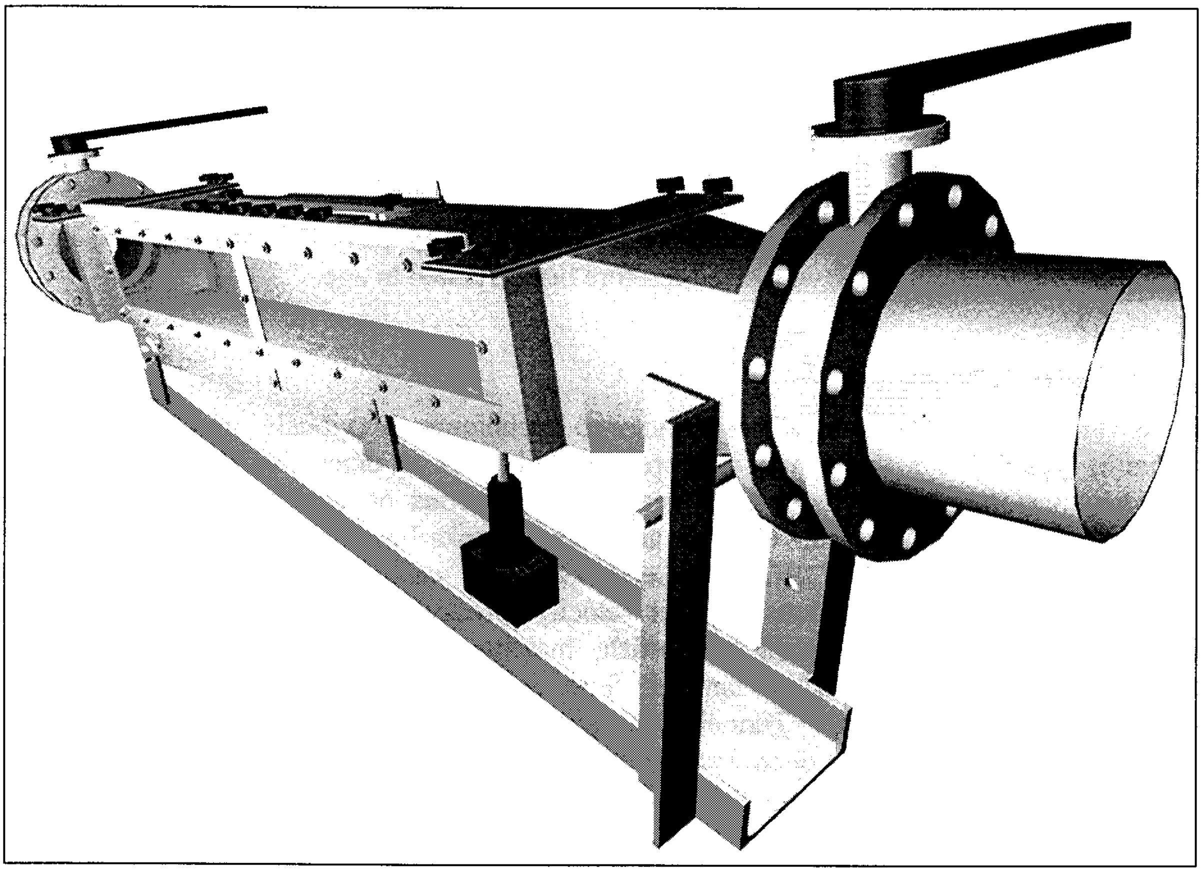


Figure 3.2a. **Three-dimensional rendering of the high-speed tunnel test section, showing window at front, access hatch at top and tilting arrangement. The swimming chamber is 1.5m long x 0.25m x 0.25m. The figure shows the tunnel in the raised position, but the burst swimming tests were carried out with the tunnel in the horizontal position.**

3.2.2 The low-speed flume

The low speed flume was used to test the sustained swimming capacity of the cyprinids and brown trout, and was modified to examine the swimming of fish up slopes. The flume tank was oval, with a long axis of approximately 8m, and speeds up to 1.2m s^{-1} could be generated in the test section (Figure 3.2b). The test section of the flume was divided up into three equal length compartments using 10mm wire mesh screens, each compartment being 1m long by 0.34m wide. Water flow around the low-speed flume was governed using a large paddle wheel and a supplementary electric pump of 20 m^3h^{-1} capacity. The pump, not shown in the figure, moved water from "downstream" of the test section to "upstream" of the test section and was used to create the low water velocities required during the acclimation period and to fine–tune the velocity at higher speeds. The paddle wheel was used to generate the faster test speeds. Flow-straightening vanes, mesh panels and honeycomb panels at the entrance to the test section ensured water flow through the test section was uniform. The hydraulic characteristics have been described by Turnpenny and Bamber (1983).

Water velocity was measured in the test sections using a calibrated low-speed Streamflo® (Nixon Instrumentation Ltd) probe and readout unit. The water depth and velocity in each of the three test sections was not the same, but became slightly shallower and faster in a downstream direction. Velocity through the three flume sections was calibrated at the start of the experiments, and a correction factor was generated for each section. This correction factor converted the speed recorded at a standard position in the middle section to the focal velocity experienced by the fish in each section.

Although fish from the same size category were tested together, these were divided randomly between the three sections. Velocity was converted from metres per second to body lengths per second (bl s^{-1}) to allow for these differences in length and test velocity between sections. Thus the variations were taken into account when calculating the results.

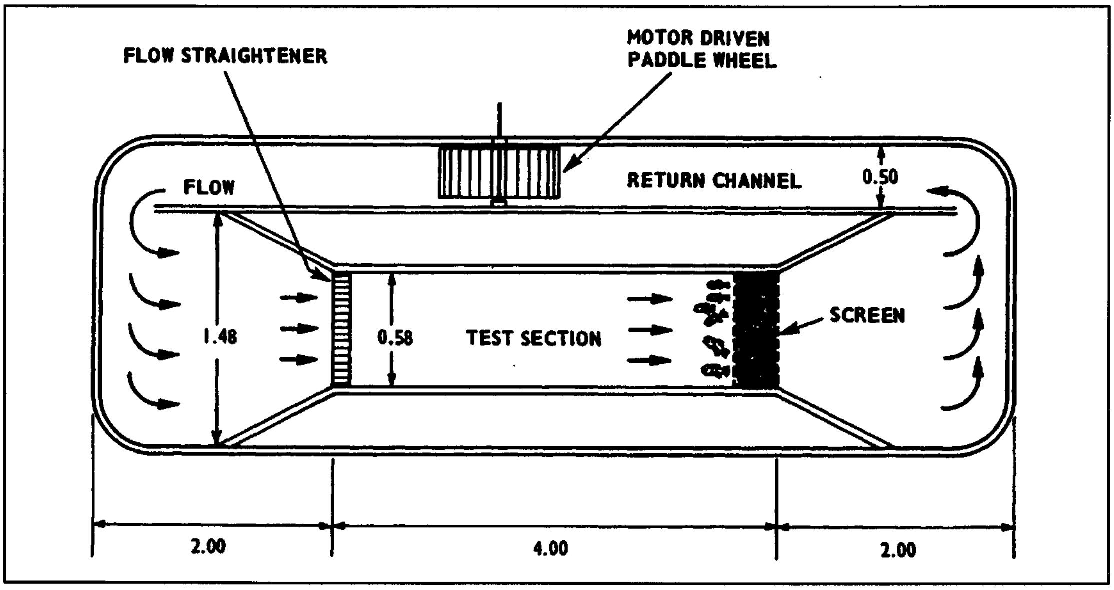


Figure 3.2b. Diagram of the low-speed flume. The three compartments referred to in the text are not shown, but were situated within the area labelled "Test Section" (from Turnpenny & Bamber, 1983).

3.2.3 The eel tunnel

The swimming capacity of elvers was tested in a specially constructed tunnel, which consisted of a two-reservoir recirculating water system and glass observation channel. The 1.8 m long observation channel was made from a plexiglass tube, with an internal diameter of 40 mm. The recirculating water flow was generated by a pump, and water flow through the test area was governed by valves.

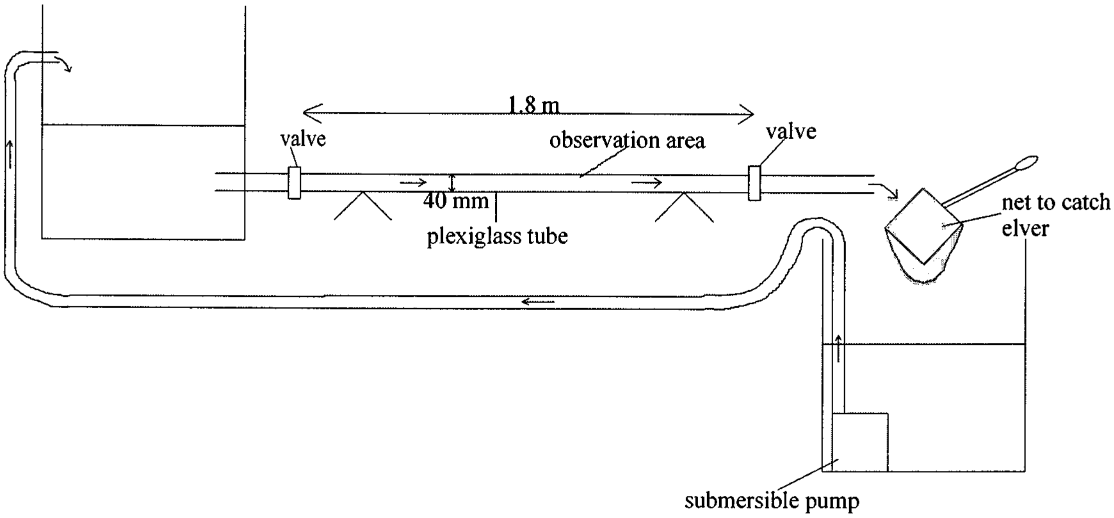


Figure 3.2c. Diagram of the eel flume. Arrows indicate the direction of water flow.

Water velocity through the elver tunnel was determined by timing the collection of a known volume of water (e.g. 10,000cm^3), and applying the formula:

$$v = 10000/at,$$

where v = water velocity (cms $^{-1}$), a is the cross sectional area of the pipe (cm^2) and t is the time (s). The internal diameter of the pipe was 4 cm, so the cross sectional area (a) = πr^2 = 12.57cm^2. Therefore:

$$v = 10000/12.57t.$$

3.3 Swimming Test Protocols

3.3.1 High-speed tunnel protocol

Burst swimming experiments were carried out in the high-speed tunnel. For each test, seven batches of three fish were used, making 21 fish in total. The fish were netted from the outdoor stock tank and placed in aerated containers near to the burst tunnel, for a settling period of three hours. The tunnel was operated for at least five minutes prior to the test to ensure the water was fully aerated, and the water temperature in the tunnel was recorded at the start and end of each test. Water velocity was measured at a fixed point for each test. The smooth glass base and sides of the flume ensured that boundary layer effects were minimised.

Three fish of similar size were carefully introduced to the tunnel to minimise handling stress, with the water flowing at 0.4, 0.5 or 0.6m s^{-1}, for small, medium and large fish respectively. The fish were allowed to acclimatise to swimming at this speed for 15 minutes, during which time any distinguishing marks on the fish were recorded. After the 15 minute acclimation period had elapsed the speed was increased to 0.8m s^{-1}, and the stopwatch was started (N.B. if the fish had been acclimatised at 0.4m s^{-1}, the speed was increased to 0.6m s^{-1} for twenty seconds, and then to 0.8m s^{-1} after this). After 20 seconds at 0.8m s^{-1}, the speed was increased to 1.0m s^{-1}. After a further 20 seconds, the speed was increased to 1.1m s^{-1} and so on, with subsequent increases of 0.1m s^{-1} occurring at 20 second intervals. The time at which each fish dropped back against the screen was recorded, and the water flow stopped. The fish were then removed from the tunnel and returned to their stock tank. Critical Burst Swimming Speed (CBSS) was calculated assuming a gradual increase in speed i.e. a 0.5cm s^{-1} increase with each second, in accordance with standard CBSS methodology (Brett, 1967). For example a 15cm fish achieved speeds of 0.8m s^{-1}, 1.0m s^{-1} and 1.2m s^{-1} for 20 seconds but at 1.4m s^{-1} it was able to swim for only for 11 seconds. The CBSS was then calculated as the speed at which the full 20s was swum, plus 11/20^{ths} of the velocity increment (0.2m s^{-1}), i.e.:

$$\text{CBSS} = 1.2 + (11/20 \times 0.2) = 1.31\text{m s}^{-1} = 8.73 \text{ bl s}^{-1}.$$

3.3.2 Low-speed flume protocol

A minimum of 21 fish of a pre-determined size range were required for each endurance test, and these were distributed so that there were at least 7 fish in each of the 3 sections of the low speed flume. A settling period of 2-3 hours was allowed before the start of each endurance-swimming test. This settling period allowed the fish to recover from any handling stress sustained during capture from the stock tanks, and to acclimatise to their new surroundings. During the settling period water velocity was set at around one body-length per second, and the channel was covered to prevent the fish jumping out.

After the settling period, the water velocity was increased gradually up to the test speed. The start of the experiment was taken as the point at which the test speed was reached, and any fish exhausted prior to this were removed and recorded as "Time = 0". Overhead cameras and lights allowed the experiment to be viewed from an adjoining observation room. Water temperature and 10 water speed measurements were taken during the settling-in time.

Each endurance test lasted for 200 minutes. As each fish became exhausted it was removed from the flume, weighed, measured and the time recorded. Each fish was returned to the stock tank as soon as possible after being removed from the flume. After 200 minutes, the water flow was slowed to a stop, and the water temperature recorded. All remaining fish were weighed and measured, with any damage to fins being recorded.

3.3.3 Eel tunnel protocol

Elver swimming capacity was tested using elvers individually. It was possible to carry out all tests on elvers using the elver tunnel, as a continuum of velocities for burst and sustainable speeds was attainable.

3.4 Problems Experienced

3.4.1 Supplies of fish

Sourcing fish of appropriate sizes from lotic environments was difficult. Fish of less than 10cm of all species proved especially difficult to acquire. In particular, small dace from flowing water were virtually impossible to obtain at certain times of the year, with the current year's fish being too small to use, and the previous year's being greater than 10 cm. Fish collection, transportation and daily husbandry also proved to be particularly time-consuming.

3.4.2 Escapees

Fish of 8cm and under were sometimes able to get through the mesh that divided the low-speed flume. Once out of the enclosures the fish were difficult to locate and recapture. In addition, fish at liberty had access to the inlet pipe of the pump, and were therefore in danger of being injured when the pump was operated. Some of the escapees were recaptured using a trap, however traps were most effective when left overnight and as a result some testing time was lost.

3.4.3 Disease

Keeping fish during high summer temperatures proved problematical, with dace and roach being particularly susceptible to 'white spot' disease. The problem appeared to be exacerbated by handling stress sustained during swim speed trials. A disinfection system for nets was introduced, in order to prevent the spread of disease from tank to tank. In addition, all fish were treated for white spot (with methylene blue) when they arrived on site, even when no symptoms were evident. The testing of sensitive species was minimised during particularly hot spells. These measures were effective in reducing mortalities. At other times of the year, fin rot and fungal infections were common, particularly in roach and dace. Again, these problems were exacerbated by the handling stress associated with swim-speed tests. Fin rot was successfully treated by bathing the fish in chloramine-T (10mg l^{-1}) for 24 hours, and outbreaks of fungal infections were kept in check by dipping the fish in a solution of malachite green (67 mgl^{-1}) for 1 minute. Only fish found to be in good condition were used in swimming trials.

3.5 Swimming Uphill, Near the Surface and Partially Submerged

3.5.1 Swimming uphill - theory

When a fish swims near the surface or when partially exposed, it must overcome the combined forces resulting from form, frictional and wave drag. When the same fish swims up an incline near the surface or when partially exposed it must also raise the submerged portion of its weight in water, and the exposed portion of its weight in air, against gravity. Larger fish have more swimming muscle, and consequently more power. However, for any given incline, as size increases, both the proportion of the fish's weight in air, and the proportion of the caudal fin exposed also increase. Consequently, the relative power required to ascend a given slope rises and the relative thrust available falls with increasing fish length. Theoretically, at some point the power required to ascend a given slope will exceed the thrust available to the fish. If power alone is the sole factor limiting a fish's ability to ascend an incline, then the point at which power required exceeds power available will be the point at which a fish is no longer able to ascend. In order to determine the point at which power required exceeds power available, the various components of drag, gravity and power were modelled for a range of fish sizes on a given slope.

3.5.2 Swimming uphill - experiment

Initially, it had been intended that the high-speed tunnel would be used for these experiments. Unfortunately, the flow conditions were found unsuitable, owing to the formation of a standing wave at the bottom of the slope when a downstream fish screen was in place. Without this screen, the fish would have been able to escape into the pump circuit. Instead, to test the findings of the model, the low-speed flume was modified to provide an inclined plane with slopes of either 5% or 20% (Figure 3.5). A thin film of water passing over the inclined plane was generated by inserting a dam board upstream of the observation section, with a head of water being maintained behind the dam board using the paddle wheel. A rectangular section channel (1.8m x 0.14m x 0.09m) was fitted below the level of the dam, so that when the water overtopped a notch in the dam board, it flowed down the slope. The depth and velocity profiles for the 5 and 20% slopes are given in Appendix 7. Prior to the tests a full morphological analysis of the fish was carried out, and relationships between length and surface area, and length and maximum body depth were calculated (Appendices 5 & 6). Test fish were retained in a basket at the downstream end of the incline, and any attempt to ascend the slope was recorded. The time taken for successful ascents was recorded on a stopwatch, and the lengths of the fish that succeeded, and those that tried and failed, were recorded. Fish that did not attempt to ascend the slope were omitted from the analysis. Fish were encouraged to ascend by raising the level of the lower basket to reduce the residual water level.

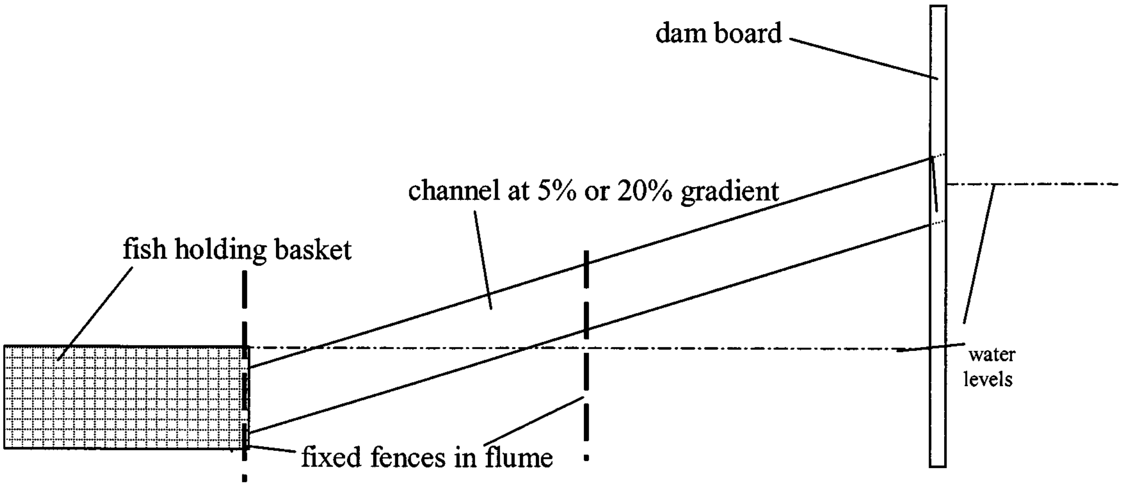


Figure 3.5. **Apparatus used to test the performance of fish swimming uphill whilst partially submerged.**

3.6 Muscle Twitch Experiments

Muscle twitch experiments were carried out using a method detailed in Wardle (1975). The contraction of the muscle was detected using an optical wedge transducer coupled to a Picoscope™ analogue-to-digital converter, with voltage changes being recorded on a laptop computer. Muscle twitch experiments were carried out with chub, roach and trout. Two muscle blocks (3 x 1 x 0.5cm each) were taken from each flank of the test fish, one from near the head and one from near the tail, giving a total of four muscle blocks per fish.

3.6.1 Muscle twitch apparatus and protocol

Fish were acclimated for several days at the test temperature. Immediately prior to dissection and testing, the test fish was killed by a sharp blow to the head. One end of a dissected muscle block was firmly secured using a double fishhook, which also served as a stimulus electrode. A thin thread was attached to the other end of the muscle, again using a double hook, which also acted as the second electrode. The opposite end of this thread was connected, via a lever, to a strip of acetate, onto which was printed a grey-scale of increasing density from clear to black. The acetate ran between two plates, one with a small hole and the other containing a camera-type photoreceptor (Figure 3.6). A cool light source (fibre-optic microscope lamp) was directed into the hole such that as the acetate was pulled between the plates, the amount of light reaching the photoreceptor varied according to the density of the grey-scale immediately adjacent to the hole. Thus, contraction of the muscle block resulted in movement of the acetate strip, a change in the density of the grey-scale adjacent to the hole and a corresponding change in the light intensity reaching the photoreceptor. This induced a measurable voltage change in the photoreceptor that could be detected by the Picoscope. Contraction times were measured from the point at which the voltage trace fell below background level, to the point at which the trace reached its lowest voltage reading. Ten individual contractions were generated per muscle block by applying direct current pulses via the electrodes, with at least 30 seconds between contractions. Dissected muscle blocks were stored in 0.1M saline (NaCl) solution, and the test block was irrigated with saline between contractions.

3.7 Statistical analysis

All statistics and tests of significance were carried out using statistical functions within MS Excel 97™.

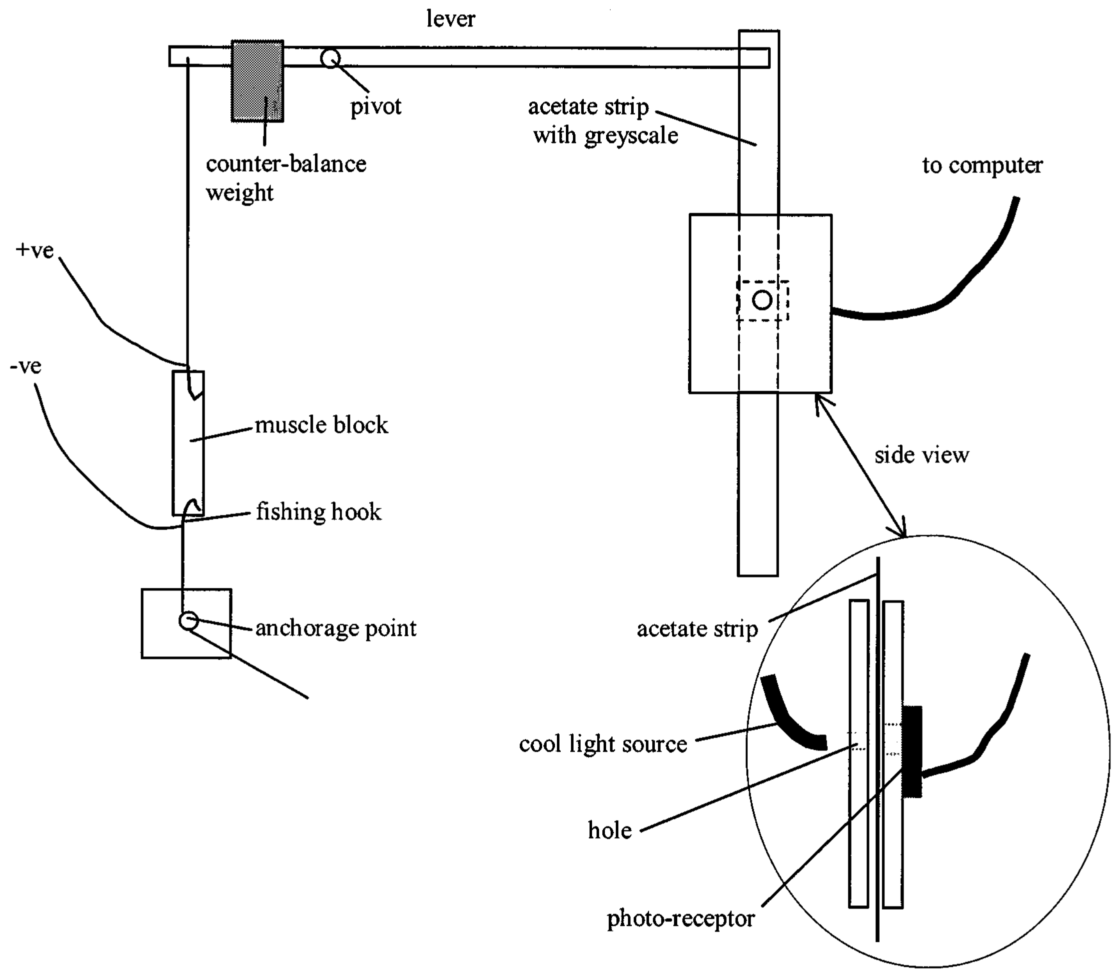


Figure 3.6. Muscle twitch apparatus based on a method detailed in Wardle (1975).

4. RESULTS AND OBSERVATIONS

4.1 Endurance Experiments – Sustained Swimming Speed

Endurance swimming tests were carried out in three different temperature ranges (< 11, 11-15 & > 15°C for the cyprinids, and <9, 9-14 & >14°C for trout). Results were divided up into three length categories, these being referred to as small (< 10cm), medium (10-15cm), and large (> 15cm). The experiments were carried out at seasonal ambient temperatures. In total, sustained swimming speeds were calculated for 3885 fish, not including elvers. 417 elver sustained swimming tests were conducted at seasonal ambient temperature, both early and late in the season, with size being determined by age.

Under normal circumstances the fish in endurance experiments took up a position in the flow and swam steadily "on the spot". A regular pattern of behaviour was seen in tiring fish, which involved more erratic swimming, and a tendency to swim rapidly upstream before dropping back to the downstream screen. Upon reaching the downstream screen the fish either burst forward once more, or dropped back onto the screen and were subsequently removed. A few fish also exhibited a form of "cheating" whereby an individual would wedge itself between the lower screen and the side-wall, using its caudal fin.

Observations showed that even with a relatively low water velocity, some fish became caught against the screens during the acclimation period. The endurance time of these fish was therefore recorded as zero. Similarly, a number of fish became caught against the screens during the initial speeding up process, but before the test speed had been reached. The endurance time of these fish was also recorded as zero. Even at the highest test speeds some fish completed the full 200 minutes, either legitimately or occasionally by "cheating" for varying lengths of time. For these reasons, the mean endurance time, which is likely to be heavily influenced by extreme values, was not considered to offer an accurate reflection of fish performance. Instead, percentiles were calculated to illustrate the relative proportions of fish failing near the start, part way through the test, or completing the full 200 minutes.

In order to calculate the percentiles for each species, all the results for a given size class and temperature range were pooled on a spreadsheet, and test speeds were converted to body-lengths per second and ranked. Percentiles of endurance time were then generated for each test speed category using the percentiles function in Microsoft Excel. Percentile charts for each size category of each species, in each temperature band are given in Appendix 1. These percentile charts of endurance time (in minutes) against water velocity (in body lengths per second) are generally consistent and show that endurance time fell at higher water velocities.

Charts showing endurance swimming speed in both metres per second and body lengths per second are included in the Appendix. These data were used to produce the SWIMIT program. Figure 4.1 provides an example of the endurance swimming output that can be generated using the program.

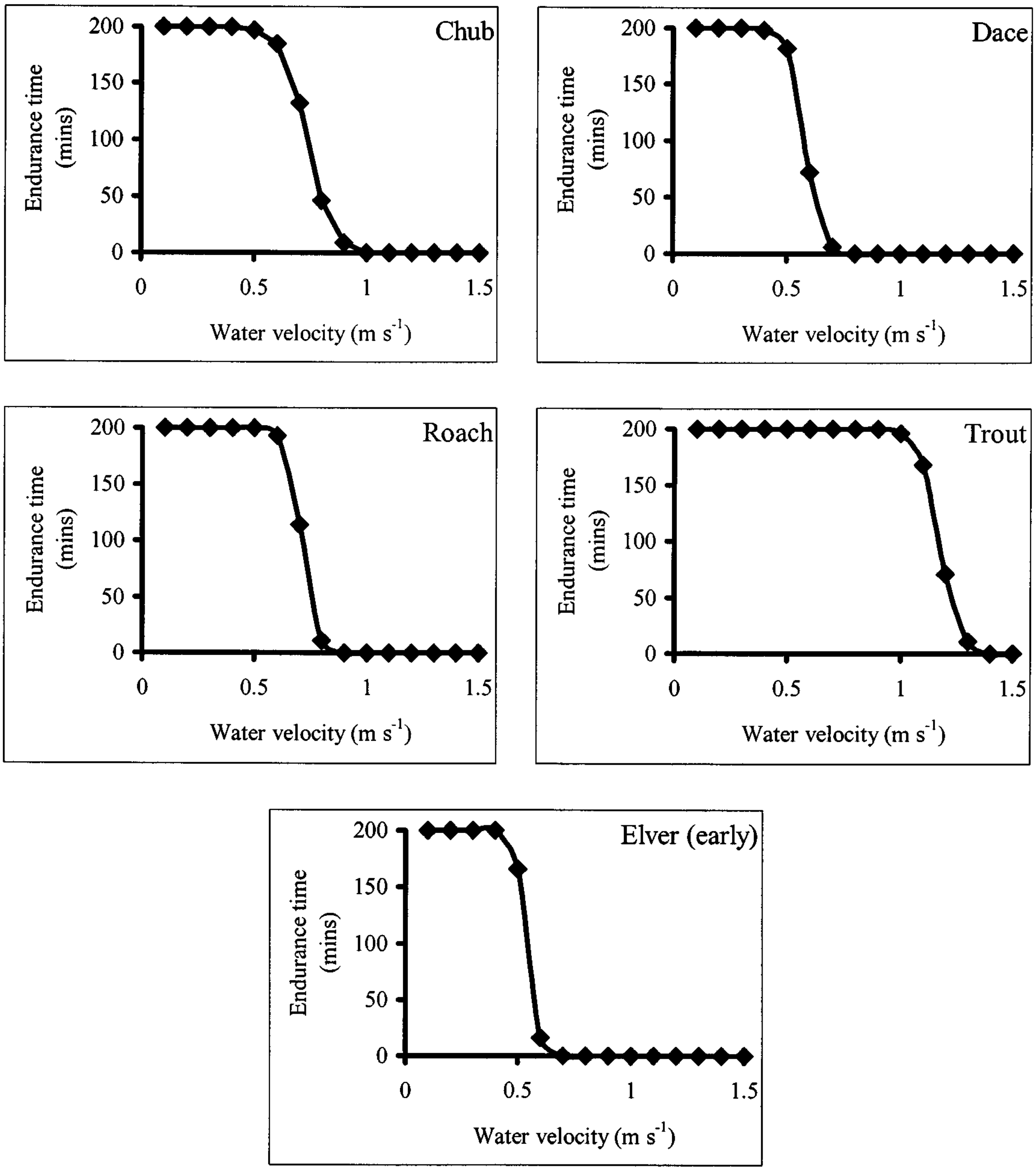


Figure 4.1 **Example of the data that was generated by the endurance swimming experiments. The charts show median endurance times of 15cm fish at 10°C for each of the 5 species, and were generated from the SWIMIT program.**

4.2 Burst Experiments – Critical Burst Swimming Speed

Critical burst swimming speed (CBSS) was determined for over 900 fish at a range of temperatures. CBSS results are also presented in fish body lengths per second. Results are summarised in Figures 4.2.1 to 4.2.4 for chub, dace, roach and trout respectively. Numerical values are given in Appendix 2.

Tables 4.2.1 to 4.2.4 give summary statistics for multiple regression analyses of CBSS versus water temperature and fish length based on the model:

$$CBSS = b_0 + b_1.\log(\text{Length}) + b_2.\log(\text{Temperature}),$$

where b_0, b_1 and b_2 are the regression coefficients. Logarithmic transformations of the independent variables Length and Temperature were used in common with other studies of this type owing to the log-normal distributions of these variables (Turnpenny and Bamber, 1983). The regression equations arising from these tables are used in the accompanying 'SWIMIT' computer program to calculate mean CBSS values and their 95% confidence intervals for different combinations of fish length and water temperature.

4.2.1 Critical burst swimming speed of chub

CBSS was determined for 230 chub, in three different temperature ranges (<11, 11-15 & >15°C). Results were divided into three length categories, referred to as small (< 10cm), medium (10-15cm) and large (> 15cm). Mean CBSS values ranged from 15.4 to 20.6, 9.9 to 10.7 and 7.5 to 8.4 bl s^{-1}, for small, medium and large chub respectively (Figures 4.2.1 a, b & c).

4.2.2 Critical burst swimming speed of dace

CBSS was determined for 215 dace, using the same temperature and length categories as used for chub. Mean CBSS values ranged from 12.5 to 20.2, 10.6 to 11.6 and 7.4 to 8.2 bl s^{-1} for small, medium and large dace respectively (Figures 4.2.2a, b & c).

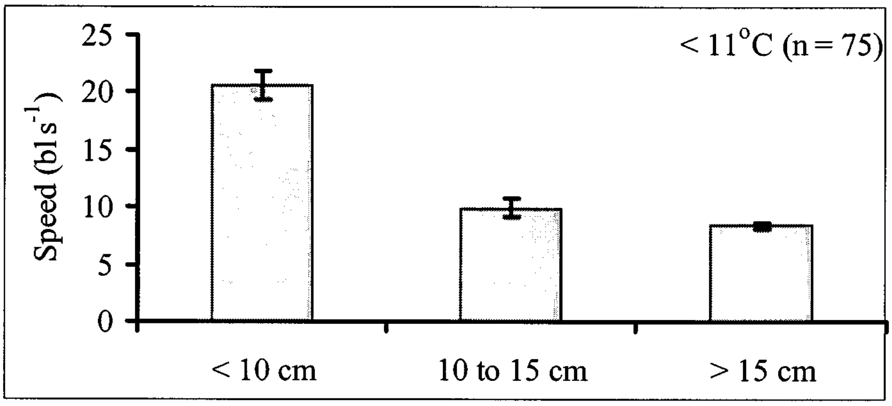
4.2.3 Critical burst swimming speed of roach

CBSS was determined for 210 roach, using the same temperature and length categories as used for chub and dace. Mean CBSS values ranged from 11.5 to 14.7, 9.5 to 10.4 and 7.6 to 8.4 bl $s^{-1}$for small, medium and large roach respectively (Figures 4.2.3a, b & c).

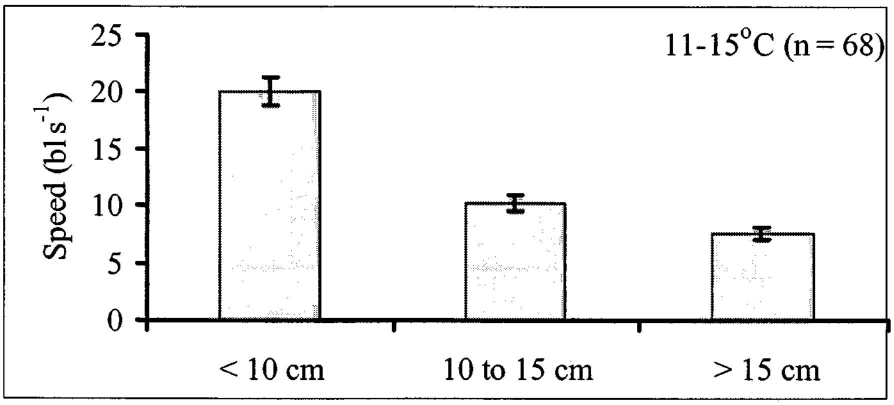
4.2.4 Critical burst swimming speed of trout.

CBSS was determined for 249 trout in four different temperatures ranges (<9, 9-14, >14 to 20 & >20°C). Results were divided into the same three length categories as used for the cyprinids. Mean CBSS values ranged from 13.1 to 18.3, 9.2 to 14.2 and 7.3 to 9.3 bl s^{-1} for small, medium and large trout respectively (Figures 4.2.4a, b & c).

CBSS values for eel are not given in this section. A continuum of velocities was available in the elver flume, and both burst and endurance swimming data are recorded together in section 4.1.



4.2.1a.



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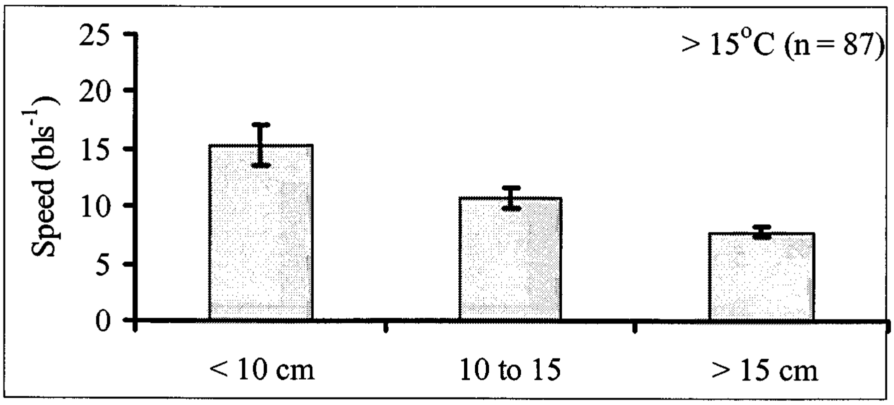
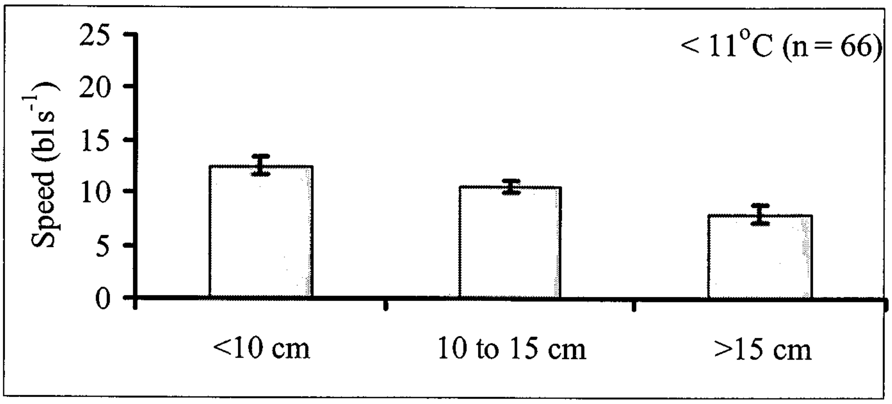
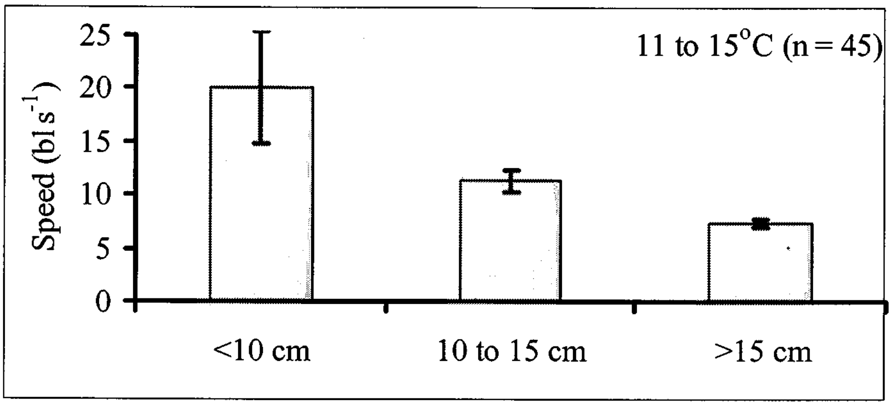


4.2.1c.

Figures 4.2.1a, b & c. Mean critical burst swimming speed (CBSS) of chub at three temperatures. Error bars represent 95% confidence limits.



4.2.2a.



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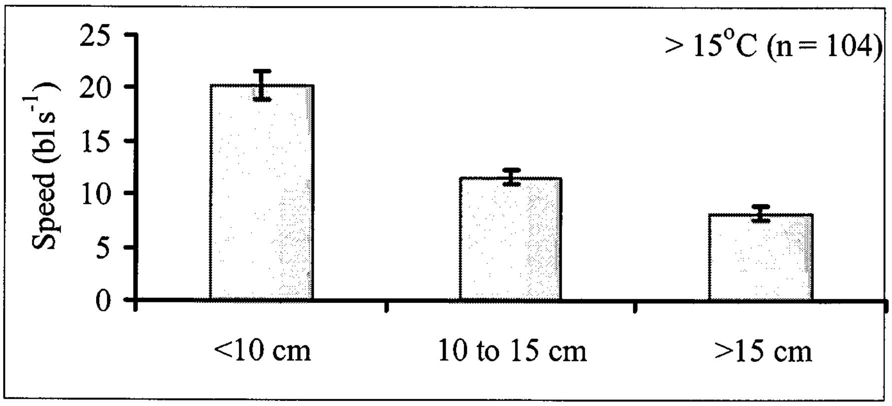
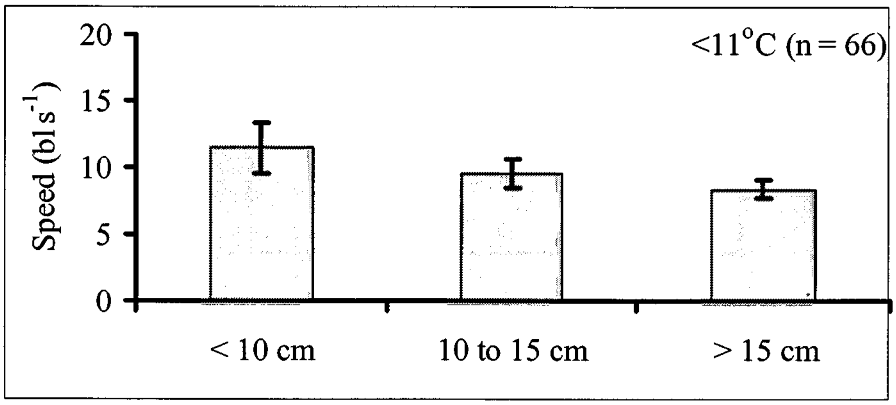


4.2.2c.

Figures 4.2.2a, b & c. Mean critical burst swimming speed (CBSS) of dace at three temperatures. Error bars represent 95% confidence limits.



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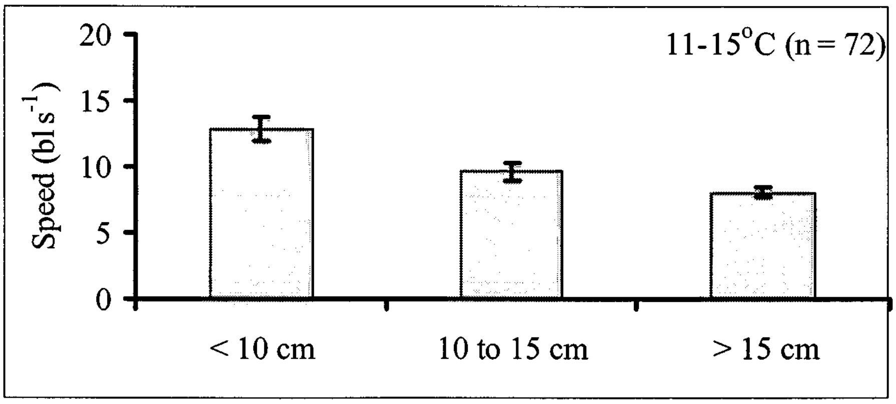
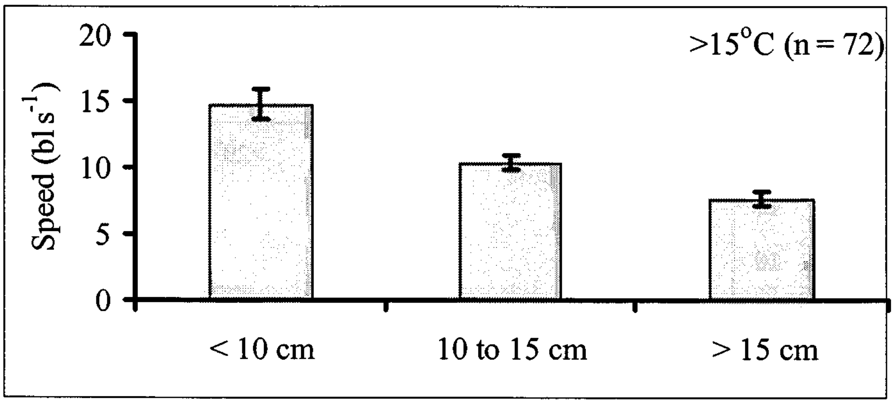
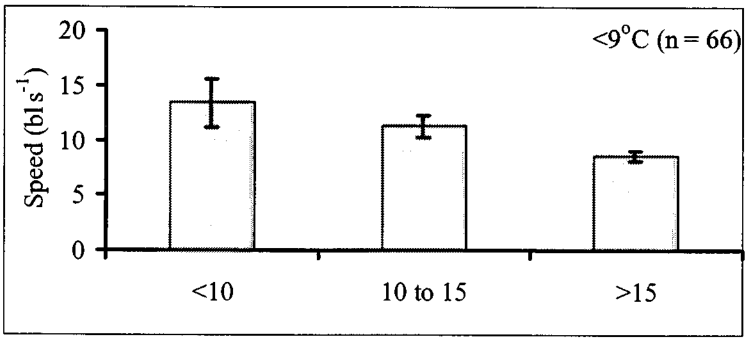


4.2.3b.



4.2.3c.

Figures 4.2.3a, b & c. Mean critical burst swimming speed (CSS) of roach at three temperatures. Error bars represent 95% confidence limits.



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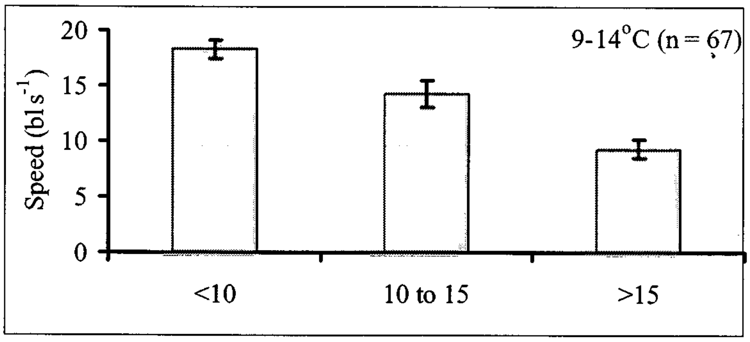

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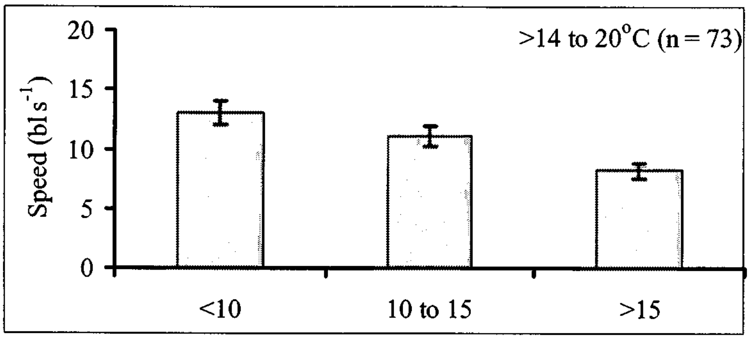

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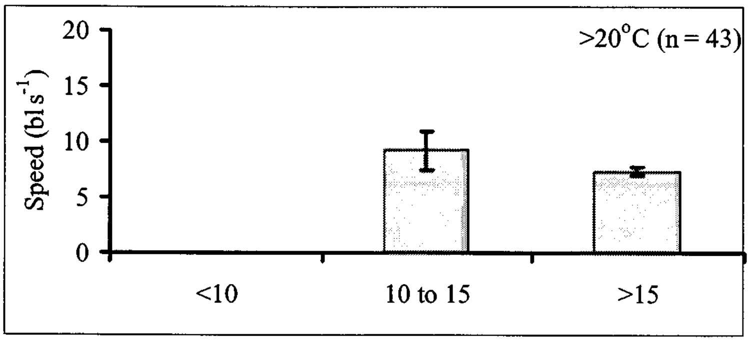


4.2.4d.

Figures 4.2.4a, b, c & d. Mean critical burst swimming speed (CSS) of brown trout at four temperatures. Error bars represent 95% confidence limits.

Table 4.2.1 Multiple regression statistics calculated for burst swimming - chub

Summary Output for Chub Regression

Regression Statistics	
Multiple R	0.691
R Square	0.478
Adjusted R Square	0.473
Standard Error	18.981
Observations	236

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	76825	38413	107	1.32153E-33
Residual	233	83941	360		
Total	235	160766			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-7.27	11.55	-0.63	0.53	-30.02	15.48
Log_Length	67.56	6.21	10.87	<0.001	55.32	79.80
Log_Temp	57.66	10.87	5.30	<0.001	36.24	79.08

Table 4.2.2 Multiple regression statistics calculated for burst swimming - dace

Summary Output for Dace Regression

Regression Statistics	
Multiple R	0.712
R Square	0.506
Adjusted R Square	0.502
Standard Error	21.951
Observations	236

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	115145	57572	119	1.93815E-36
Residual	233	112275	482		
Total	235	227419			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*
Intercept	-18.99	12.20	-1.56	0.12	-43.02
Log_Length	100.30	6.57	15.26	<0.001	87.35
Log_Temp	35.80	7.62	4.70	<0.001	20.79

Table 4.2.3 Multiple regression statistics calculated for burst swimming - roach

Summary Output for Roach Regression

Regression Statistics	
Multiple R	0.592
R Square	0.351
Adjusted R Square	0.345
Standard Error	22.252
Observations	236

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	62356	31178	63.0	1.37156E-22
Residual	233	115366	495		
Total	235	177722			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-49.73	17.45	-2.85	<0.001	-84.12	-15.34
Log_Length	111.36	10.21	10.91	<0.001	91.25	131.47
Log_Temp	46.12	11.01	4.19	<0.001	24.43	67.81

Table 4.2.4 Multiple regression statistics calculated for burst swimming - trout

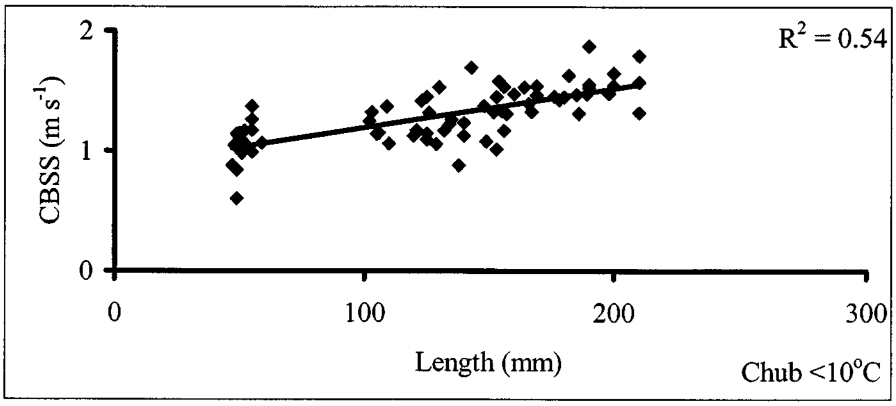
Summary Output for Trout Regression

Regression Statistics	
Multiple R	0.201
R Square	0.041
Adjusted R Square	0.032
Standard Error	27.349
Observations	236

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	7359	3680	4.920	0.00808
Residual	233	174272	748		
Total	235	181632			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	186.699	21.95	8.51	<0.001	143.46	229.94
Log_Length	-7.495	17.39	-0.43	0.67	-41.76	26.77
Log_Temp	-33.910	11.15	-3.04	0.003	-55.87	-11.95



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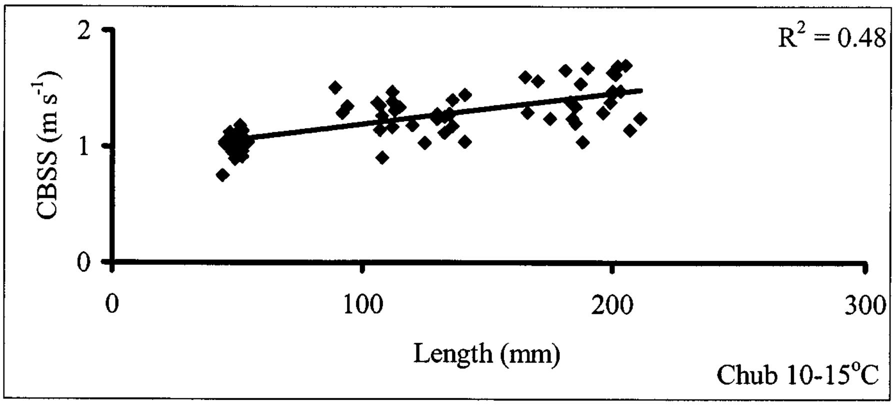

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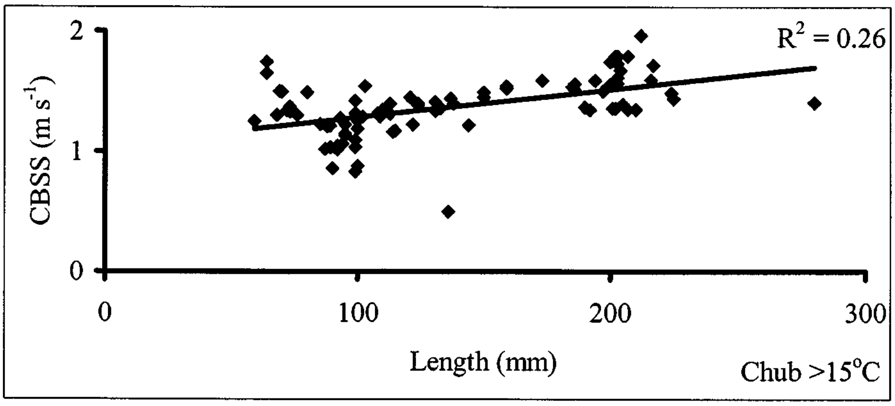
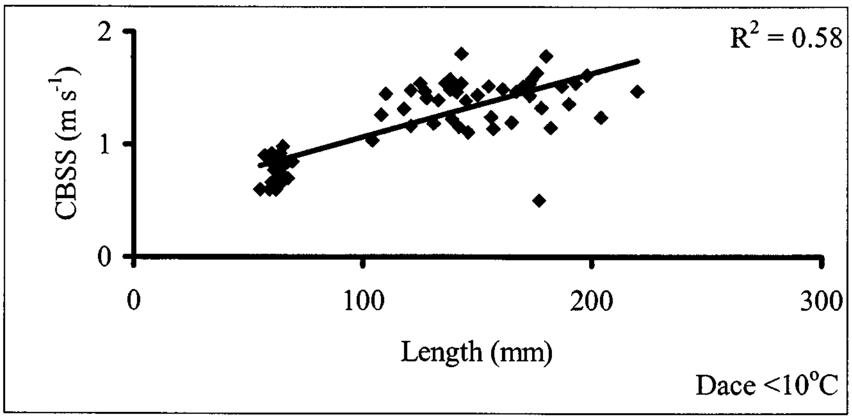
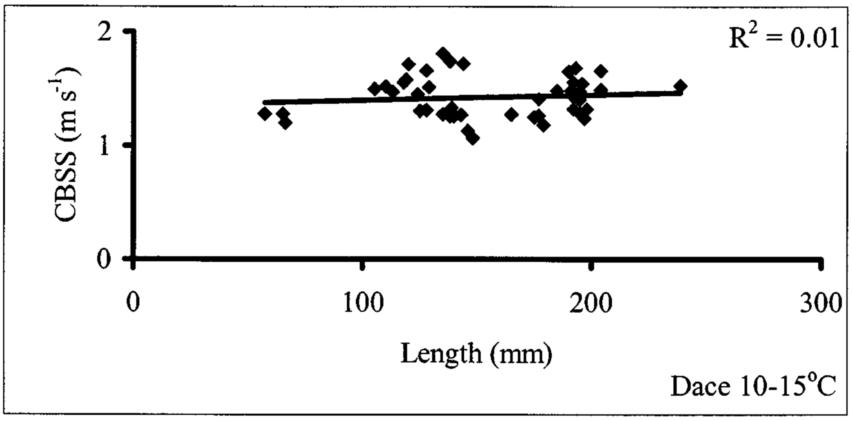


4.2.5c

Figures 4.2.5a, b & c. Relationship between length and CBSS for chub in three different temperature categories.



4.2.6a



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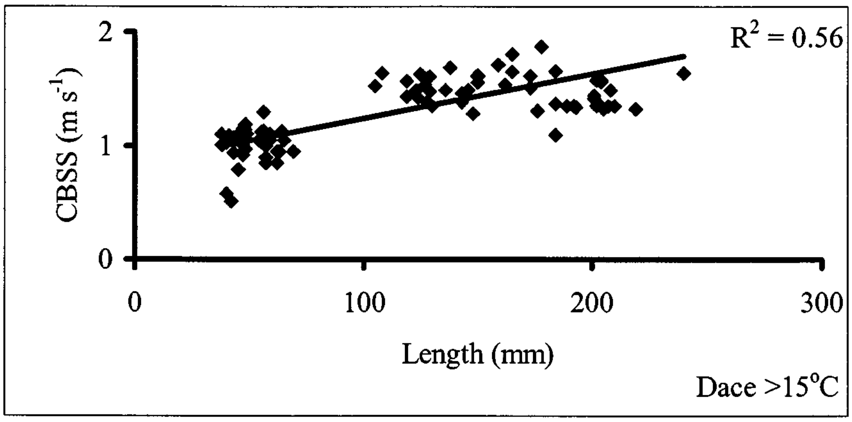
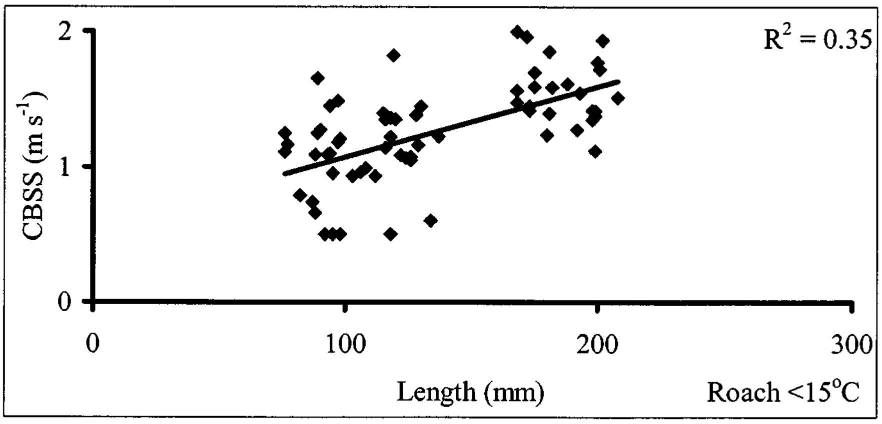


4.2.6c

Figures 4.2.6a, b & c. Relationship between length and CBSS for dace in three different temperature categories.



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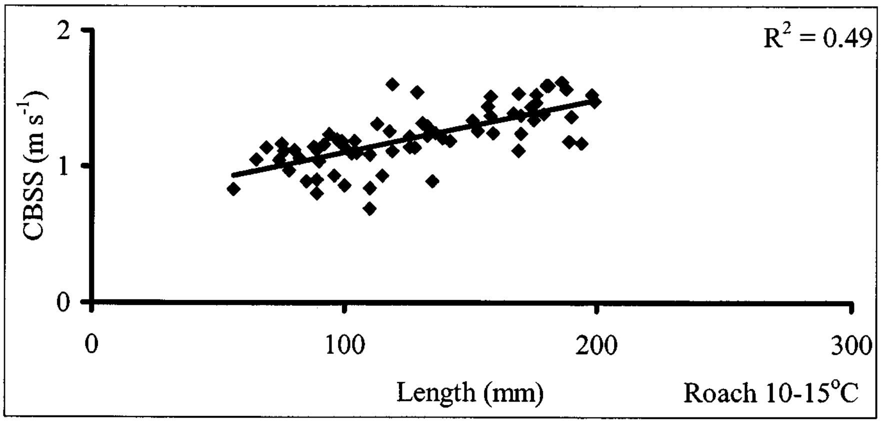

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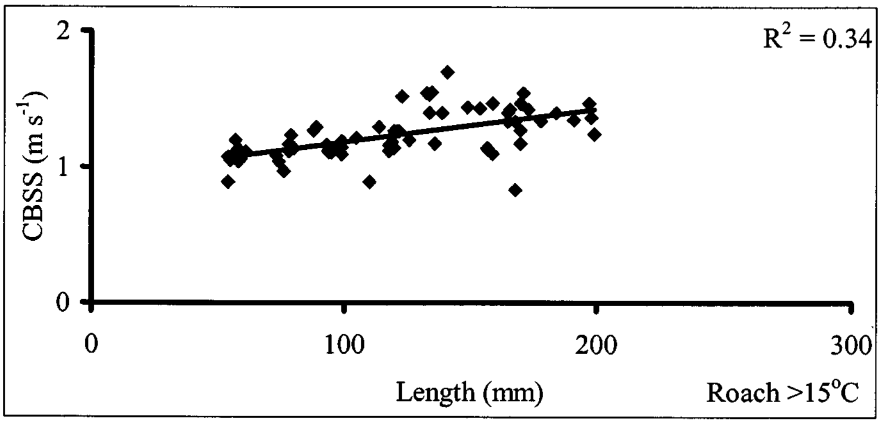
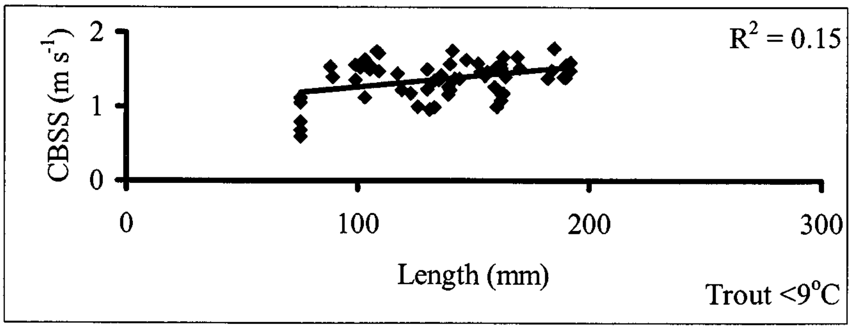


4.2.7c

Figures 4.2.7a, b & c. Relationship between length and CBSS for roach in three different temperature categories.



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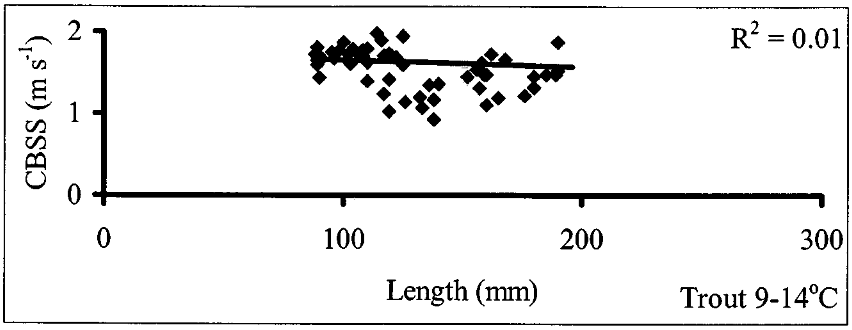

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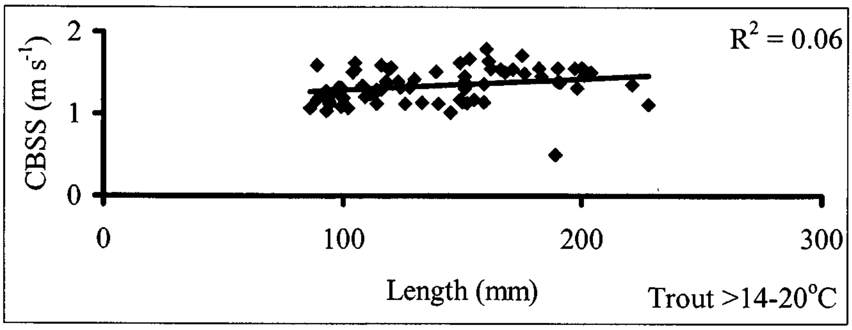
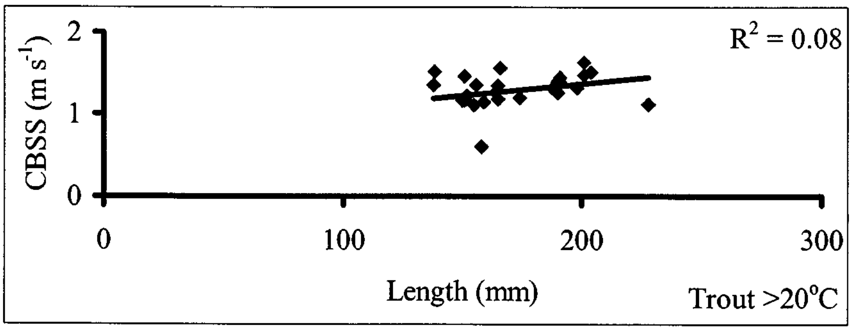


4.2.8c



4.2.8d

Figures 4.2.8a, b, c & d. Relationship between length and CBSS for trout in four different temperature categories.

4.3 Swimming Uphill, Near the Surface and Partially Submerged

Equations given in this section refer to those given in section 2.3.

4.3.1 Drag

To illustrate the drag forces acting upon, and the power available to a fish, a chub of 0.15m in length, swimming at 1 m s^{-1}, up a 20% slope is used as an example.

Using the equation given by Bainbridge (1961), the combined drag experienced by a chub of 0.15 m in length, swimming at 1 m s^{-1} is given by:

$$D_t = ½\rho A U^2\ 1.2C_f$$

Substituting figures, this gives:

$$D_t\ = (0.5 \text{ x } 1.02 \text{ x } (0.407 \text{ x } 0.15^2) \text{ x } 1^2 \text{ x } 1.2 \text{ x } 0.00117 = 0.0000065 \text{ Newtons.}$$

In terms of wave drag, if the fish is half exposed, the total drag acting on the fish will be increased by a factor of around 3.5, and the total power required to overcome this drag will increase accordingly.

The total power required to overcome form, frictional and wave drag (*Pr*) is therefore:

$$P_r = (D_t.U,) \text{ x } 3.5 \quad \text{i.e.}$$

$$P_r = (0.0000065 \text{ x } 1) \text{ x } 3 = \ 0.0000227 \text{ Watts.}$$

4.3.2 Swimming uphill

If the weight of a fish in water is assumed to be 5% of its weight in air, then the power required (P_g) to raise a 0.15m chub (total weight in air = 0.0572 kg), by 0.2m, up a 20% incline at a speed of 1m s^{-1} (not including the drag force) is:

$$P_g = ((0.0572/100 \text{ x } 5) \text{ x } 0.2 \text{ x } 9.81/1) = 0.00561 \text{ Watts.}$$

However, if half of the fish is exposed above the surface of the water, the power required (P_g) is the sum of that required to raise the weight in air of the exposed half (P_{ge}) and that required to raise the weight in water of the submerged half (P_{gs}):

P_{ge} = ((0.0572/2) x 0.2 x 9.81/1) = 0.0561 Watts
plus
P_{gs} = ((0.0572/2)/100) x 5) x 0.2 x 9.81/1 = 0.0028 Watts.

Therefore:

$$P_g = (P_{ge} + P_{gs}) = 0.0589 \text{ Watts.}$$

Consequently, for a given fish, the greater the proportion of the fish exposed above the surface, the more power is required to raise the fish against gravity (Figure 4.3a).

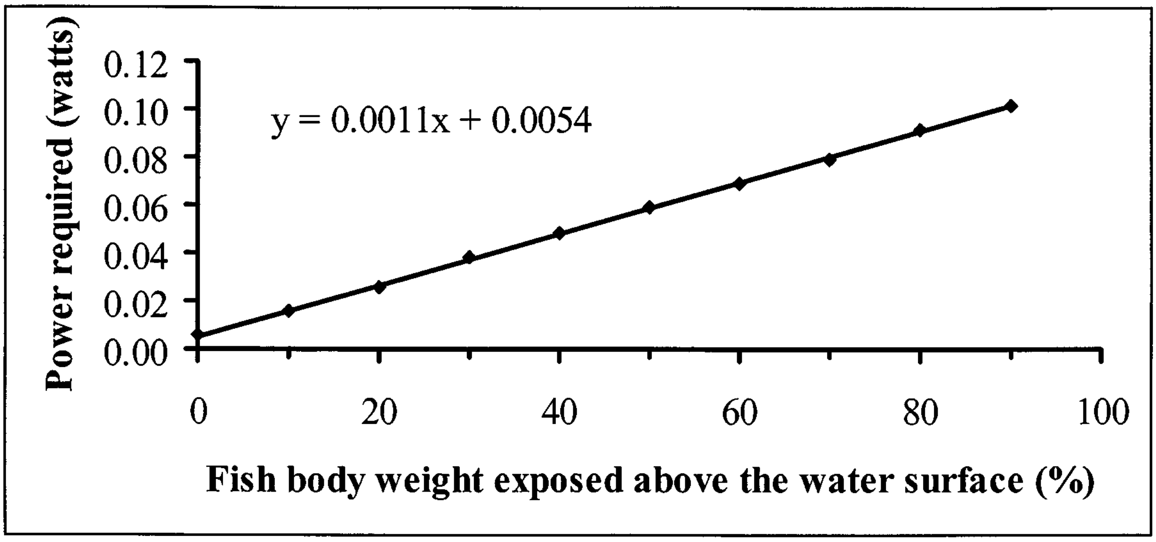


Figure 4.3a. **Relationship between the power required to raise a 0.15m chub 0.2m up a 20% slope at 1m s^{-1}, and the proportion of the fish exposed above the water surface.**

The total power required to raise a half exposed 0.15m fish by 0.2m up a 20% slope at 1m s^{-1} is therefore a combination of the total power required to overcome drag (P_r) plus the total power required to overcome gravity (P_g):

$$P_{tot} = P_r + P_g = 0.0000227 + 0.0591 = 0.0591227 \text{ Watts}$$

4.3.3 Power available

The power available to a fish for swimming is governed by the mass of the swimming muscle, the proportion of which rises with increasing length. The power available (P_a) to a fully submerged fish of 0.15m in length (total weight in air = 0.0563 kg) is given by:

$$P_a = 0.5W_m \times F_p \times e, \quad \text{i.e.}$$

$$P_a = 0.5\ (0.0572/100 \times 56.2) \times 80 \times 0.75 = 0.964 \text{ Watts}$$

In the case of a half exposed fish, the main sources of propulsion i.e. the caudal fin and caudal peduncle are also half exposed, and it is reasonable to assume that the reduction in available power would decrease accordingly:

$$P_a = 0.949/2 = 0.482 \text{ Watts}$$

From the chart (Figure 4.3b), it can be seen that more thrust is available to the fish, even when partially submerged, than is required to ascend the slope.

This suggests that factors other than power influence the ability of fish to ascend slopes.

Thus the following hypothesis was postulated:

> *The burst swimming ability of partially submerged fish ascending an incline will not be reduced compared with the burst swimming ability of fully submerged fish of the same size*

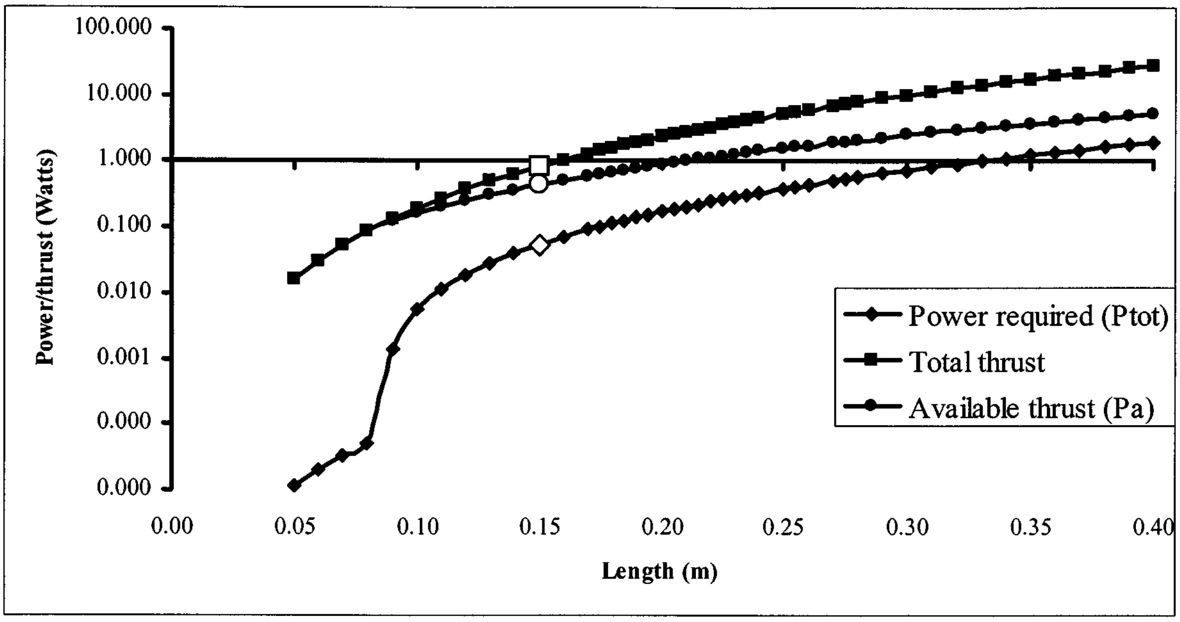


Figure 4.3b. **Relationship between chub length and total thrust, available thrust, and power required to raise the fish by 0.2m up a 20% slope at 1m s^{-1}. Water depth on the slope is set so that a 0.15m chub would be half exposed. Open symbols show the values for a 0.15m chub as described.**

4.3.4 Experimental results

In order to test the hypothesis, slopes of 5% and 20% carrying a thin film of water were created in the modified low-speed flume. Summary data for the swimming uphill experiments carried out with chub, roach and trout are given in Table 4.3.

Table 4.3 **Summary data for fish swimming up slopes whilst partially submerged. Error measures around means are 95% confidence limits.**

			Passes					Try & fail		
	Slope	Attempts	No.	Pass %	Range (m)	Mean length (m)	Mean time (s)	No.	Range (m)	Mean length
Chub	5%	190	124	65.26	0.07 - 0.29	0.17 +/- 0.01	1.87 +/- 0.22	66	0.07 - 0.16	0.08 +/- 0.004
Chub	20%	71	32	45.07	0.16 - 0.29	0.21 +/- 0.01	1.58 +/- 0.18	39	0.08 - 0.29	0.12 +/- 0.02
Roach	5%	188	63	33.51	0.09 - 0.17	0.13 +/- 0.01	3.20 +/- 0.33	125	0.07 - 0.17	0.12 +/- 0.004
Roach	20%	68	0	0.00	*	*	*	68	0.07 - 0.21	0.13 +/- 0.01
Trout	5%	27	22	81.48	0.11 - 0.20	0.16 +/- 0.02	2.96 +/- 1.55	5	0.11 - 0.16	0.12 +/- 0.02
Trout	20%	11	8	72.73	0.12 - 0.22	0.17 +/- 0.03	1.25 +/- 0.34	3	0.19 - 0.20	0.20 +/- 0.02

As the fish were swimming a known distance, and the mean water velocity on the slope was known, by timing the ascent the burst swimming speed of the fish could be calculated, and compared with the results from the high speed tunnel (Figures 4.3.4a, b & c). Fish that did not complete the ascent could not be accurately timed, and were not included, although the same number of fish were used in each trial. Far fewer fish attempted to ascend the steeper slope, and this may reflect the higher approach velocities at the base of the slope.

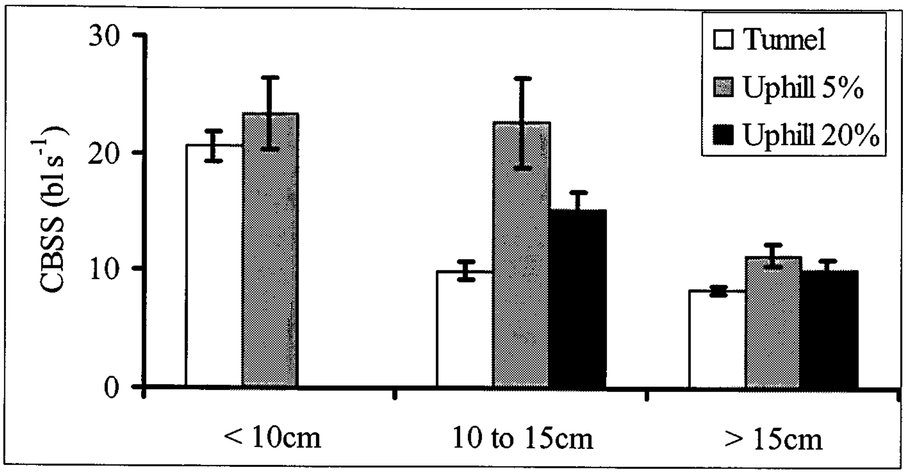


Figure 4.3.4a. Burst swimming of chub compared for level tunnel (fully submerged) and 5% and 20% uphill slope (partially submerged) conditions. Error bars are 95% confidence limits. All chub <10cm failed at the 20% slope.

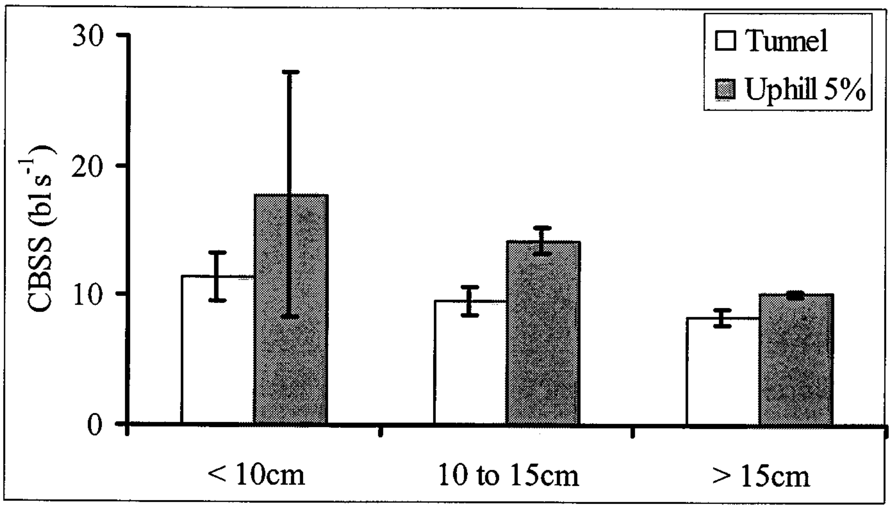


Figure 4.3.4b. Burst swimming of roach compared for level tunnel (fully submerged) and 5% and 20% uphill slope (partially submerged) conditions. Error bars are 95% confidence limits. All roach failed the 20% slope.

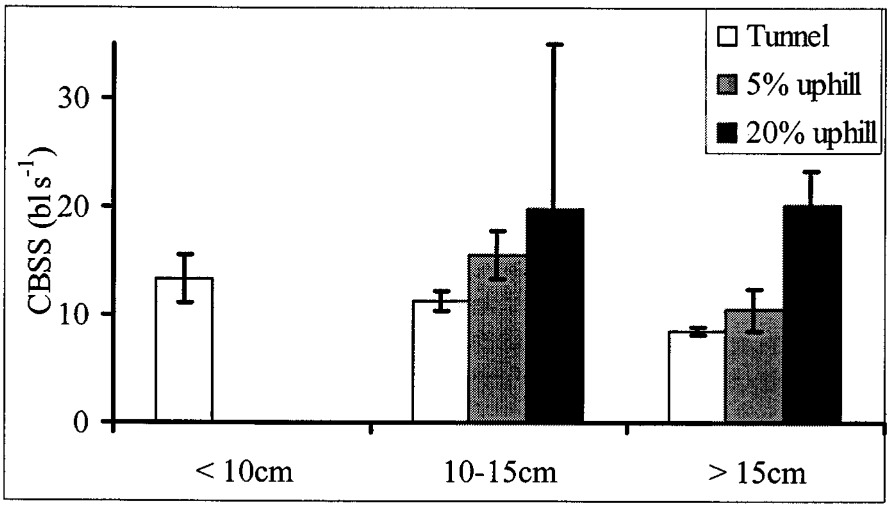


Figure 4.3.4c. Burst swimming of trout compared for level tunnel (fully submerged) and 5% and 20% uphill slope (partially submerged) conditions. Error bars are 95% confidence limits. No <10cm trout were tested.

4.4 Muscle Twitch Experiments

Twitch experiments were attempted with brown trout, chub and roach. Despite extensive testing using a range of stimulus voltage and pulse duration, a measurable twitch was not produced from cyprinid muscles. Although small contractions were observed, these were less than 5% of those obtained with trout and did not produce repeatable readings from the apparatus. Thus it was not feasible to generate useful results for cyprinids by this method.

Muscle twitch results were collected from six trout (range = 18.5 to 22.5 cm, mean = 20.1 cm), with four muscle blocks from each fish being tested. Minimum contraction times ranged from 20.8 to 76.8 ms, with a mean of 40.8 ms (Table 4.4).

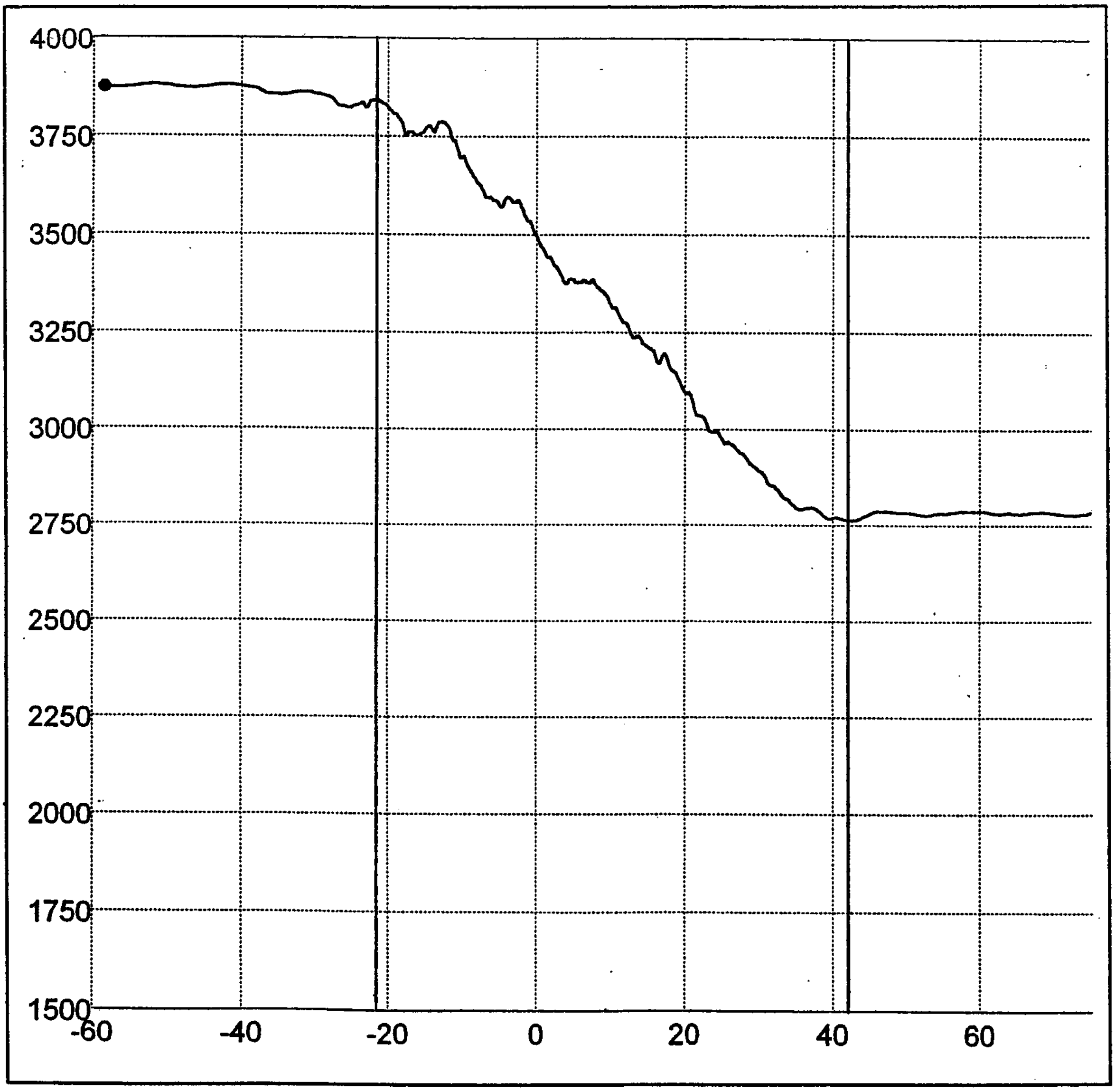


Figure 4.4.1. A typical trace from a muscle twitch experiment. Vertical lines denote the start and end points of the contraction. Units on the x-axis are time in milliseconds, units on the y-axis are arbitrary.

Using Wardle's (1975) stride length of 0.7, the theoretical maximum swimming speed (*M*) can be calculated for each fish using the formula:

$$M = AL/2T,$$

Where A is the stride length (0.7), L is the length of the fish in metres and T is the minimum muscle contraction time in seconds.

Table 4.4 **Summary of results from muscle twitch experiments with trout.**

			Contraction time (s)		Maximum speed	
Length (m)	**No. of obs.**	**Mean temp. (^{o}C)**	**Mean**	**Minimum**	**m s^{-1}**	**bl s^{-1}**
0.185	9	11.5	0.098	0.077	0.843	4.557
0.185	27	16.5	0.085	0.034	1.916	10.355
0.190	27	14.0	0.060	0.021	3.197	16.827
0.205	25	15.0	0.044	0.031	2.315	11.290
0.215	5	13.0	0.082	0.053	1.433	6.667
0.225	14	9.0	0.081	0.030	2.660	11.824
				Mean	**2.061**	**10.25**

The mean maximum theoretical swimming speed of trout (length range 0.185 – 0.225m) at temperatures ranging from 9 to 16.5°C is therefore 2.061 m s^{-1}, or 10.25 bl s^{-1}.

The relationship between maximum swimming speed and temperature is investigated in Figure 4.4.2. An increasing trend of swimming speed with temperature is shown, although the low R-squared value indicates that the trend is not significant at the $P = 0.05$ level.

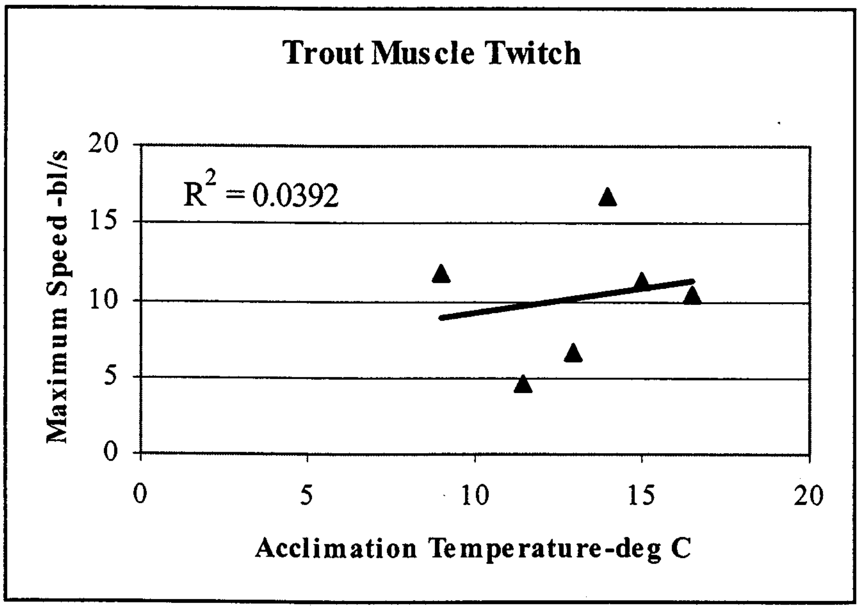


Figure 4.4.2 maximum swimming speed versus fish acclimation temperature in trout, using data given in Table 4.4.

5. ANALYSIS AND DISCUSSION

5.1 General Discussion

The aim of this experimental investigation was to provide data that are applicable to the wild situation. During the course of the project, every effort was made to ensure that the results obtained bear the closest resemblance possible to the swimming of fish in their natural environment. However, there are a number of areas where this was not possible. One aspect concerns the motivation of the fish to achieve their full potential. It was noticeable that even at relatively low velocities, in both burst and endurance tests, some fish appeared not to want to swim. As in all populations, not all individuals have the same ability. In some instances, it is possible that those individuals apparently reluctant to swim were in fact at the upper limit of their capabilities. However, given the low velocities involved and the superior performance of other similarly sized individuals, it seems likely that on at least some occasions fish opted not to swim at speeds well within their physical capabilities. Hence, the motivational status of the fish can be just as important as the physiological ability in determining the swimming achievement.

The problem of a lack of motivation to swim is not only difficult to distinguish from reduced ability, but is also particularly difficult to overcome. Use of an unnatural stimulus, such as an electric shock, has been used in other experiments, for example the study of fast starts in rainbow trout (Webb *et al.*, 1991). However, such treatments may in themselves affect the swimming ability of the fish, and may have a differing effect according to body length and distance from the source of the stimulus. In addition, the natural motivation of a wild individual will change over time according to the situation. For example, a fish moving upstream to reach spawning grounds is likely to have a higher motivation to ascend a given structure, than the same individual at another time of the year. Similarly, a fish being pursued by a predator might be expected to attain a higher burst speed than the same individual ascending a fish pass.

Consequently, as the experiments carried out for this project involved no artificial stimuli, the results obtained may not always reflect the maximum physical capability of highly motivated fish in the wild.

Each of the flume types was designed to provide smooth laminar flow and minimise the effects of the boundary layer. It was noticeable that in all tests fish remained close to the bottom of the flume for most of the time. In addition, fish tended to favour the sides of the channel over the centre. It is likely that the water velocity close to the base and sides of the flume would be slightly slower than in the middle, however it is considered that the smooth design of the flumes would result in this difference being minimal. Cross–sectional flow measurements carried out by Turnpenny & Bamber (1983) showed little difference in water velocity across the channel.

Relevant published data covering the species of interest were rare. Bainbridge (1960) carried out some observations on the swimming speed of dace of between 10.0 and 21.4 cm in length, although no temperature data were provided. As the experiments were conducted over periods of 20 seconds, the results can be compared with those recorded during our burst swimming tests. Bainbridge (1960) estimated that dace swimming speed ranged from 50 cm s^{-1} for a 10 cm fish, to 90 cm s^{-1} for 20 cm fish, corresponding approximately to speeds of 5 to

4.5 bl s^{-1}. These values are generally lower than those collected during our studies, which ranged from 3 to 13 bl s^{-1} for fish in the same size range at temperatures below 10°C. This encourages us to believe that the experimental conditions used here were as favourable as can probably be achieved in the laboratory. Further in-depth comparison with the studies reported in the literature review are not warranted, owing to the generally small numbers of fish and doubtful experimental techniques.

The data collected during the study have a number of potential applications. Peake *et al.*, (1997a & b) used swimming performance data for various salmonids and other species to generate models from which fishery managers could evaluate the water velocity at which fish could pass culverts. The computer program SWIMIT formulated during this study can be used in a similar way (see Appendix 3). For example, by inputting a range of variables for a given fish pass (water velocity, temperature etc.) the predicted success rate for fish of a given size can be calculated. Alternatively, when designing new structures, the maximum water velocity allowing passage of all but, say, 10% of fish of a given size at a particular temperature, can be calculated. Similarly the risk of entrainment of fish at water intakes can be assessed at a range of temperatures, and new intakes can be designed with approach velocities that will help to minimise the risk of entrainment during critical periods of the year.

5.2 Endurance Experiments – Sustained Swimming Speeds

Endurance swimming ability varied according to both fish size and temperature. There was a tendency in all species for a large proportion of the test fish to either fail very early in the test, or to complete the full 200 minutes. Consequently, mean endurance times are likely to be unrepresentative and misleading. By using percentiles a more meaningful indication of the likely endurance swimming ability was provided.

The endurance swimming ability of elvers was poor in comparison with the other species tested. Few elvers, either early or late in the season, managed more than a few seconds or minutes at speeds in excess of 2 bl s^{-1}. The results agree well with those of McCleave (1980) who tested elvers from the Severn estuary. McCleave showed that elvers migrated up through a channel more quickly when a gravel substrate was present, taking advantage of the slower boundary layer, hence they probably seldom even attempt to swim in open water when migrating up rivers. Results of the 'open-water' experiments reported here do provide a basis for predicting the ascendability of a structure or channel provided that the velocity profile in the boundary layer can be determined.

In a study of endurance swimming Katapodis (1992) analysed literature data using dimensionless variables and proposed relationships between speed and endurance for fish swimming in the subcarangiform (relevant to trout and cyprinid species) and anguilliform (relevant to eels) modes. Katapodis found that for each swimming mode the data tended to collapse within a relatively small region of the graph, even though diverse species, data sources and test methods had been used. In order to compare the findings of our study with the endurance curves given in Katapodis (1992), our data were transformed into the dimensionless fish speed F_f, and the dimensionless endurance t_* using the following formulae:

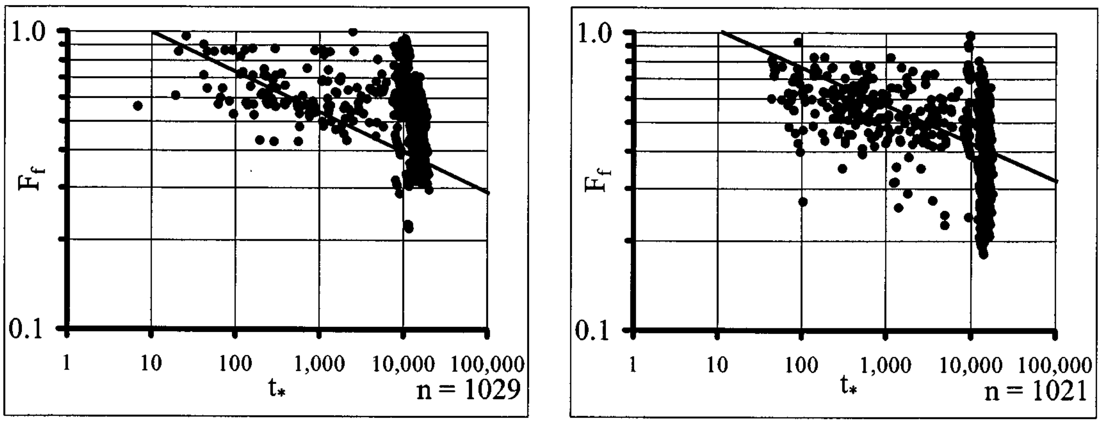
$$F_f = U/(\sqrt{g}l)$$

and

$$t_* = t\sqrt{g}/l$$

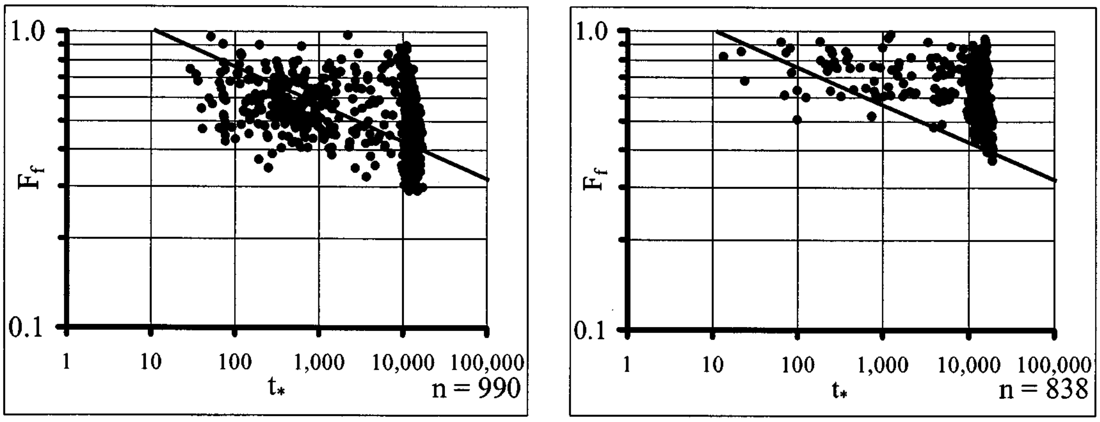
where U is speed (m s^{-1}), g is gravity (9.8m s^{-1}) and l is the length of the fish (m).

Fish that did not perform in the swimming trials had an endurance time of 0 seconds, and were excluded as they could not be plotted on a logarithmic scale. The trendline given by Katapodis for each swimming mode was then overlayed onto our data (Figures 5.3a to e).



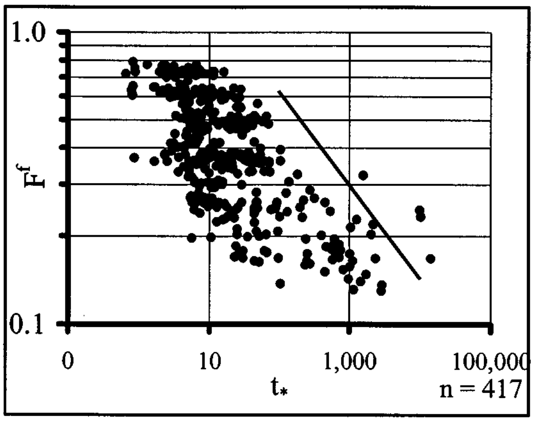
a. Chub

b. Dace



c. Roach

d. Trout



e. Elver

Figures 5.2a to e. Endurance swimming of chub, dace, roach, trout & elver plotted on the dimensionless axes proposed by Katapodis (1992). The line represents the relationship between the dimensionless fish speed (F_f) and the dimensionless endurance (t_*) for carangiform (a-d) and anguiliform (e) swimming modes, as given in Katapodis (1992).

The relationship proposed by Katapodis (1992) provides a reasonable description of our data, particularly for the three cyprinid species. The data for trout tends to be above the line suggesting that their performance was better than would have been predicted. Conversely the vast majority of the elver data falls below the line indicating that results from our experiments demonstrate a poorer level of swimming performance than would have been predicted using the relationship proposed by Katapodis (1992). However, Katapodis' trend lines were generated from data sets of 394 and 79 observations for carangiform and anguiliform swimming modes respectively, compared with data sets of 3878 and 417 generated by our experiments.

5.3 Burst Experiments – Critical Burst Swimming Speed

Burst swimming ability also varied according to both fish length and temperature, as is shown particularly by the multiple regression analyses reported in Tables 4.2.1 to 4.2.4. The differences from zero of the coefficients for both effects were highly significant ($P<0.001$) for all three cyprinid species. That for trout and water temperatures was also significant ($P<0.003$) but the trout size-related coefficient was non-significant ($P=0.67$). The reason for this appears to have been the tendency for smaller trout to hide from the flow by anchoring themselves to the bottom. Although there were periods during which normal, strong swimming was observed, these were interspersed with periods during which the fish arched their bodies, creating negative lift that anchored them to the floor. This behaviour allowed them to remain in position without vigorously beating their tail. Whilst the behaviour might not directly help a small trout to ascend a fish pass, it would allow the fish to recover between period of burst swimming without losing ground. This behaviour would also have obvious advantages in resisting entrainment at a water intake. These clearly were not true 'open-water' swimming values, which is a problem that has beset many previous studies involving epibenthic life stages.

In order to compare our experimental findings with the salmonid maximum swimming speeds proposed by Beach (1984), maximum CBSS values were calculated for a range of trout length classes. These data were then plotted, along with those proposed by Beach, to show the range of maximum swimming speeds, at a range of temperatures (Figure 5.3).

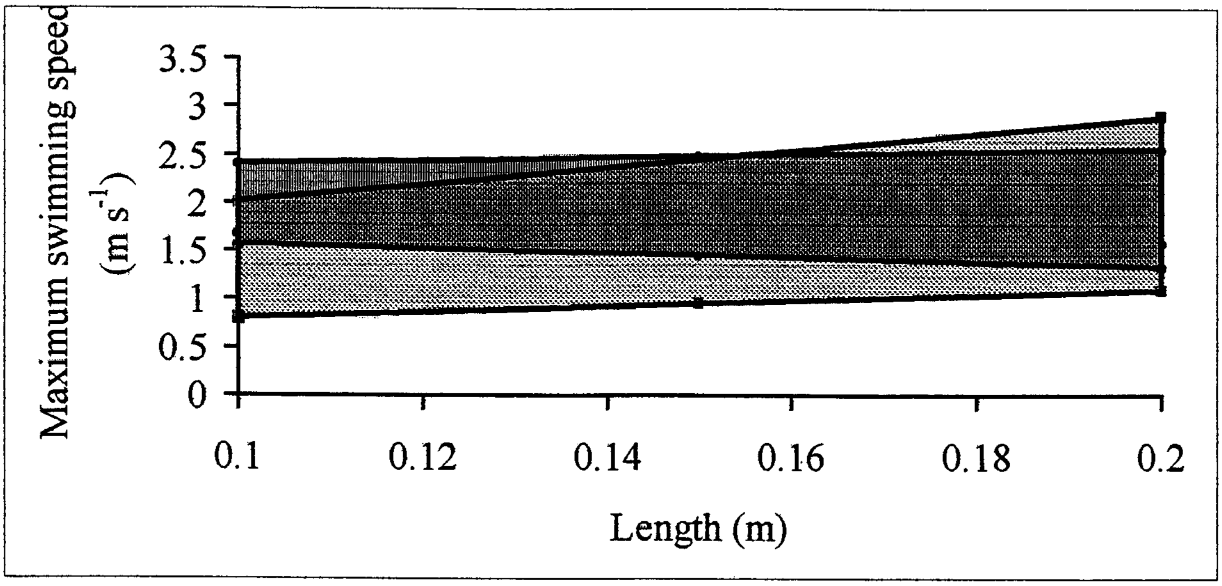


Figure 5.3. **Comparison between the maximum trout swimming speeds recorded in our experiments (<9 to >20°C, striped area behind) and those proposed for salmonids by Beach (1984) (2 to 18°C, pale shaded area overlayed).**

The two sets of data show a high degree of correlation over the length range tested. The main difference between the two data sets is the rate of change in maximum swimming speed with increasing length. The maximum speed values proposed by Beach increase much more rapidly with increased length than is suggested by our experimental data. This may reflect the high speeds attained by small trout by hiding from the flow. These data result in an overestimation at the lower end of the maximum speed range, and result in the apparent reduction in swimming speed with increasing length. If the trend found in our test data with fish length were continued it would suggest that Beach's lines would over predict swimming speeds of larger salmonids. This aspect merits further experimental investigation.

5.4 Swimming Uphill, Near the Surface and Partially Submerged

The model generated to describe the relationship between the available propulsive power and the theoretical required power at a range of submersion depths, and on different slopes, provided interesting results. It would appear that power available exceeds the theoretically required power level, even when the fish is partially submerged, and swimming up a slope. Friction between the underside of the fish and the substratum is likely to vary between substrata types, and according to the degree to which the fish is exposed, however no data were available, and friction was not included in the calculations.

The experimental results demonstrated that some fish tried and failed to ascend, even where the available power was much greater than the theoretical power required. This suggests, perhaps not surprisingly, that power is not the only factor governing the ability of a fish to ascend a slope. Indeed the maximum speed at which a fish can beat its tail will govern the upper limit of burst swimming, and is likely to become limiting for small fish as water velocity increases, regardless of immersion depth. Overall, the burst swimming ability of fish swimming up a slope whilst partially submerged was at least as good as the burst swimming of fully submerged fish in the burst swimming experiments. There is of course an obvious bias in that fish that tried and failed are not included in the analysis, which is likely to result in the mean for the remainder being artificially high. However, the results are based on real measurements, and although they refer to the upper end of the ability range, they still provide an accurate indication of the upper limit of burst swimming.

On this basis, the hypothesis that burst swimming ability is not reduced by being partially submerged is therefore accepted.

In all tests, only one fish succeeded in ascending the slope at a second attempt, having tried once and failed. It seems that at this temperature at least, a fish which attempts an ascent of this type and fails at the first try, is unlikely to be successful at a second attempt, unless given adequate time to recover, or the flow characteristics change in the fish's favour. Recovery time following burst swimming can be as much as 24 hours (Wardle, 1977). Assuming these experimental observations are applicable in the wild, this result has obvious implications for situations when wild fish can be seen attempting to ascend slopes, for instance the face of a Crump weir. In such situations, if the fish seen to try and fail are taken to be unlikely to succeed until fully rested, or until the flow changes, the true impact of the structure as a block and/or delay to migration can be assessed.

In each experiment there were a number of fish which did not approach the slope, and others which approached the slope but did not attempt to ascend. Fish that did not approach or attempt to ascend the slope were excluded from the analysis. There is a possibility that fish can sense the nature of the flow upstream of their position, and instinctively choose not to try the ascent. If this is the case, there is the potential for bias in the results. Indeed the flow characteristics in the approach to such a slope could have a strong influence on the number of fish that attempt the ascent, and has obvious implications for the future design of fish passes and weirs.

The maximum time for a successful completion of the slope was 5.95 seconds, with the majority of fish completing the ascent in less than 3 seconds. This is substantially below the 20 second criteria which is used to determine burst swimming capacity. In fact, it would require a much larger apparatus to provide a 20 second run at burst speed, much more suited to a field experiment. It was also noticeable that the fish that recorded the slowest times during these tests tended to pause on the ramp, completing the ascent in two or more "bursts". Bainbridge (1960) reported a rapid decline in burst swimming of dace between 1 second and 20 seconds. If burst speed is used as the design criterion for upstream fish passage applications, it should at least provide a comfortable margin of safety where shorter bursts are required.

Any behavioural alteration in motivational status in response to rising or falling temperatures will affect the validity of the results, and is an important consideration for future studies. Many fish species are known to make upstream migrations within rivers in order to breed, usually during spring and early summer for UK cyprinids (e.g. Lucas & Mercer, 1996). Conversely, downstream migrations to low velocity areas have been observed in autumn and winter (e.g. Lucas & Batley, 1996) and after spawning (Clough *et al.*, 1998). Consequently, the motivation to swim, and the performance of fish in swimming trials, may be influenced by trends in both temperature and day length. Indeed, although none successfully ascended the 20% slope the percentage of small chub attempting to ascend rose from 5.6% at 8°C, to 23.5% at 9°C and 48.6% at 10°C, for the same group of fish tested on different days within the same week.

The ultimate aim of these experiments was to provide a value for the minimum swimming depth below which fish were unable to ascend each of the slopes. However, the experimental observations indicate that water depth alone is not the limiting factor and it can not therefore be considered in isolation. As water flows down a short slope it becomes progressively shallower and faster (Appendix 7), and forms a standing wave where it levels off. Consequently, the length of the ascent and the velocity of the water must also be considered along with the depth. The largest fish to complete the ascent of the 20% slope was a chub of 290mm, which was also the largest fish tested. From the chart data given in Appendix 5 the maximum body depth of a chub of this size is around 75mm. Mean water depth on the 20% slope was 24.8mm, which means that around two thirds of this fish was exposed above water level. In the same experiment none of the chub under 160mm successfully completed the ascent, despite being completely submerged, suggesting that water velocity was the limiting factor regardless of water depth. Consequently, it is not possible to provide a value for minimum swimming depth in isolation from water velocity. However, the experiments did show that providing the water velocity is within the achievable range, chub can ascend a short 20% slope with only one third of their body depth submerged.

5.5 Muscle Twitch

Results from the burst swimming experiments for large trout (>15cm) at >14°C indicated a mean maximum sustainable swimming speed of 8.16 bl s^{-1}. The muscle twitch results gained for trout gave a mean theoretical maximum swimming speed of 10.25 bl s^{-1}, for trout of between 18.5 and 22.5cm. These results suggest that fish in burst experiments were swimming near their full capacity and that the results gained in burst swimming experiments are a realistic approximation to maximum swimming speed. It also demonstrates that the stepwise increase in water velocity is a valid technique for ascertaining maximum swimming speed. Further, although it was suggested earlier that fish in experiments may not be fully motivated to achieve their full swimming potential, any reduction in the degree of motivation does not appear to have manifested itself as a substantial reduction in the burst swimming of trout.

Were a fish able to attain the theoretical maximum swimming speed, it seems unlikely that it would be able to sustain that speed for very long. Studies on the burst swimming of dace by Bainbridge (1960) showed that swimming speed declined rapidly over the first few seconds of the tests, and had reached a sustainable level within ten seconds.

It is not clear why cyprinid muscles failed to respond measurably to electrical stimulus, especially considering the magnitude of the response observed with trout muscle using an identical set up. Unfortunately, it was beyond the scope of the present study to investigate this further. Obviously cyprinid muscle is capable of measurable contractions, otherwise the fish would have difficulty in swimming at all. An alternative approach to stimulating the muscle is therefore required for future studies.

6. CONCLUSIONS

6.1 Endurance Swimming

Endurance swimming ability varies according to both fish size and temperature. Test fish tended to either fail early in the experiment, or complete the full 200 minutes and mean endurance times are likely to be unrepresentative and misleading. The data collected nevertheless provide a good indication of swimming endurance, at least of minimum capabilities, for the species, size ranges and temperatures tested.

6.2 Burst Swimming

Burst swimming ability also varied according to both fish length and temperature. Generally, speed increased with both temperature and length, although in trout, a coldwater species, there was evidence that burst speed declined at the highest temperatures tested. Measured in terms of body lengths per second (as opposed to cms^{-1}), the burst speed declined with fish length. This has been found in most previous studies and is considered to be a hydrodynamic scaling effect.

Burst swimming results obtained in the present study exceed those found in the few previous studies where the same species have been tested, confirming the merits of the experimental techniques deployed here.

6.3 Swimming Uphill and Partially Submerged

Burst swimming performance of any of the species tested was not reduced when swimming uphill on 5% and 20% slopes whilst partially submerged under the conditions tested. This accords with the predictions made on theoretical grounds, taking account of the muscle power available and 'propeller'-thrust of the fish's tail and the increased power required to overcome gravity and wave-generated drag.

The implication of these results is that extra power required to ascend a slope whilst partially submerged is not a factor limiting the ability of fish. Maximum tail beat frequency, which for a given fish is likely to be much the same whether fully or partially submerged, will be one of the factors limiting the ability of fish to ascend slopes whilst partially submerged.

6.4 Muscle Twitch

Muscle twitch experiments demonstrated that the mean theoretical maximum swimming speed was slightly higher than the observed mean from burst swimming experiments. This suggests that fish in burst experiments were swimming near to their full capacity, and that the results gained in burst swimming experiments were close to maximum swimming speeds. It also shows that the stepwise increase in water velocity is a valid technique for ascertaining burst swimming speed.

Cyprinid muscle failed to respond measurably, despite using the same apparatus that worked well for trout muscle. A different technique for stimulating the muscle is required before meaningful results can be gained for cyprinid muscles.

6.5 The 'SWIMIT' Computer Program

The data shown in this written Report are a summary of the information gained from the study. The SWIMIT computer program, which is designed to work with the MS Excel 97 (or higher) programme, provides more comprehensive access to the experimental data. Details of it can be found in Appendix 8.

7. RECOMMENDATIONS

1. The present study has dealt with a small number of the freshwater fish species found in Britain, and has been limited in size range up to about 30cm fish length. There is regulatory and conservation interest in a much wider range of species, including small epibenthic species such as bullhead (*Cottus gobio* (L.)) and stoneloach (*Barbatula barbatula* (L.)) and other cyprinid and percid species, and migratory species such as lampreys and shads. It is recommended that a prioritised list of these should be drawn up for future testing.
2. In view of the good performance of the methods used here, it is recommended that the same methods should be used in future studies. Our experiences with fish condition at high summer temperatures in particular indicate that at least a modest level of temperature control of facilities would be helpful.
3. For species that are particularly sensitive to handling or of high conservation merit, consideration should be given to setting up a portable test facility that can be used on the riverbank. This would eliminate much of the stress associated with handling and transport and would enable the fish to be returned direct to source.
4. It was noted that during endurance swimming tests some fish completed the full 200 minutes, even at the highest velocities. For future studies it would be useful to have a flume facility which offered maximum speeds in excess of 1.4m s^{-1}. A modification to the existing Fawley endurance flume, replacing the paddle wheel with an impeller, would allow much higher water velocities to be generated.

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Appendix 1 – Endurance Experiments - Summary Data

Tables of percentiles

Large chub, < 11°C

Speed	Percentiles of endurance time (mins)							
(bl s^{-1})	90	80	70	60	50	40	20	1
2	200	200	200	200	200	200	200	200
3	25	162.4	200	200	200	200	200	200
4	0	0	3.6	8.6	37	200	200	200

Large chub, 11-15°C

Speed	Percentiles of endurance time (mins)							
(bl s^{-1})	90	80	70	60	50	40	20	1
2	200	200	200	200	200	200	200	200
3	200	200	200	200	200	200	200	200
4	3	5.8	23	137.6	200	200	200	200

Large chub, > 15°C

Speed	Percentiles of endurance time (mins)							
(bl s^{-1})	90	80	70	60	50	40	20	1
2	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
3	16.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
4	3.3	8.7	16.3	36.0	200.0	200.0	200.0	200.0
5	0.0	0.0	0.0	3.0	3.8	160.9	200.0	200.0

Medium chub, < 11°C

Speed	Percentiles of endurance time (mins)							
(bl s^{-1})	90	80	70	60	50	40	20	1
3	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
4	0.0	3.8	102.8	200.0	200.0	200.0	200.0	200.0
5	0.3	9.4	69.8	200.0	200.0	200.0	200.0	200.0
6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	200.0

Medium chub, 11-15°C

Speed	Percentiles of endurance time (mins)							
(bl s^{-1})	90	80	70	60	50	40	20	1
2	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
3	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
4	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
5	44.2	152.6	200.0	200.0	200.0	200.0	200.0	200.0
6	0.0	0.0	19.2	27.2	87.0	200.0	200.0	200.0

Medium chub, > 15°C

Speed	**Percentiles of endurance time (mins)**							
(bl s^{-1})	**90**	**80**	**70**	**60**	**50**	**40**	**20**	**1**
3	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
4	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
5	162.5	200.0	200.0	200.0	200.0	200.0	200.0	200.0
6	4.3	5.1	29.4	80.5	96.0	200.0	200.0	200.0

Small chub, < 11°C

Speed	**Percentiles of endurance time (mins)**							
(bl s^{-1})	**90**	**80**	**70**	**60**	**50**	**40**	**20**	**1**
5	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
6	7.6	50.7	200.0	200.0	200.0	200.0	200.0	200.0
7	121.3	200.0	200.0	200.0	200.0	200.0	200.0	200.0
8	55.2	200.0	200.0	200.0	200.0	200.0	200.0	200.0
9	21.9	27.7	140.2	195.2	200.0	200.0	200.0	200.0
10+	1.7	3.0	44.2	200.0	200.0	200.0	200.0	200.0

Small chub, 11-15°C

Speed	**Percentiles of endurance time (mins)**							
(bl s^{-1})	**90**	**80**	**70**	**60**	**50**	**40**	**20**	**1**
2	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
3	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
4	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
5	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
6	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
7	150.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
8	4.7	200.0	200.0	200.0	200.0	200.0	200.0	200.0
9	0.0	40.0	91.3	163.6	200.0	200.0	200.0	200.0
10	120.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
11	0.0	0.0	0.0	0.0	0.0	2.7	200.0	200.0
12+	0.0	0.0	0.0	1.1	2.2	7.1	200.0	200.0

Small chub, > 15°C

Speed	**Percentiles of endurance time (mins)**							
(bl s^{-1})	**90**	**80**	**70**	**60**	**50**	**40**	**20**	**1**
6	3.7	102.0	200.0	200.0	200.0	200.0	200.0	200.0
7	122.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
8	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
9	158.7	193.0	200.0	200.0	200.0	200.0	200.0	200.0
10+	25.3	182.0	200.0	200.0	200.0	200.0	200.0	200.0

Large dace, < 11°C

Speed (bl s^{-1})	Percentiles of endurance time (mins)							
	90	80	70	60	50	40	20	1
1	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
2	162.2	200.0	200.0	200.0	200.0	200.0	200.0	200.0
3	7.6	26.1	55.9	200.0	200.0	200.0	200.0	200.0
4	0.0	0.0	0.0	0.0	0.0	0.9	40.0	200.0

Large dace, 11-15°C

Speed (bl s^{-1})	Percentiles of endurance time (mins)							
	90	80	70	60	50	40	20	1
1	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
2	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
3	8.2	37.6	63.4	200.0	200.0	200.0	200.0	200.0
4	0.2	1.6	3.6	4.8	7.1	12.3	75.5	200.0
5	3.2	4.6	5.7	6.4	7.1	9.9	17.3	29.6

Large dace, > 15°C

Speed (bl s^{-1})	Percentiles of endurance time (mins)							
	90	80	70	60	50	40	20	1
2	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
3	2.4	5.7	15.2	31.2	51.6	200.0	200.0	200.0
4	0.0	0.0	3.3	5.9	8.6	54.1	200.0	200.0
5	0.0	0.0	0.0	0.0	0.0	0.0	15.8	200.0

Medium dace, < 11°C

Speed (bl s^{-1})	Percentiles of endurance time (mins)							
	90	80	70	60	50	40	20	1
1	117.9	200.0	200.0	200.0	200.0	200.0	200.0	200.0
2	26.4	200.0	200.0	200.0	200.0	200.0	200.0	200.0
3	147.2	200.0	200.0	200.0	200.0	200.0	200.0	200.0
4	11.5	60.8	172.4	200.0	200.0	200.0	200.0	200.0
5	0.0	0.0	0.0	0.0	1.5	4.1	19.1	200.0
6	0.0	0.0	0.0	0.0	0.0	0.0	7.2	200.0
7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Medium dace, 11-15°C

Speed	Percentiles of endurance time (mins)							
(bl s^{-1})	90	80	70	60	50	40	20	1
2	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
3	8.1	15.2	73.8	200.0	200.0	200.0	200.0	200.0
4	3.8	11.9	69.4	200.0	200.0	200.0	200.0	200.0
5	6.4	8.0	12.7	97.0	200.0	200.0	200.0	200.0
6	2.4	3.8	7.6	23.7	31.0	46.0	200.0	200.0
7	1.4	1.5	1.5	2.4	3.8	5.2	16.5	32.0

Medium dace, > 15°C

Speed	Percentiles of endurance time (mins)							
(bl s^{-1})	90	80	70	60	50	40	20	1
2	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
3	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
4	61.2	200.0	200.0	200.0	200.0	200.0	200.0	200.0
5	3.1	4.6	84.2	200.0	200.0	200.0	200.0	200.0
6	5.6	7.7	47.0	123.5	200.0	200.0	200.0	200.0

Small dace, < 11°C

Speed	Percentiles of endurance time (mins)							
(bl s^{-1})	90	80	70	60	50	40	20	1
4	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
5	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
6	40.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
7	0.0	0.0	0.0	0.0	0.0	40.0	120.0	200.0
8	0.0	0.0	0.0	0.0	0.0	0.0	0.4	200.0
9	0.0	0.2	1.0	2.0	3.0	9.0	10.0	200.0
10	1.0	1.0	2.4	3.0	3.5	4.0	5.2	200.0

Small dace, 11-15°C

Speed	Percentiles of endurance time (mins)							
(bl s^{-1})	90	80	70	60	50	40	20	1
8	0.0	0.2	1.0	6.6	15.0	200.0	200.0	200.0
9	0.0	0.0	0.4	122.0	200.0	200.0	200.0	200.0
10	0.0	0.8	21.8	160.4	200.0	200.0	200.0	200.0
11	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
12	22.7	200.0	200.0	200.0	200.0	200.0	200.0	200.0
13	0.0	0.0	0.0	3.2	200.0	200.0	200.0	200.0
14	0.0	0.0	0.0	0.0	0.0	0.0	0.0	200.0
15	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Large roach, < 11°C

Speed	**Percentiles of endurance time (mins)**							
(bl s^{-1})	**90**	**80**	**70**	**60**	**50**	**40**	**20**	**1**
2	62.8	184.4	200.0	200.0	200.0	200.0	200.0	200.0
3	1.0	2.0	5.8	9.4	15.0	35.8	200.0	200.0
4	0.0	1.0	1.0	2.0	2.6	4.0	5.0	170.9
5+	0.0	0.0	0.0	0.0	0.0	0.0	2.0	105.3

Large roach, 11-15°C

Speed	**Percentiles of endurance time (mins)**							
(bl s^{-1})	**90**	**80**	**70**	**60**	**50**	**40**	**20**	**1**
2	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
3	2.5	20.6	143.5	200.0	200.0	200.0	200.0	200.0
4+	0.0	0.0	0.0	0.0	1.1	3.5	10.0	200.0

Large roach, > 15°C

Speed	**Percentiles of endurance time (mins)**							
(bl s^{-1})	**90**	**80**	**70**	**60**	**50**	**40**	**20**	**1**
3	5.0	10.7	14.1	17.3	35.0	112.6	200.0	200.0
4+	0.0	0.0	0.0	1.1	4.1	5.8	59.6	200.0

Medium roach, < 11°C

Speed	**Percentiles of endurance time (mins)**							
(bl s^{-1})	**90**	**80**	**70**	**60**	**50**	**40**	**20**	**1**
2	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
3	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
4	1.4	8.0	42.0	200.0	200.0	200.0	200.0	200.0
5	0.0	2.6	5.0	10.2	11.1	69.4	200.0	200.0
6	0.0	2.2	5.0	8.6	19.4	66.2	200.0	200.0
7	6.6	8.2	11.4	16.2	18.6	24.6	64.0	200.0

Medium roach, 11-15°C

Speed	**Percentiles of endurance time (mins)**							
(bl s^{-1})	**90**	**80**	**70**	**60**	**50**	**40**	**20**	**1**
2	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
3	125.6	200.0	200.0	200.0	200.0	200.0	200.0	200.0
4	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
5	2.1	7.2	13.3	200.0	200.0	200.0	200.0	200.0
6	0.0	0.8	2.1	13.2	110.2	200.0	200.0	200.0
7	0.0	0.0	0.0	9.2	23.0	36.8	107.6	200.0

Medium roach, > 15°C

Speed (bl s^{-1})	Percentiles of endurance time (mins)							
	90	80	70	60	50	40	20	1
2	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
3	127.7	200.0	200.0	200.0	200.0	200.0	200.0	200.0
4	4.3	12.5	33.4	200.0	200.0	200.0	200.0	200.0
5	0.0	1.3	3.0	4.9	14.1	87.2	200.0	200.0
6	0.0	0.0	0.0	0.1	5.3	6.8	14.8	200.0
7	0.0	0.0	3.9	7.9	9.9	12.0	135.0	200.0

Small roach, < 11°C

Speed (bl s^{-1})	Percentiles of endurance time (mins)							
	90	80	70	60	50	40	20	1
3	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
4	9.0	13.8	198.5	200.0	200.0	200.0	200.0	200.0
5	0.5	5.0	13.4	200.0	200.0	200.0	200.0	200.0
6	0.0	0.0	0.1	1.9	175.0	200.0	200.0	200.0
7	0.0	1.6	20.2	44.4	200.0	200.0	200.0	200.0
8	0.0	0.8	2.0	2.0	4.0	15.6	88.2	200.0

Small roach, 11-15°C

Speed (bl s^{-1})	Percentiles of endurance time (mins)							
	90	80	70	60	50	40	20	1
3	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
4	93.2	200.0	200.0	200.0	200.0	200.0	200.0	200.0
5	0.0	7.0	7.0	9.0	200.0	200.0	200.0	200.0
6	0.0	2.0	5.0	6.7	15.7	57.6	200.0	200.0
7	0.2	1.7	3.9	6.4	54.4	159.4	200.0	200.0
8	0.0	10.0	40.0	110.0	200.0	200.0	200.0	200.0
9	0.0	0.0	0.0	0.5	1.3	98.3	185.4	200.0
10	0.0	0.0	0.0	0.0	0.0	0.0	83.0	200.0

Small roach, > 15°C

Speed (bl s^{-1})	Percentiles of endurance time (mins)							
	90	80	70	60	50	40	20	1
5	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
6	0.0	0.5	2.7	144.4	200.0	200.0	200.0	200.0
7	0.8	35.0	173.4	200.0	200.0	200.0	200.0	200.0
>8	0.0	0.0	1.0	9.0	53.0	114.0	200.0	200.0

Large trout, < 9°C

Speed (bl s^{-1})	**Percentiles of endurance time (mins)**							
	90	**80**	**70**	**60**	**50**	**40**	**20**	**1**
2	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
3	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
4	172.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
5+	0.1	94.2	184.8	200.0	200.0	200.0	200.0	200.0

Large trout, 9-14°C

Speed (bl s^{-1})	**Percentiles of endurance time (mins)**							
	90	**80**	**70**	**60**	**50**	**40**	**20**	**1**
2	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
3	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
4	195.2	200.0	200.0	200.0	200.0	200.0	200.0	200.0
5	3.6	161.7	200.0	200.0	200.0	200.0	200.0	200.0

Large trout, > 14°C

Speed (bl s^{-1})	**Percentiles of endurance time (mins)**							
	90	**80**	**70**	**60**	**50**	**40**	**20**	**1**
3	197.3	200.0	200.0	200.0	200.0	200.0	200.0	200.0
4	61.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
5	21.7	200.0	200.0	200.0	200.0	200.0	200.0	200.0
6	0.0	0.0	3.5	7.6	200.0	200.0	200.0	200.0

Medium trout, < 9°C

Speed (bl s^{-1})	**Percentiles of endurance time (mins)**							
	90	**80**	**70**	**60**	**50**	**40**	**20**	**1**
3	48.7	84.0	200.0	200.0	200.0	200.0	200.0	200.0
4	0.0	152.0	200.0	200.0	200.0	200.0	200.0	200.0
5	0.0	145.6	200.0	200.0	200.0	200.0	200.0	200.0
6	2.4	15.2	129.4	200.0	200.0	200.0	200.0	200.0
7+	0.0	0.2	1.3	3.4	200.0	200.0	200.0	200.0

Medium trout, 9-14°C

Speed (bl s^{-1})	**Percentiles of endurance time (mins)**							
	90	**80**	**70**	**60**	**50**	**40**	**20**	**1**
3	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
4	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
5	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
6	150.9	200.0	200.0	200.0	200.0	200.0	200.0	200.0
7	36.1	69.2	84.3	108.0	200.0	200.0	200.0	200.0
8+	40.0	60.5	71.3	82.0	141.0	200.0	200.0	200.0

Medium trout, > 14°C

Speed	**Percentiles of endurance time (mins)**							
(bl s^{-1})	**90**	**80**	**70**	**60**	**50**	**40**	**20**	**1**
4	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
5	29.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
6+	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0

Small trout, < 9°C

Speed	**Percentiles of endurance time (mins)**							
(bl s^{-1})	**90**	**80**	**70**	**60**	**50**	**40**	**20**	**1**
4	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
5	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
6+	181.3	200.0	200.0	200.0	200.0	200.0	200.0	200.0

Small trout, 9-14°C

Speed	**Percentiles of endurance time (mins)**							
(bl s^{-1})	**90**	**80**	**70**	**60**	**50**	**40**	**20**	**1**
4	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
5	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
6	67.8	200.0	200.0	200.0	200.0	200.0	200.0	200.0
7	102.5	187.0	200.0	200.0	200.0	200.0	200.0	200.0
8+	23.2	93.0	139.4	171.8	192.5	200.0	200.0	200.0

Small trout, > 14°C

Speed	**Percentiles of endurance time (mins)**							
(bl s^{-1})	**90**	**80**	**70**	**60**	**50**	**40**	**20**	**1**
5	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
6	200.0	200.0	200.0	200.0	200.0	200.0	200.0	200.0
7+	20.7	122.4	200.0	200.0	200.0	200.0	200.0	200.0

Appendix 2 – Burst experiments - summary data.

Mean critical swimming speed of chub (bl s^{-1})

	< 10 cm			10 to 15 cm			> 15 cm		
Temp °C	**No. of fish**	**mean**	**95% c.l.**	**No. of fish**	**mean**	**95% c.l.**	**No. of fish**	**mean**	**95% c.l.**
< 11	21	20.6	1.3	24	9.9	0.7	30	8.4	0.3
11 to 15	23	20.0	1.2	22	10.3	0.7	23	7.5	0.5
> 15	31	15.4	1.7	26	10.7	0.8	30	7.8	0.4

Mean critical swimming speed of dace (bl s^{-1})

	<10 cm			10 to 15 cm			>15 cm		
Temp °C	**No. of fish**	**mean**	**95% c.l.**	**No. of fish**	**mean**	**95% c.l.**	**No. of fish**	**mean**	**95% c.l.**
< 11	21	12.5	0.8	23	10.6	0.6	22	8.0	0.8
11 to 15	3	20.1	5.3	21	11.3	1.0	21	7.4	0.3
> 15	44	20.2	1.3	27	11.6	0.6	33	8.2	0.6

Mean critical swimming speed of roach (bl s^{-1})

	< 10 cm			10 to 15 cm			> 15 cm		
Temp °C	**No. of fish**	**mean**	**95% c.l.**	**No. of fish**	**mean**	**95% c.l.**	**No. of fish**	**mean**	**95% c.l.**
< 11	21	11.5	1.8	21	9.5	1.1	24	8.4	0.6
11 to 15	21	12.8	0.9	25	9.7	0.7	26	8.1	0.4
> 15	30	14.7	1.1	21	10.4	0.5	21	7.6	0.5

Mean critical swimming speed of brown trout (bl s^{-1})

	< 10 cm			10 to 15 cm			> 15 cm		
Temp °C	**No. of fish**	**mean**	**95% c.l.**	**No. of fish**	**mean**	**95% c.l.**	**No. of fish**	**mean**	**95% c.l.**
< 9	10	13.4	2.2	29	11.3	1.0	27	8.5	0.4
9 to 14	10	18.3	0.8	36	14.2	1.2	21	9.3	0.8
>14 to 20	14	13.1	1.0	29	11.1	0.8	30	8.2	0.6
> 20	*	*	*	5	9.2	1.7	38	7.3	0.4

Appendix 3 – List of endurance swimming experiments carried outincluding details of fish source, length ranges, test temperatures and test water velocities.

Date	Species	Source	No. of fish	Length category (cm)	Mean temp. (^{o}C)	Water speed (cm s^{-1})
26-Feb-98	dace	River Meon	21	10-15	11.6	70
27-Feb-98	dace	River Meon	21	10-15	12.6	60
11-Mar-98	dace	River Meon	21	10-15	9.3	100
26-Mar-98	dace	River Meon	27	10-15	9.9	40
27-Apr-98	dace	River Meon	45	>15	14.2	80
29-Apr-98	dace	River Meon	45	>15	13.3	40
15-May-98	dace	River Meon	45	>15	19.0	80
20-May-98	dace	River Meon	45	>15	19.8	90
01-Jun-98	dace	River Meon	*	>15	17.4	100
02-Jun-98	dace	River Meon	45	>15	17.5	100
01-Mar-99	dace	River Meon	21	10-15	9.3	50
02-Mar-99	dace	River Meon	21	>15	10.3	60
05-Mar-99	dace	River Meon	21	>15	9.9	50
10-Mar-99	dace	River Meon	21	10-15	9.4	70
11-Mar-99	dace	River Meon	21	>15	9.6	90
12-Mar-99	dace	River Meon	21	10-15	9.6	90
16-Mar-99	dace	River Meon	21	>15	10.4	80
17-Mar-99	dace	River Meon	21	10-15	11.4	80
18-Mar-99	dace	River Meon	21	>15	12.4	60
19-Mar-99	dace	River Meon	21	10-15	12.6	50
22-Mar-99	dace	River Meon	21	>15	11.8	70
24-Mar-99	dace	River Meon	21	10-15	12.3	90
06-Apr-99	dace	River Meon	21	>15	12.6	90
14-Apr-99	dace	River Meon	21	>15	10.5	40
15-Apr-99	dace	River Meon	21	10-15	10.8	80
16-Apr-99	dace	River Meon	21	10-15	10.9	30
19-Apr-99	dace	River Meon	21	>15	10.9	70
22-Apr-99	dace	River Meon	21	>15	12.9	50
12-May-99	dace	River Meon	21	10-15	17.0	90
14-Jul-99	dace	River Meon	21	>15	21.1	70
15-Jul-99	dace	River Meon	21	10-15	21.0	80
19-Jul-99	dace	River Meon	21	10-15	20.9	70
20-Jul-99	dace	River Meon	21	10-15	21.0	60
22-Jul-99	dace	River Meon	24	>15	20.4	60
02-Sep-99	dace	River Thames	7	<10	21.4	60
03-Sep-99	dace	River Thames	14	<10	23.1	60
06-Sep-99	dace	River Thames	8	<10	21.3	50
07-Sep-99	dace	River Thames	8	<10	23.1	50
08-Sep-99	dace	River Thames	7	<10	22.3	50
10-Nov-99	dace	River Thames	21	<10	12.9	60
29-Nov-99	dace	River Thames	3	<10	12.2	70
02-Dec-99	dace	River Thames	21	<10	13.3	80
08-Dec-99	dace	River Thames	21	<10	11.4	90
13-Dec-99	dace	River Thames	21	<10	10.1	60
15-Dec-99	dace	River Thames	29	<10	12.6	70
05-Jan-00	dace	River Thames	27	<10	8.5	50
11-Jan-00	dace	River Thames	26	<10	8.8	40
19-Jan-00	dace	River Thames	25	<10	7.0	70

Date	Species	Source	No. of fish	Length category (cm)	Mean temp. (^{o}C)	Water speed (cm s^{-1})
17-Jun-98	chub	River Colne	45	15-20	17.5	60
24-Jun-98	chub	River Colne	44	15-20	18.2	80
30-Jun-98	chub	River Colne	36	15-20	18.2	100
15-Oct-98	chub	River Colne	21	10-15	16.7	90
21-Oct-98	chub	River Colne	24	10-15	14.8	55
23-Oct-98	chub	River Colne	24	10-15	16.5	60
26-Oct-98	chub	River Colne	24	10-15	11.4	70
27-Oct-98	chub	River Colne	21	15-20	12.5	90
29-Oct-98	chub	River Colne	21	15-20	13.4	80
30-Oct-98	chub	River Colne	27	10-15	12.8	80
03-Nov-98	chub	River Colne	27	10-15	10.6	60
04-Nov-98	chub	River Colne	24	15-20	10.7	66
09-Nov-98	chub	River Colne	21	15-20	11.3	70
19-Nov-98	chub	River Colne	21	15-20	7.1	60
26-Nov-98	chub	River Colne	21	10-15	7.0	80
30-Nov-98	chub	River Colne	21	15-20	10.0	80
04-Dec-98	chub	River Colne	25	10-15	9.5	90
09-Dec-98	chub	River Colne	21	15-20	10.8	90
14-Dec-98	chub	River Colne	21	10-15	12.4	90
16-Dec-98	chub	River Colne	21	15-20	12.7	60
05-Jan-99	chub	Hatchery	*	<10	*	40
06-Jan-99	chub	Hatchery	*	<10	*	60
07-Jan-99	chub	Hatchery	*	<10	*	66
08-Jan-99	chub	Hatchery	*	<10	*	69
12-Jan-99	chub	Hatchery	8	<10	5.5	50
13-Jan-99	chub	Hatchery	8	<10	7.7	50
14-Jan-99	chub	Hatchery	8	<10	8.9	50
20-Jan-99	chub	Hatchery	7	<10	10.6	40
21-Jan-99	chub	Hatchery	7	<10	9.5	40
21-Jan-99	chub	Hatchery	7	<10	12.8	60
22-Jan-99	chub	Hatchery	7	<10	10.1	40
25-Jan-99	chub	Hatchery	7	<10	10.6	60
26-Jan-99	chub	Hatchery	7	<10	11.0	60
27-Jan-99	chub	Hatchery	7	<10	9.7	60
28-Jan-99	chub	Hatchery	7	<10	9.7	60
29-Jan-99	chub	Hatchery	7	<10	10.0	60
01-Feb-99	chub	Hatchery	7	<10	8.2	30
03-Feb-99	chub	Hatchery	7	<10	9.1	30
04-Feb-99	chub	Hatchery	7	<10	11.0	40
05-Feb-99	chub	Hatchery	7	<10	11.3	40
08-Feb-99	chub	Hatchery	7	<10	7.3	30
12-Feb-99	chub	River Colne	21	10-15	6.8	70
17-Mar-99	chub	Hatchery	7	<10	11.5	40
19-Mar-99	chub	Hatchery	7	<10	11.3	30
22-Mar-99	chub	Hatchery	8	<10	11.0	30
23-Mar-99	chub	Hatchery	7	<10	11.7	30
24-Mar-99	chub	Hatchery	7	<10	13.0	50
29-Mar-99	chub	Hatchery	7	<10	11.9	50
30-Mar-99	chub	Hatchery	7	<10	12.8	50
20-Apr-99	chub	River Colne	21	10-15	11.4	50
13-May-99	chub	River Colne	21	>15	17.8	90
27-May-99	chub	River Colne	21	10-15	16.7	80
03-Jun-99	chub	Dockens water	7	<10	18.2	60
04-Jun-99	chub	Dockens water	7	<10	18.6	60
07-Jun-99	chub	Dockens water	7	<10	18.4	60
08-Jun-99	chub	River Colne	21	10-15	16.7	70
09-Jun-99	chub	River Colne	21	>15	16.4	70
01-Jul-99	chub	Calverton	8	<10	19.6	50
07-Jul-99	chub	Calverton	8	<10	22.5	50
08-Jul-99	chub	Calverton	8	<10	24.2	50
09-Aug-99	chub	Hatchery	17	<10	20.8	90
17-Aug-99	chub	Hatchery	20	<10	18.9	80
18-Aug-99	chub	Hatchery	18	<10	19.5	70
19-Aug-99	chub	Hatchery	20	<10	19.8	90
23-Aug-99	chub	Hatchery	20	<10	18.9	80
25-Aug-99	chub	Hatchery	21	<10	19.3	70
04-Nov-99	chub	Hatchery	17	<10	14.6	80
09-Nov-99	chub	Hatchery	21	<10	13.1	90
18-Nov-99	chub	Hatchery	21	<10	10.6	70
22-Nov-99	chub	Hatchery	21	<10	9.0	90
30-Nov-99	chub	River Colne	21	10-15	12.8	80

Date	Species	Source	No. of fish	Length tegory (c	Mean temp. (°C)	Water speed (cm s^{-1})
15-Jun-98	roach	River Meon	45	10-15	16.5	70
13-Oct-98	roach	River Colne	21	<10	15.0	90
16-Oct-98	roach	River Colne	24	<10	16.7	70
20-Oct-98	roach	River Colne	36	10-15	14.1	60
22-Oct-98	roach	River Colne	27	10-15	16.1	90
28-Oct-98	roach	River Colne	27	10-15	13.4	80
02-Nov-98	roach	River Colne	30	10-15	10.7	60
05-Nov-98	roach	River Colne	24	10-15	10.4	40
10-Nov-98	roach	River Colne	27	10-15	11.8	80
01-Dec-98	roach	River Colne	24	>15	10.6	60
03-Dec-98	roach	River Colne	36	<10	9.9	50
23-Apr-99	roach	Soton Pond	21	<10	13.3	50
26-Apr-99	roach	Soton Pond	21	>15	13.5	70
27-Apr-99	roach	Soton Pond	21	10-15	14.4	60
28-Apr-99	roach	Soton Pond	21	<10	15.2	70
29-Apr-99	roach	Soton Pond	21	>15	14.3	90
30-Apr-99	roach	Soton Pond	21	10-15	15.0	60
07-May-99	roach	River Meon	21	>15	16.2	90
11-May-99	roach	River Meon	21	<10	16.7	90
24-May-99	roach	River Meon	21	10-15	16.1	80
28-May-99	roach	River Meon	21	>15	18.4	80
01-Jun-99	roach	River Meon	21	10-15	17.6	80
03-Jun-99	roach	River Meon	21	<10	19.0	90
16-Jul-99	roach	River Meon	21	10-15	21.2	90
26-Jul-99	roach	River Meon	19	10-15	21.0	90
02-Sep-99	roach	Hatchery	21	<10	19.9	80
03-Sep-99	roach	Hatchery	21	<10	21.2	80
06-Sep-99	roach	Hatchery	22	<10	21.5	70
26-Oct-99	roach	River Hamble	21	<10	14.0	70
10-Nov-99	roach	River Hamble	21	>15	13.0	40
12-Nov-99	roach	River Hamble	21	>15	12.3	60
15-Nov-99	roach	River Hamble	21	>15	12.0	50
16-Nov-99	roach	River Hamble	18	<10	11.6	40
17-Nov-99	roach	River Hamble	21	10-15	10.9	70
19-Nov-99	roach	River Hamble	21	>15	10.1	50
23-Nov-99	roach	River Hamble	21	<10	9.6	60
24-Nov-99	roach	River Hamble	21	10-15	10.8	90
25-Nov-99	roach	River Hamble	21	<10	11.1	50
10-Dec-99	roach	River Hamble	21	10-15	9.8	70
04-Jan-00	roach	River Hamble	21	<10	8.5	50
06-Jan-00	roach	River Hamble	21	<10	9.3	50
07-Jan-00	roach	River Hamble	21	10-15	9.5	60
10-Jan-00	roach	River Hamble	21	<10	8.0	90
12-Jan-00	roach	River Hamble	21	<10	9.5	80
13-Jan-00	roach	River Hamble	21	>15	8.8	40
14-Jan-00	roach	River Hamble	21	<10	8.5	90
20-Jan-00	roach	River Hamble	21	>15	7.0	80

Date	Species	Source	No. of fish	Length category (cm)	Mean temp. (°C)	Water speed (cm s^{-1})
26-Feb-98	brown trout	River Wey	21	10-15	11.6	70
27-Feb-98	brown trout	River Wey	21	10-15	12.6	60
06-Mar-98	brown trout	River Wey	21	10-15	10.1	40
11-Mar-98	brown trout	River Wey	21	10-15	9.3	100
22-Apr-98	brown trout	Hatchery	45	>15	10.7	60
24-Apr-98	brown trout	Hatchery	45	>15	12.9	100
01-May-98	brown trout	Hatchery	45	>15	13.4	40
08-May-98	brown trout	River Wey	36	>15	14.0	70
11-May-98	brown trout	River Wey	36	>15	16.2	70
14-May-98	brown trout	River Wey	36	>15	16.4	80
19-May-98	brown trout	River Wey	36	>15	19.9	90
28-May-98	brown trout	River Wey	36	>15	16.6	100
13-Nov-98	brown trout	River Wey	21	>15	8.6	60
18-Nov-98	brown trout	River Wey	30	10-15	7.0	60
23-Nov-98	brown trout	River Wey	21	10-15	6.6	70
27-Nov-98	brown trout	River Wey	21	>15	8.8	80
02-Dec-98	brown trout	River Wey	21	>15	10.6	80
07-Dec-98	brown trout	River Wey	27	10-15	7.3	80
08-Dec-98	brown trout	River Wey	21	>15	9.4	90
10-Dec-98	brown trout	River Wey	24	>15	11.9	60
11-Dec-98	brown trout	River Wey	24	10-15	11.9	70
15-Dec-98	brown trout	River Wey	24	10-15	13.2	90
21-Dec-98	brown trout	River Wey	21	>15	8.5	70
22-Dec-98	brown trout	River Wey	24	10-15	9.4	80
11-Feb-99	brown trout	River Wey	21	10-15	6.0	90
03-Mar-99	brown trout	Dockens water	21	<10	11.0	60
04-Mar-99	brown trout	Dockens water	21	<10	10.9	70
08-Mar-99	brown trout	Dockens water	21	<10	8.2	70
09-Mar-99	brown trout	Dockens water	21	<10	9.2	90
07-Apr-99	brown trout	Dockens water	21	<10	13.4	80
04-May-99	brown trout	Dockens water	21	<10	15.5	90
06-May-99	brown trout	Dockens water	21	10-15	15.9	90
10-May-99	brown trout	Dockens water	21	<10	16.0	80
02-Jun-99	brown trout	Dockens water	21	10-15	18.6	80
10-Jun-99	brown trout	Dockens water	20	10-15	16.5	70
09-Jul-99	brown trout	Dockens water	21	>15	21.8	90
02-Nov-99	brown trout	Dockens water	13	<10	14.3	60
26-Nov-99	brown trout	Dockens water	13	<10	12.8	50
14-Dec-99	brown trout	Dockens water	13	<10	10.5	70
16-Dec-99	brown trout	Dockens water	14	<10	14.1	70
18-Jan-00	brown trout	Dockens water	21	10-15	6.8	90

Details of elver experiments:

	Dates	Source	Mean length (mm)	Mean temp. (°C)
Early	7th April to 30th April	River Severn	67.61+/- 0.57	11.10 +/- 0.32
Late	28th June to 30th July	River Severn	147.76 +/- 4.81	18.64 +/- 0.12

Appendix 4 – List of burst swimming experiments carried out including details of fish source, length ranges, test temperatures and test water velocities.

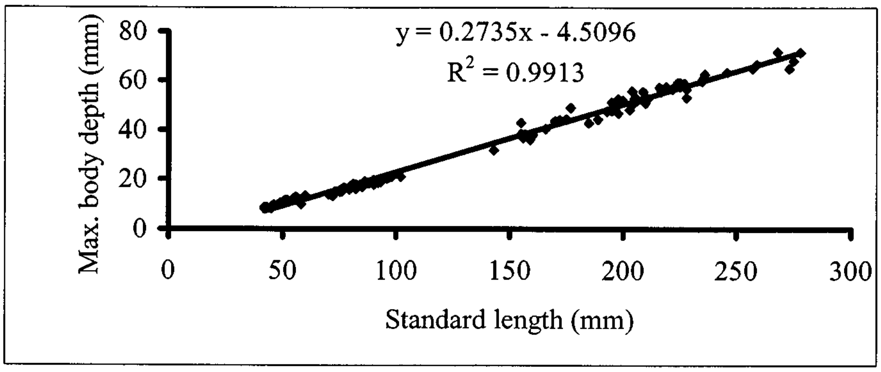
Date	Species	Source	No. of fish	Mean length (mm)	Mean CSS (m s-1)	Water temp. (°C)
05-Aug-98	dace	River Meon	3	110	1.08	18.5
17-Aug-98	dace	River Meon	3	202	1.36	21.7
17-Aug-98	dace	River Meon	3	207	1.35	21.7
17-Aug-98	dace	River Meon	3	210	1.35	21.7
18-Aug-98	dace	River Meon	3	202	1.58	21.7
18-Aug-98	dace	River Meon	3	205	1.33	21.7
18-Aug-98	dace	River Meon	3	202	1.39	21.7
19-Aug-98	dace	River Meon	3	124	1.42	20.5
19-Aug-98	dace	River Meon	3	108	1.64	20.5
19-Aug-98	dace	River Meon	3	136	1.49	20.5
24-Aug-98	dace	River Meon	3	123	1.49	17.3
24-Aug-98	dace	River Meon	3	105	1.52	17.3
24-Aug-98	dace	River Meon	3	129	1.48	17.3
25-Aug-98	dace	River Meon	3	208	1.49	18.2
25-Aug-98	dace	River Meon	3	204	1.57	18.2
25-Aug-98	dace	River Meon	3	204	1.56	18.2
09-Sep-98	dace	River Meon	3	128	1.39	18.4
09-Sep-98	dace	River Meon	2	106	1.37	18.4
09-Sep-98	dace	River Meon	3	119	1.43	18.4
15-Sep-98	dace	River Meon	3	204	1.49	14.5
15-Sep-98	dace	River Meon	3	195	1.48	14.5
15-Sep-98	dace	River Meon	3	196	1.54	14.5
04-Mar-99	dace	River Meon	3	143	1.45	8.5
04-Mar-99	dace	River Meon	3	107	1.25	8.7
04-Mar-99	dace	River Meon	3	144	1.39	8.8
04-Mar-99	dace	River Meon	3	130	1.31	8.9
09-Mar-99	dace	River Meon	3	159	1.28	6.5
09-Mar-99	dace	River Meon	3	151	1.26	7.0
09-Mar-99	dace	River Meon	3	121	1.45	7.0
09-Mar-99	dace	River Meon	3	175	1.25	7.0
09-Mar-99	dace	River Meon	3	176	1.43	7.5
11-Mar-99	dace	River Meon	3	195	1.52	8.0
11-Mar-99	dace	River Meon	3	185	1.38	8.5
11-Mar-99	dace	River Meon	3	189	1.69	8.5
11-Mar-99	dace	River Meon	3	135	1.61	9.0
18-Mar-99	dace	River Meon	3	140	1.28	12.0
18-Mar-99	dace	River Meon	3	128	1.61	12.0
18-Mar-99	dace	River Meon	3	109	1.49	12.5
18-Mar-99	dace	River Meon	3	132	1.61	13.0
22-Mar-99	dace	River Meon	3	188	1.37	11.0
22-Mar-99	dace	River Meon	3	176	1.34	11.0
22-Mar-99	dace	River Meon	3	122	1.55	11.2
22-Mar-99	dace	River Meon	3	144	1.31	11.3
06-Apr-99	dace	River Meon	3	188	1.35	12.2
06-Apr-99	dace	River Meon	3	209	1.36	12.6
06-Apr-99	dace	River Meon	3	133	1.28	12.8
09-Apr-99	dace	River Meon	3	193	1.41	13.1
09-Apr-99	dace	River Meon	3	192	1.63	13.3
14-Apr-99	dace	River Meon	3	174	1.48	9.7
12-May-99	dace	River Meon	3	220	1.46	16.2
12-May-99	dace	River Meon	3	186	1.47	16.4
12-May-99	dace	River Meon	3	161	1.30	16.5
12-May-99	dace	River Meon	3	191	1.35	16.7
14-Jul-99	dace	River Meon	3	139	1.50	20.5
14-Jul-99	dace	River Meon	3	129	1.62	20.7
14-Jul-99	dace	River Meon	3	141	1.43	20.8
16-Jul-99	dace	River Meon	3	149	1.50	19.1
16-Jul-99	dace	River Meon	3	133	1.42	19.2
16-Jul-99	dace	River Meon	3	162	1.68	19.5
16-Jul-99	dace	River Meon	3	176	1.73	19.7
11-Aug-99	dace	River Meon	3	44	0.79	19.2
11-Aug-99	dace	River Meon	3	45	0.86	19.3
06-Sep-99	dace	River Thames	3	52	0.86	24.1
06-Sep-99	dace	River Thames	3	41	1.04	24.3
06-Sep-99	dace	River Thames	3	49	1.11	24.4
06-Sep-99	dace	River Thames	3	44	1.01	24.6
08-Sep-99	dace	River Thames	3	45	1.06	23.6
08-Sep-99	dace	River Thames	3	44	1.09	23.7
08-Sep-99	dace	River Thames	3	57	1.17	23.9
08-Sep-99	dace	River Thames	3	47	1.12	24.0
26-Oct-99	dace	River Thames	3	63	1.14	15.0

Date	Species	Source	No. of fish	Mean length (mm)	Mean CSS (m s^{-1})	Water temp. (°C)
05-Aug-98	chub	River Colne	3	200	1.56	18.5
11-Aug-98	chub	River Colne	3	212	1.96	20.9
11-Aug-98	chub	River Colne	3	200	1.74	20.9
20-Aug-98	chub	River Colne	3	204	1.67	20.5
20-Aug-98	chub	River Colne	3	202	1.79	20.5
20-Aug-98	chub	River Colne	3	207	1.79	20.5
09-Sep-98	chub	River Colne	3	203	1.56	18.5
09-Sep-98	chub	River Colne	3	203	1.73	18.5
09-Sep-98	chub	River Colne	3	203	1.79	18.5
19-Oct-98	chub	River Colne	3	141	1.44	12.5
19-Oct-98	chub	River Colne	3	141	1.04	12.1
19-Oct-98	chub	River Colne	3	135	1.28	12.5
10-Nov-98	chub	River Colne	3	133	1.12	13
10-Nov-98	chub	River Colne	3	115	1.34	13
11-Nov-98	chub	River Colne	3	175	1.24	11
11-Nov-98	chub	River Colne	3	166	1.29	11
11-Nov-98	chub	River Colne	3	170	0.76	11
13-Nov-98	chub	River Colne	3	136	1.18	10
13-Nov-98	chub	River Colne	3	133	1.25	10
13-Nov-98	chub	River Colne	3	185	1.20	10.5
13-Nov-98	chub	River Colne	3	185	1.34	11
13-Nov-98	chub	River Colne	3	188	1.04	9
27-Nov-98	chub	River Colne	3	137	1.11	9
27-Nov-98	chub	River Colne	3	125	1.38	9.5
27-Nov-98	chub	River Colne	3	103	1.24	9.5
01-Dec-98	chub	River Colne	3	166	1.46	8
01-Dec-98	chub	River Colne	3	182	1.46	8
01-Dec-98	chub	River Colne	3	171	1.44	8
10-Dec-98	chub	River Colne	3	139	1.17	9
10-Dec-98	chub	River Colne	3	108	1.19	9
10-Dec-98	chub	River Colne	3	124	1.18	9.5
10-Dec-98	chub	River Colne	3	144	1.40	10
10-Dec-98	chub	River Colne	3	153	1.23	10
15-Dec-98	chub	River Colne	3	200	1.44	11
15-Dec-98	chub	River Colne	3	127	1.16	11.5
15-Dec-98	chub	River Colne	3	132	1.30	11.5
19-Dec-98	chub	River Colne	3	126	1.22	10
19-Dec-98	chub	River Colne	3	199	1.56	10
19-Dec-98	chub	River Colne	3	154	1.40	10
12-Jan-99	chub	Hatchery	3	54	0.97	8
12-Jan-99	chub	Hatchery	3	50	0.94	8
12-Jan-99	chub	Hatchery	3	50	1.10	8
13-Jan-99	chub	Hatchery	3	49	1.01	9
13-Jan-99	chub	Hatchery	3	51	1.07	9.5
13-Jan-99	chub	Hatchery	3	53	1.26	9.5
13-Jan-99	chub	Hatchery	3	53	1.07	10
22-Jan-99	chub	Hatchery	3	50	0.97	11.5
22-Jan-99	chub	Hatchery	3	51	1.09	11.5
22-Jan-99	chub	Hatchery	3	48	1.03	11.5
25-Jan-99	chub	Hatchery	3	50	1.04	11.5
25-Jan-99	chub	Hatchery	3	50	0.90	11.5
25-Jan-99	chub	Hatchery	3	51	1.02	11.5
25-Jan-99	chub	Hatchery	3	48	1.11	11.5
09-Mar-99	chub	*	3	*	1.56	7.5
09-Apr-99	chub	River Colne	3	111	1.32	12.8
09-Apr-99	chub	Hatchery	3	92	1.38	12.9
09-Apr-99	chub	River Colne	3	194	1.33	13.5
09-Apr-99	chub	River Colne	3	108	1.40	13.6
09-Apr-99	chub	River Colne	3	187	1.53	13.8
09-Apr-99	chub	River Colne	3	179	1.62	13.9
12-Apr-99	chub	River Colne	3	109	1.07	12.2
12-Apr-99	chub	River Colne	3	206	1.33	12.4
12-Apr-99	chub	River Colne	3	195	1.66	12.7
13-May-99	chub	River Colne	3	135	1.10	16
13-May-99	chub	River Colne	3	125	1.39	16.2
13-May-99	chub	River Colne	3	111	1.33	16.4
13-May-99	chub	River Colne	3	104	1.36	16.6
13-May-99	chub	River Colne	3	138	1.32	16.7
14-May-99	chub	Hatchery	3	91	1.25	16.1
14-May-99	chub	Hatchery	3	97	1.32	16.4
14-May-99	chub	River Colne	3	112	1.33	16.5

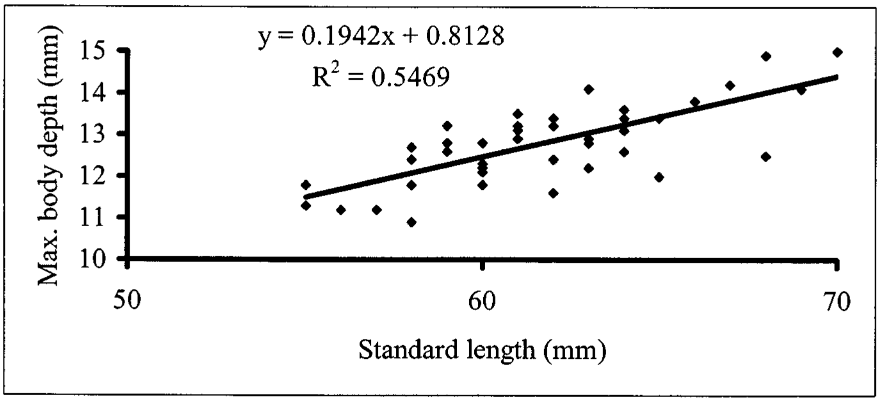
Date	Species	Source	No. of fish	Mean length (mm)	Mean CSS (m s^{-1})	Water temp. (°C)
23-Oct-98	roach	River Colne	3	96	1.11	16.8
27-Oct-98	roach	River Colne	3	90	1.04	13.0
28-Oct-98	roach	River Colne	3	167	1.39	14.5
28-Oct-98	roach	River Colne	3	149	1.34	14.5
30-Oct-98	roach	River Colne	3	113	1.31	12.0
05-Nov-98	roach	River Colne	3	95	0.95	9.0
05-Nov-98	roach	River Colne	3	88	1.09	9.0
05-Nov-98	roach	River Colne	3	98	1.21	10.0
06-Nov-98	roach	River Colne	3	126	1.22	10.0
06-Nov-98	roach	River Colne	3	115	0.93	10.2
06-Nov-98	roach	River Colne	3	110	1.09	10.5
12-Nov-98	roach	River Colne	3	126	1.14	11.0
12-Nov-98	roach	River Colne	3	110	0.69	11.0
12-Nov-98	roach	River Colne	3	110	0.84	11.0
12-Nov-98	roach	River Colne	3	89	0.90	11.0
12-Nov-98	roach	River Colne	3	99	1.19	11.0
12-Nov-98	roach	River Colne	3	96	0.93	11.0
08-Mar-99	roach	River Colne	3	172	1.53	7.0
08-Mar-99	roach	River Colne	3	191	1.42	7.5
11-Mar-99	roach	River Colne	3	94	1.40	9.0
11-Mar-99	roach	River Colne	3	175	1.67	9.5
16-Mar-99	roach	River Colne	3	187	1.68	8.5
16-Mar-99	roach	River Colne	3	187	1.84	9.0
16-Mar-99	roach	River Colne	3	86	1.33	9.5
16-Mar-99	roach	River Colne	3	122	1.54	10.0
19-Mar-99	roach	River Colne	3	93	1.19	12.2
19-Mar-99	roach	River Colne	3	122	1.47	12.4
19-Mar-99	roach	River Colne	3	185	1.52	12.5
19-Mar-99	roach	River Colne	3	186	1.53	12.7
13-Apr-99	roach	Soton Pond	3	173	1.49	11.6
13-Apr-99	roach	Soton Pond	3	183	1.30	11.6
13-Apr-99	roach	Soton Pond	3	179	1.51	11.7
14-Apr-99	roach	Soton Pond	3	199	1.48	9.2
14-Apr-99	roach	Soton Pond	3	89	1.13	9.3
14-Apr-99	roach	Soton Pond	3	120	1.29	9.4
20-Apr-99	roach	Soton Pond	3	87	0.97	9.7
20-Apr-99	roach	Soton Pond	3	121	1.02	9.9
20-Apr-99	roach	Soton Pond	3	187	1.45	10.2
20-Apr-99	roach	Soton Pond	3	192	1.35	10.4
23-Apr-99	roach	Soton Pond	3	86	1.02	11.4
23-Apr-99	roach	Soton Pond	3	102	1.05	11.6
23-Apr-99	roach	Soton Pond	3	151	1.27	11.8
23-Apr-99	roach	Soton Pond	3	141	1.22	11.9
23-Apr-99	roach	Soton Pond	3	132	1.23	11.9
26-Apr-99	roach	Soton Pond	3	133	1.18	12.0
26-Apr-99	roach	Soton Pond	3	70	1.12	12.1
26-Apr-99	roach	Soton Pond	3	103	1.12	12.2
27-Apr-99	roach	Soton Pond	3	71	0.98	13.6
27-Apr-99	roach	Soton Pond	3	172	1.31	13.8
27-Apr-99	roach	Soton Pond	3	91	0.86	14.0
28-Apr-99	roach	Soton Pond	3	82	1.08	14.3
28-Apr-99	roach	Soton Pond	3	173	1.24	14.5
07-May-99	roach	River Meon	3	119	1.23	16.2
07-May-99	roach	River Meon	3	115	1.22	16.3
07-May-99	roach	River Meon	3	95	1.19	16.6
07-May-99	roach	River Meon	3	117	1.09	16.7
11-May-99	roach	River Meon	3	180	1.46	16.8
11-May-99	roach	River Meon	3	186	1.40	16.9
24-May-99	roach	River Meon	3	96	1.14	16.0
24-May-99	roach	River Meon	3	80	1.18	16.1
24-May-99	roach	River Meon	3	78	1.09	16.4
28-May-99	roach	River Meon	3	126	1.39	17.9
28-May-99	roach	River Meon	3	134	1.54	18.1
28-May-99	roach	River Meon	3	143	1.51	18.3
28-May-99	roach	River Meon	3	75	1.08	18.8
28-May-99	roach	River Meon	3	96	1.12	19.1
01-Jun-99	roach	River Meon	3	162	1.39	17.7
01-Jun-99	roach	River Meon	3	167	1.26	18.0
01-Jun-99	roach	River Meon	3	164	1.29	18.2
01-Jun-99	roach	River Meon	3	186	1.14	18.6
01-Jun-99	roach	River Meon	3	162	1.26	18.8

Date	Species	Source	No. of fish	Mean length (mm)	Mean CSS (m s^{-1})	Water temp. (°C)
20-Oct-98	brown trout	River Colne	3	180	1.32	13.1
22-Oct-98	brown trout	River Colne	3	176	1.22	14.0
22-Oct-98	brown trout	River Colne	3	160	1.10	14.0
27-Oct-98	brown trout	River Colne	3	126	1.14	14.0
27-Oct-98	brown trout	River Colne	3	117	1.24	14.0
28-Oct-98	brown trout	River Colne	3	136	1.35	15.0
04-Nov-98	brown trout	River Colne	3	119	1.03	10.5
20-Nov-98	brown trout	River Wey	3	133	1.07	9.0
20-Nov-98	brown trout	River Wey	3	132	1.19	9.0
20-Nov-98	brown trout	River Wey	3	138	0.92	9.0
24-Nov-98	brown trout	River Wey	3	188	1.45	7.0
24-Nov-98	brown trout	River Wey	3	161	1.34	7.0
24-Nov-98	brown trout	River Wey	3	166	1.45	8.0
25-Nov-98	brown trout	River Wey	3	133	1.33	8.0
25-Nov-98	brown trout	River Wey	3	130	0.98	8.5
25-Nov-98	brown trout	River Wey	3	141	1.46	8.5
26-Nov-98	brown trout	River Wey	3	186	1.52	8.0
26-Nov-98	brown trout	River Wey	3	163	1.31	8.0
26-Nov-98	brown trout	River Wey	3	162	1.42	8.5
03-Dec-98	brown trout	River Wey	3	161	1.45	6.0
03-Dec-98	brown trout	River Wey	3	189	1.54	6.0
03-Dec-98	brown trout	River Wey	3	154	1.50	6.5
08-Dec-98	brown trout	River Wey	3	144	1.41	6.0
08-Dec-98	brown trout	River Wey	3	118	1.37	6.0
08-Dec-98	brown trout	River Wey	3	131	1.28	6.5
08-Dec-98	brown trout	River Wey	3	135	1.48	7.0
11-Dec-98	brown trout	River Wey	3	190	1.63	9.0
11-Dec-98	brown trout	River Wey	3	158	1.44	9.0
11-Dec-98	brown trout	River Wey	3	185	1.49	9.5
10-Mar-99	brown trout	Dockens Water	3	101	1.73	9.0
10-Mar-99	brown trout	Dockens Water	3	97	1.73	9.0
10-Mar-99	brown trout	Dockens Water	3	104	1.86	9.0
10-Mar-99	brown trout	Dockens Water	3	92	1.62	9.0
10-Mar-99	brown trout	Dockens Water	3	98	1.83	9.0
10-Mar-99	brown trout	Dockens Water	3	111	1.74	9.0
12-Mar-99	brown trout	Dockens Water	3	102	1.43	8.5
12-Mar-99	brown trout	Dockens Water	3	104	1.62	8.5
12-Mar-99	brown trout	Dockens Water	3	103	1.75	9.0
12-Mar-99	brown trout	Dockens Water	3	94	1.67	9.0
08-Apr-99	brown trout	Dockens Water	3	120	1.82	11.6
08-Apr-99	brown trout	Dockens Water	3	114	2.06	12.2
08-Apr-99	brown trout	Dockens Water	3	188	2.12	12.5
09-Apr-99	brown trout	Dockens Water	3	134	1.38	12.5
09-Apr-99	brown trout	Dockens Water	3	156	1.51	12.8
12-Apr-99	brown trout	Dockens Water	3	120	1.68	11.6
12-Apr-99	brown trout	Dockens Water	3	120	1.60	11.9
12-Apr-99	brown trout	Dockens Water	3	169	1.86	12.1
16-Apr-99	brown trout	Dockens Water	3	104	1.53	8.4
16-Apr-99	brown trout	Dockens Water	3	95	1.47	8.6
30-Apr-99	brown trout	Dockens Water	3	94	1.11	14.3
04-May-99	brown trout	Dockens Water	3	146	1.30	16.2
04-May-99	brown trout	Dockens Water	3	156	1.35	16.4
04-May-99	brown trout	Dockens Water	3	163	1.57	16.6
04-May-99	brown trout	Dockens Water	3	185	1.54	16.9
06-May-99	brown trout	Dockens Water	3	99	1.31	15.8
06-May-99	brown trout	Dockens Water	3	94	1.36	16.0
06-May-99	brown trout	Dockens Water	3	97	1.17	16.1
07-May-99	brown trout	Dockens Water	3	114	1.34	15.3
07-May-99	brown trout	Dockens Water	3	142	1.11	15.4
07-May-99	brown trout	Dockens Water	3	120	1.45	15.5
07-May-99	brown trout	Dockens Water	3	123	1.45	15.6
07-May-99	brown trout	Dockens Water	3	115	1.26	15.7
10-May-99	brown trout	Dockens Water	3	156	1.35	15.7
10-May-99	brown trout	Dockens Water	3	173	1.61	16.0
10-May-99	brown trout	Dockens Water	3	158	1.51	16.2
10-May-99	brown trout	Dockens Water	3	203	1.14	16.5
11-May-99	brown trout	Dockens Water	3	101	1.48	16.0
11-May-99	brown trout	Dockens Water	3	98	1.22	16.3
11-May-99	brown trout	Dockens Water	3	123	1.24	16.5
14-May-99	brown trout	Dockens Water	3	98	1.22	15.6
22-Jul-99	brown trout	Dockens Water	3	211	1.37	18.9
22-Jul-99	brown trout	Dockens Water	3	193	1.37	19.1

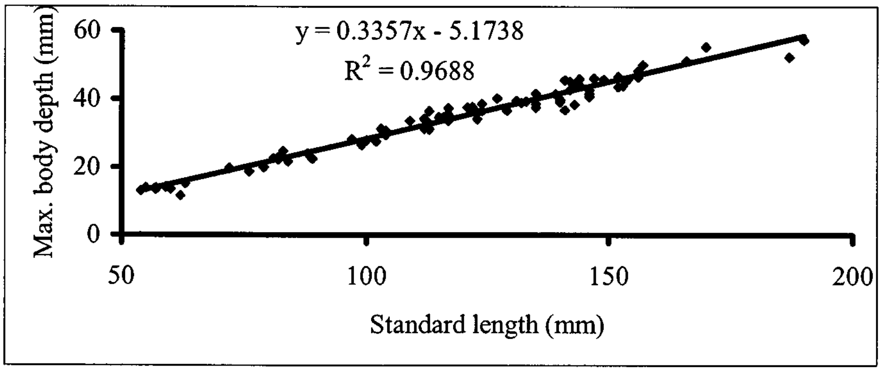
Appendix 5 - Standard Length-versus-Maximum Body Depth Charts



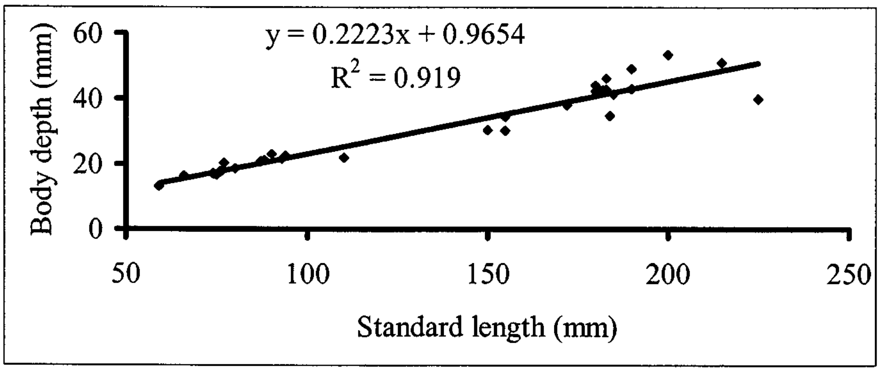
Chub



Dace

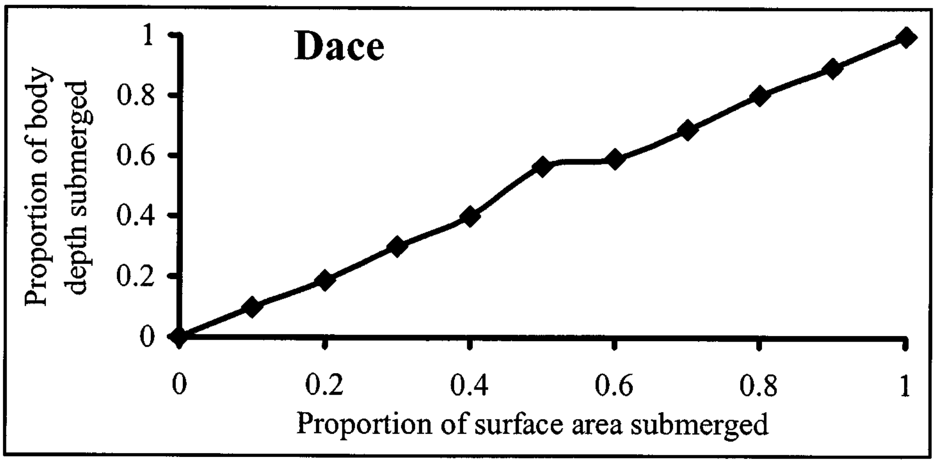


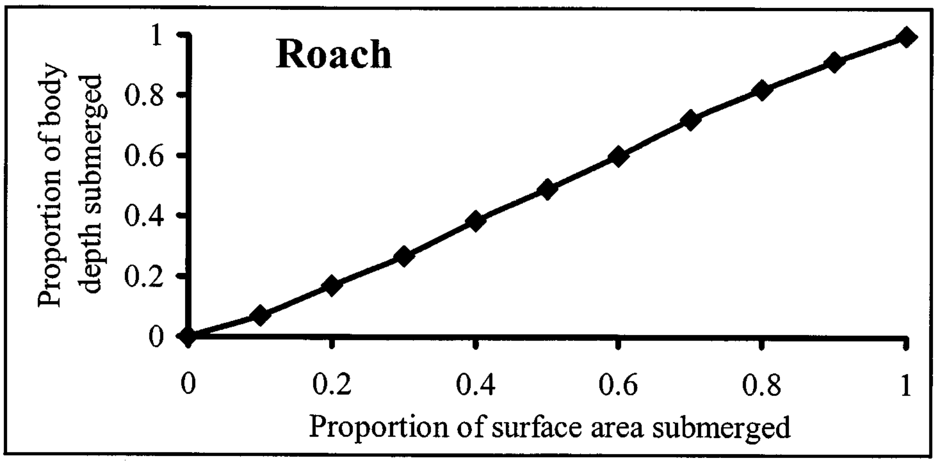
Roach

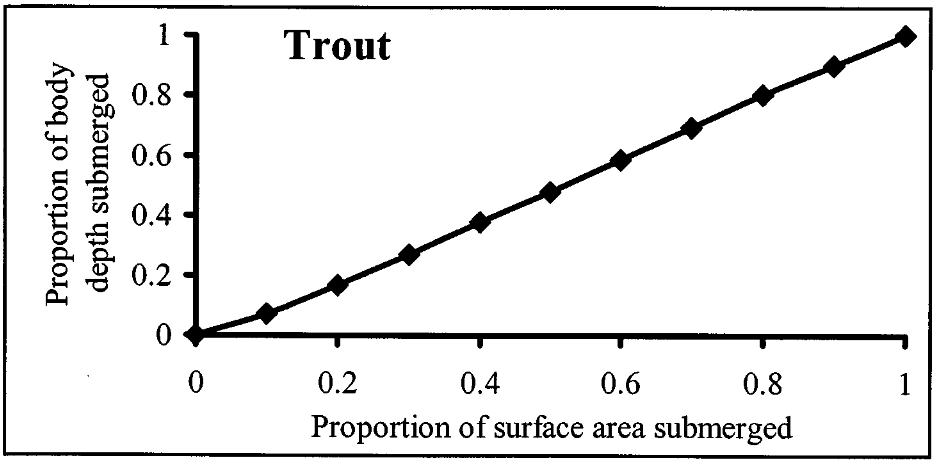


Trout

Appendix 6 - Relationship between proportion of body depth submerged and proportion of surface area submerged.

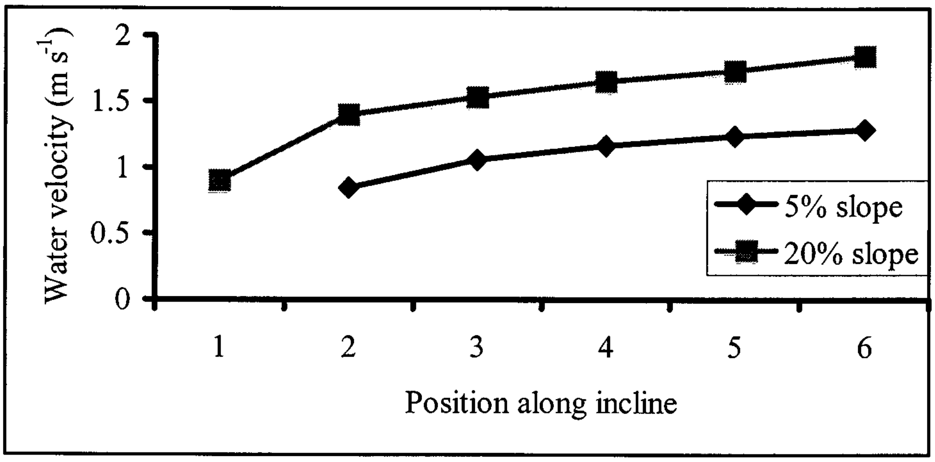


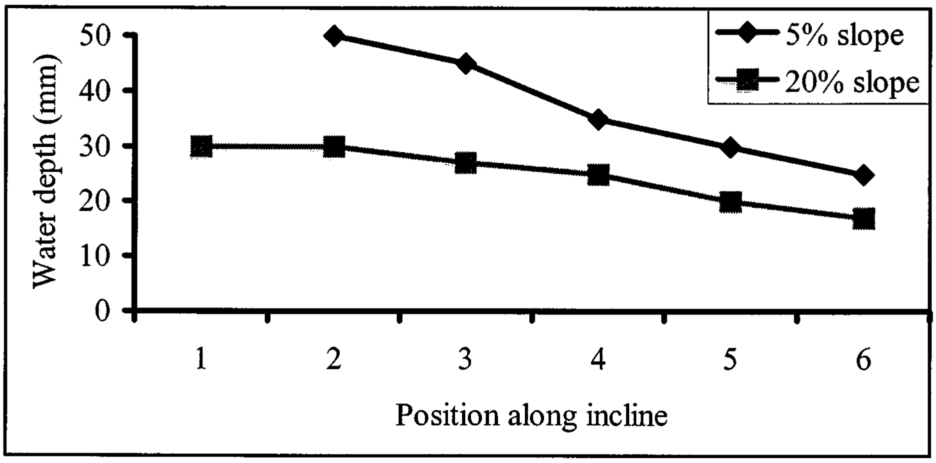




Appendix 7 - Water Depths Measured in Fish Ascent Experiments

The change in both water velocity and water depth on the 5% and 20% slopes. Position 1 is at the top of the slope, and position 6 is at the bottom.





Appendix 8 – SWIMIT vers. 1.0 for Excel 97 Operating Instructions

Appendix 8 – SWIMIT vers. 1.0 for Excel 97 Operating Instructions

'SWIMIT' VERSION 1.0 Copyright Environment Agency 2000.

Operating Instructions

Introduction

'SWIMIT' is program for estimating fish swimming speeds and endurance within a Microsoft Excel environment. The data on which estimates are based were derived from experimental measurements on fish carried out at Fawley Aquatic Research Laboratories under the Environment Agency's National R & D Programme, Project no. W2-026. The following fish species are included in the present version of the program:

Brown trout (*Salmo trutta*)

Dace (*Leuciscus leuciscus*)

Chub (*Leuciscus cephalus*)

Roach (*Rutilus rutilus*).

Elver (*Anguilla anguilla*)

Sustained and burst swimming speeds of these species were obtained over a size range of approximately 5-30cm and at water temperatures ranging from around 5° to 22°C. Elvers were tested in early (spring) and late season (summer/autumn).

Note: for brown trout, behavioural effects made estimates for fish <13cm in length unreliable (see Report). The results used for predictions made here are based on fish of >13cm in length. Confidence intervals on this data set are wide and a zero lower limit is shown in most cases.

The SWIMIT program provides ready access to swimming speed estimates based on the experimental data. For more information about how measurements were made and the more detailed results, the R & D Report for the project should be consulted.

How 'SWIMIT' Works

The program operates as a database that contains statistically processed data from the study. From values of the input parameters given by the user, the database tables are accessed to find the nearest match to that requested by the user. The main input parameters include:

- Fish length (cm)
- Water temperature (oC)
- The percentile response required (50th or 90th %ile swimming speed are the speeds attained by 50% or 90% of the population, respectively)
- The velocity of the water (cm.s-1) (for swimming endurance time estimates only).

Water temperature for sustained swimming speed and endurance calculations is treated in the following three bands:

- 11°C (coarse fish) or <9°C (trout)
- 11.1-15°C (coarse fish) or 9-14°C (trout)
- >15-22°C (coarse fish) or 14.1-22°C (trout).

The program will accept values outside these ranges but will base estimates on the nearest range and will show a warning flag.

All swimming speed data are stored within the database as body-lengths-per-second (BL.s^{-1}) values but are converted to absolute swimming speeds by multiplying by the body length value. Using the BL.s^{-1} convention in this way makes the program more efficient.

Sustained swimming speeds and endurance times at specified velocities are calculated from the endurance time versus speed

(BL.s^{-1}) tables given in the report. As the experiments were run for a maximum of 200 minutes, endurance times fell between zero and this upper limit. In the program, the data are modelled by a set of logistic curves of the form:

$$\text{Endurance time (min)} = 200/(1 + \exp(K*(U-N))),$$

where U is the water speed (BLs^{-1}), and K and N are coefficients representing slope and offset (speed intercept) respectively. Regressions of K and N on temperature and length were used to generate the overall model, allowing maximum sustained swimming speed and endurance time to be calculated for any fish within the length and temperature ranges of the experiments.

In the case of burst data for species other than elver, estimates are derived from multiple regression equations of the form:

Burst speed ($cm.s^{-1}$)= a + b.LOG(length) + c.LOG(temperature).

The actual coefficients of these equations and their associated statistics are given in the R & D Report. In these cases, the program does not give percentile estimates but gives the predicted mean value and associated 90% confidence limits.

Layout of the Program

SWIMIT has been designed for ease of use but a basic working knowledge of Excel is assumed. On first loading the program, the title page will be seen. The database pages are locked and hidden to prevent inadvertent corruption of the data. The user-visible portion of the program comprises seven worksheets, any of which can be viewed by selecting the tabs at the bottom of the screen using the cursor and mouse. The worksheets are as follows:

- Title Title page and information,
- Instructions Description of 'SWIMIT' and user instructions,
- plus five 'species' worksheets:
- Brown trout Input/output forms for calculating trout swimming speeds/endurance,
- Chub Input/output forms for calculating chub swimming speeds/endurance,
- Dace Input/output forms for calculating dace swimming speeds/endurance,
- Roach Input/output forms for calculating roach swimming speeds/endurance,
- Elver . Input/output forms for calculating elver swimming speeds/endurance.

Each of the five 'species' worksheets is divided into two pages. Page 1 allows calculation of the sustained or burst swimming speed of the species for a given fish length, water temperature and selected percentile value. Page two calculates the swimming endurance time for a given water velocity, according to fish length and water temperature.

Using the Program

As the visual display characteristics of different personal computers vary, it is recommended that you first select a screen 'zoom' factor that fits the page to the width of the screen. This must be done for each worksheet. Do this using the "View/..Zoom" drop-down menu within Excel until the best size is obtained.

To operate the program, first use the cursor/mouse to select the required species worksheet. Use the Page Up/Down keys or scroll keys to select either Page 1 or Page 2 as required (see above). Enter the required input parameter values in the cells provided.

Note: input cells are normally have a cream-coloured background, whereas output cells have a white-coloured background, but input cells may be coloured red if an out-of-range value has been entered (see Errors and Warnings below). Only input cells are accessible to the user. All other cells have been locked.

Pages 1 and Page 2 operate completely independently. If you wish to use both pages, the input values must be entered separately for each page.

Once the input values have been entered, the output cells will show the required values. Certain conditions will be flagged as error or warning states.

Printing

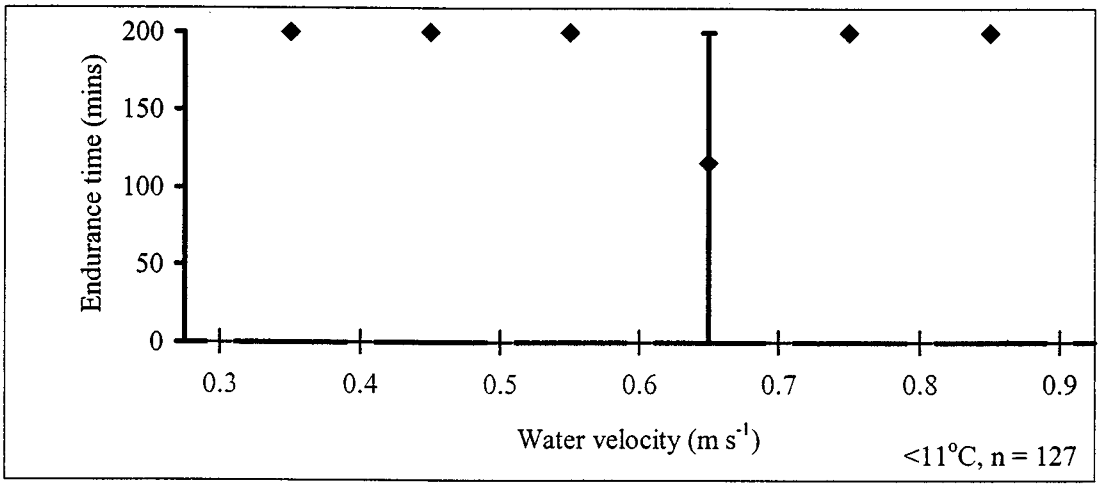
To print out the calculated values for a species, select the Excel printer icon at the top of the screen using the cursor and mouse. This will send the entire worksheet (i.e. pages 1 & 2) to your printer. The program has been set up to print in black and white only, with no colour background, to save printer ink and reduce printing time.

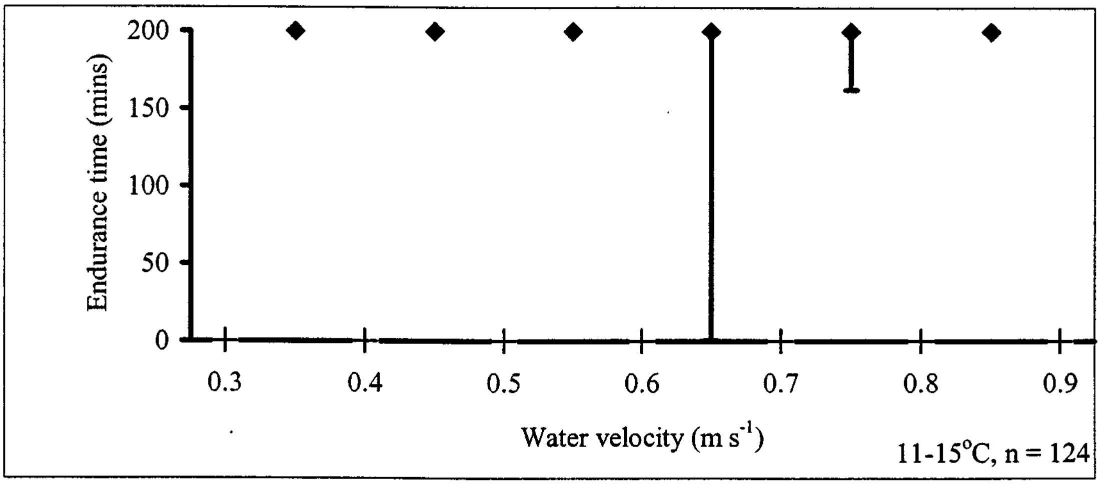
Errors and Warnings

1. If an output cell returns the sign: "#VALUE!" or "#NUM!" then it has not been possible to obtain a valid estimate. This usually means a data entry mistake. Check the inpout values and units.

2. If the background colour of an input cell changes from cream to red, this is a warning flag. It means that the input values are outside the experimental ranges and therefore that output values are extrapolations and should be treated with caution.

Appendix 9 – Median endurance swimming data in three temperature categories, with water velocities given in metres per second. Error bars represent upper and lower quartiles. Non visible errors bars are hidden behind the data point.





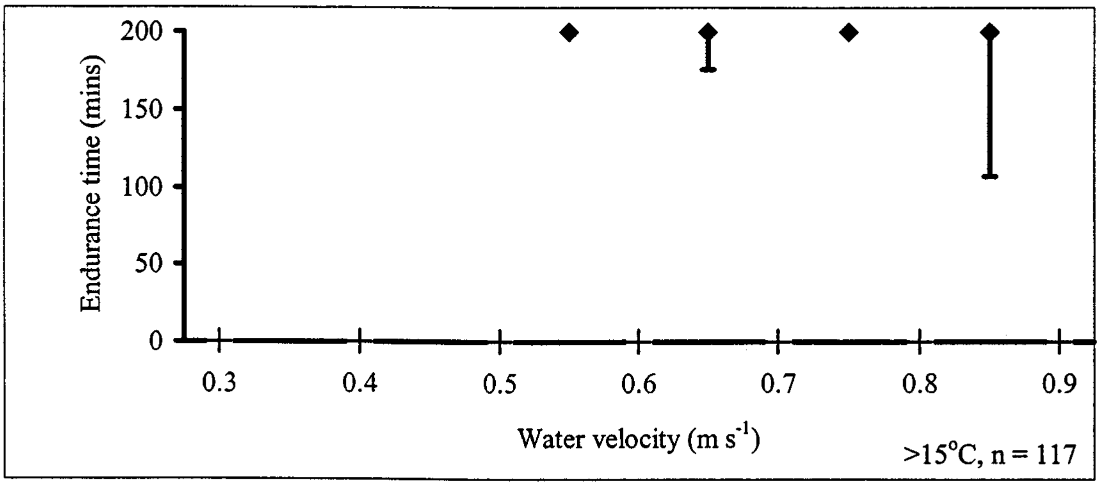


Figure A9 chub a. Median endurance of small chub in three temperature categories.

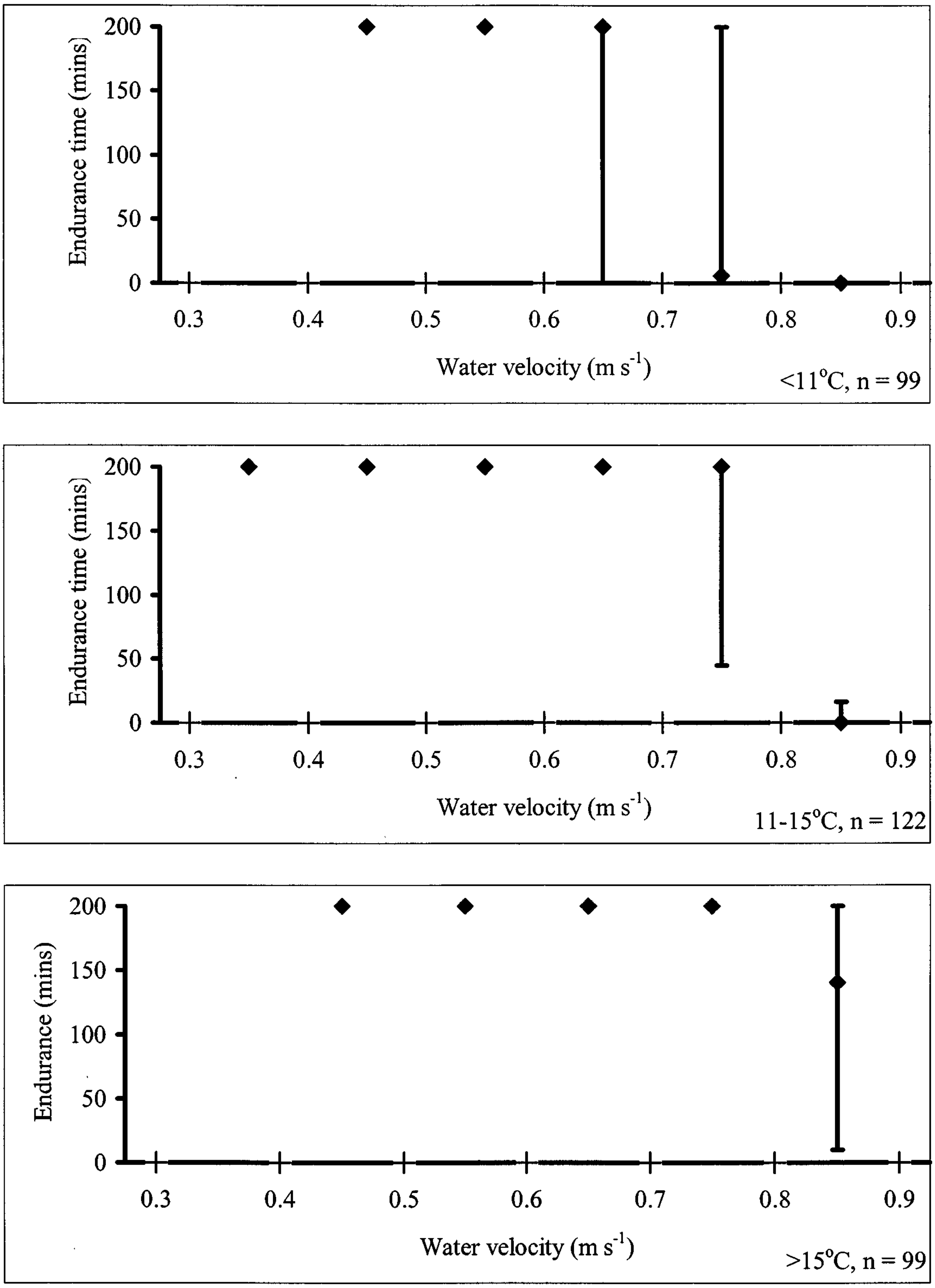


Figure A9 chub b. Median endurance of medium chub in three temperature categories.

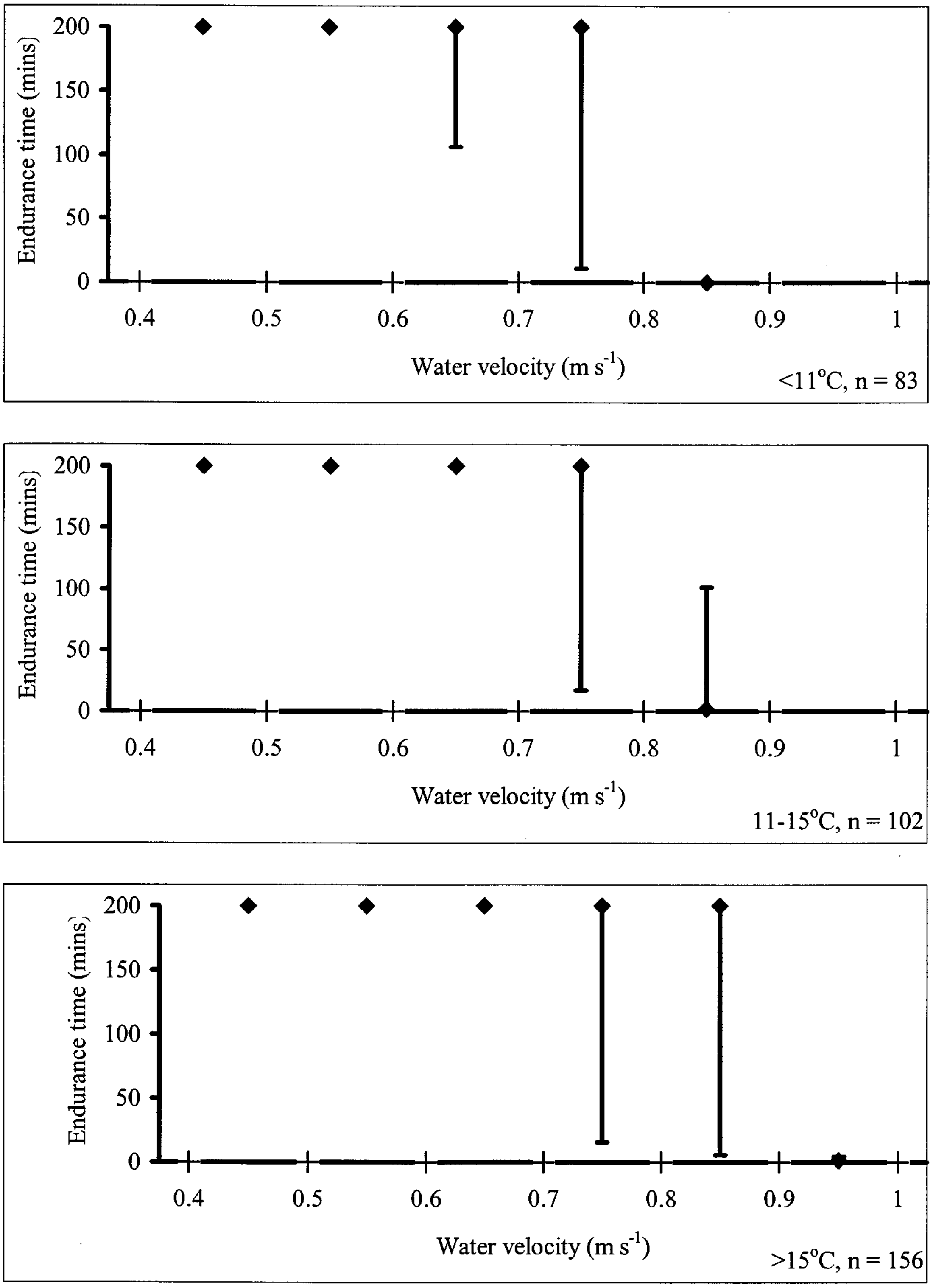


Figure A9 chub c. Median endurance of large chub in three temperature categories.

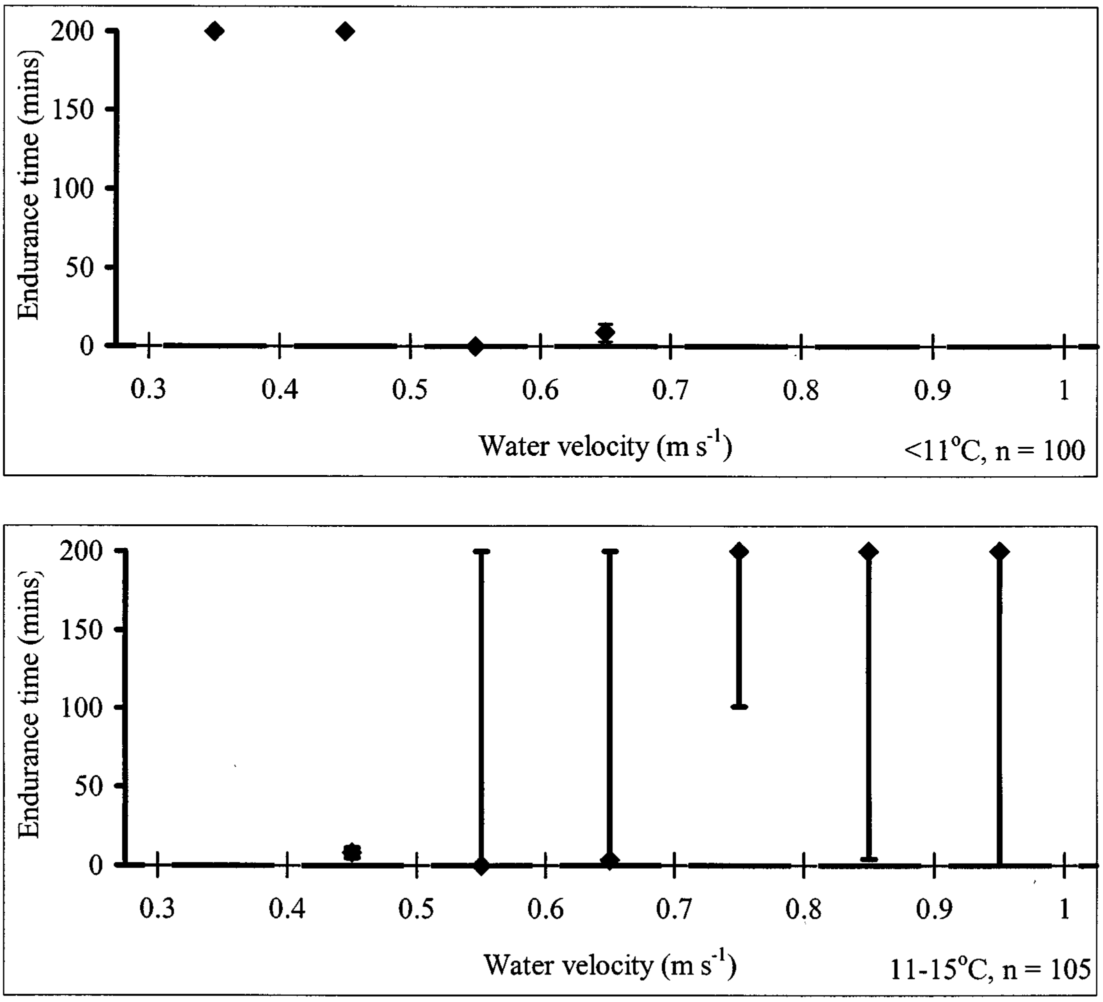
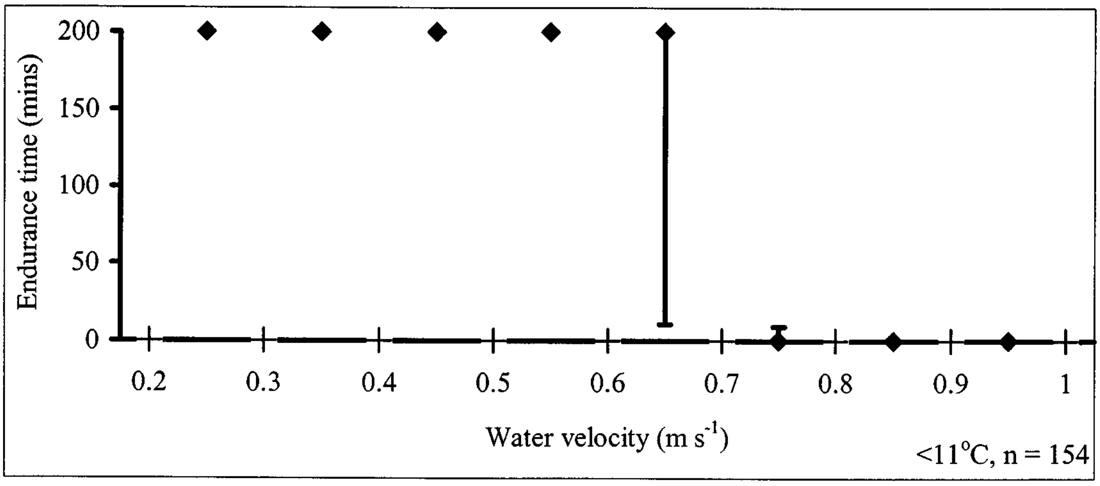
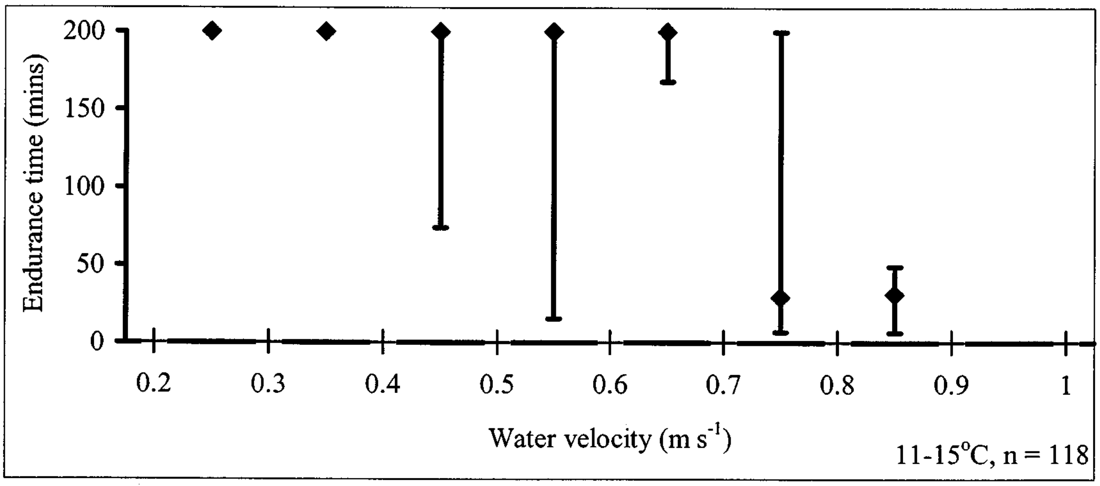


Figure A9 dace a. Median endurance of small dace in three temperature categories.





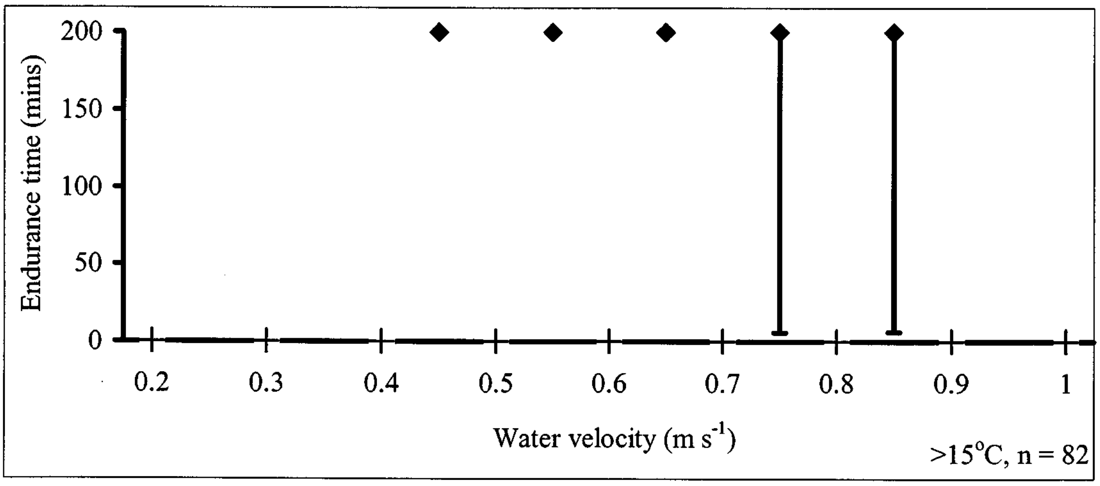


Figure A9 dace b. Median endurance of medium dace in three temperature categories.

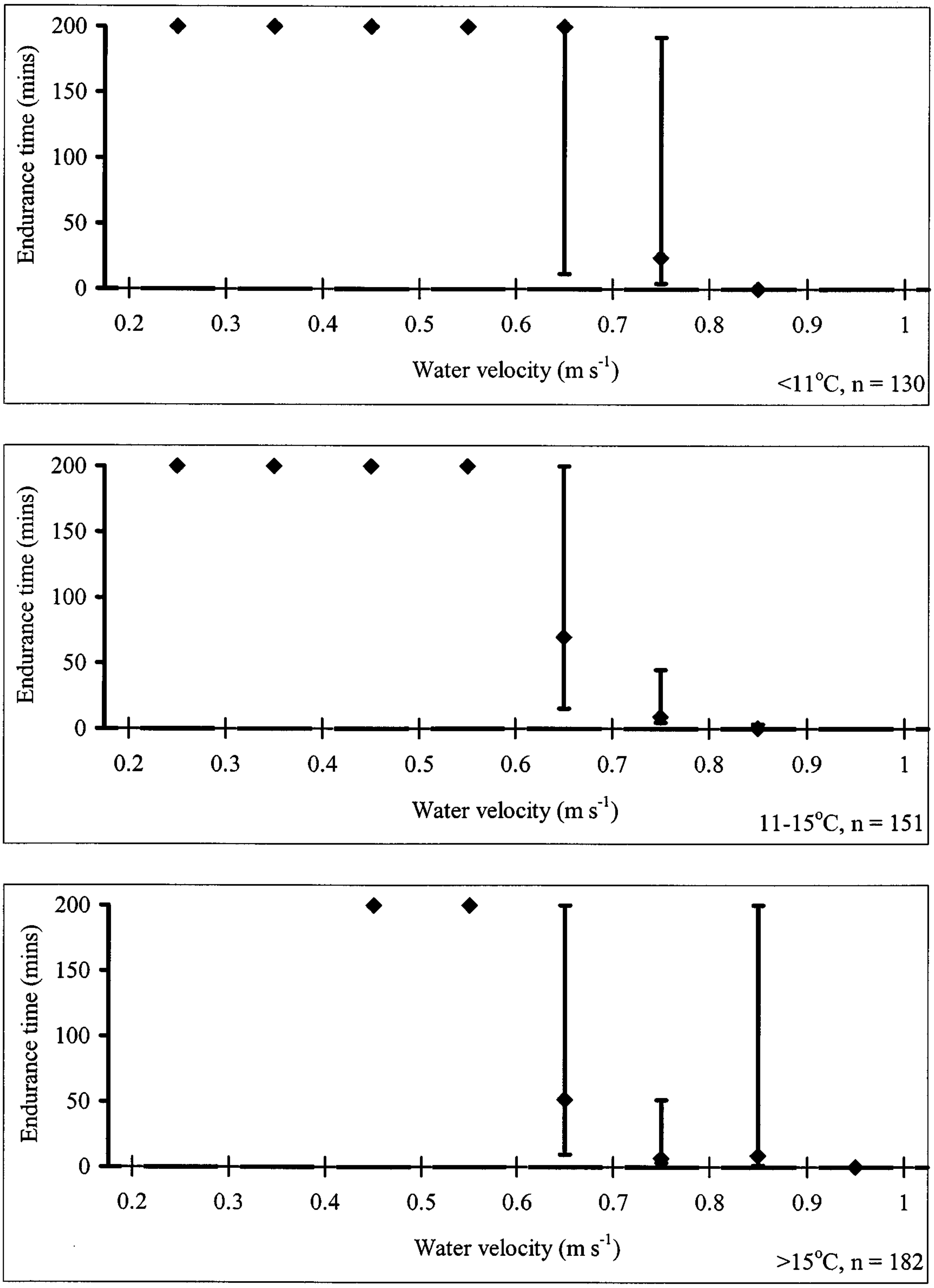


Figure A9 dace c. Median endurance of large dace in three temperature categories.

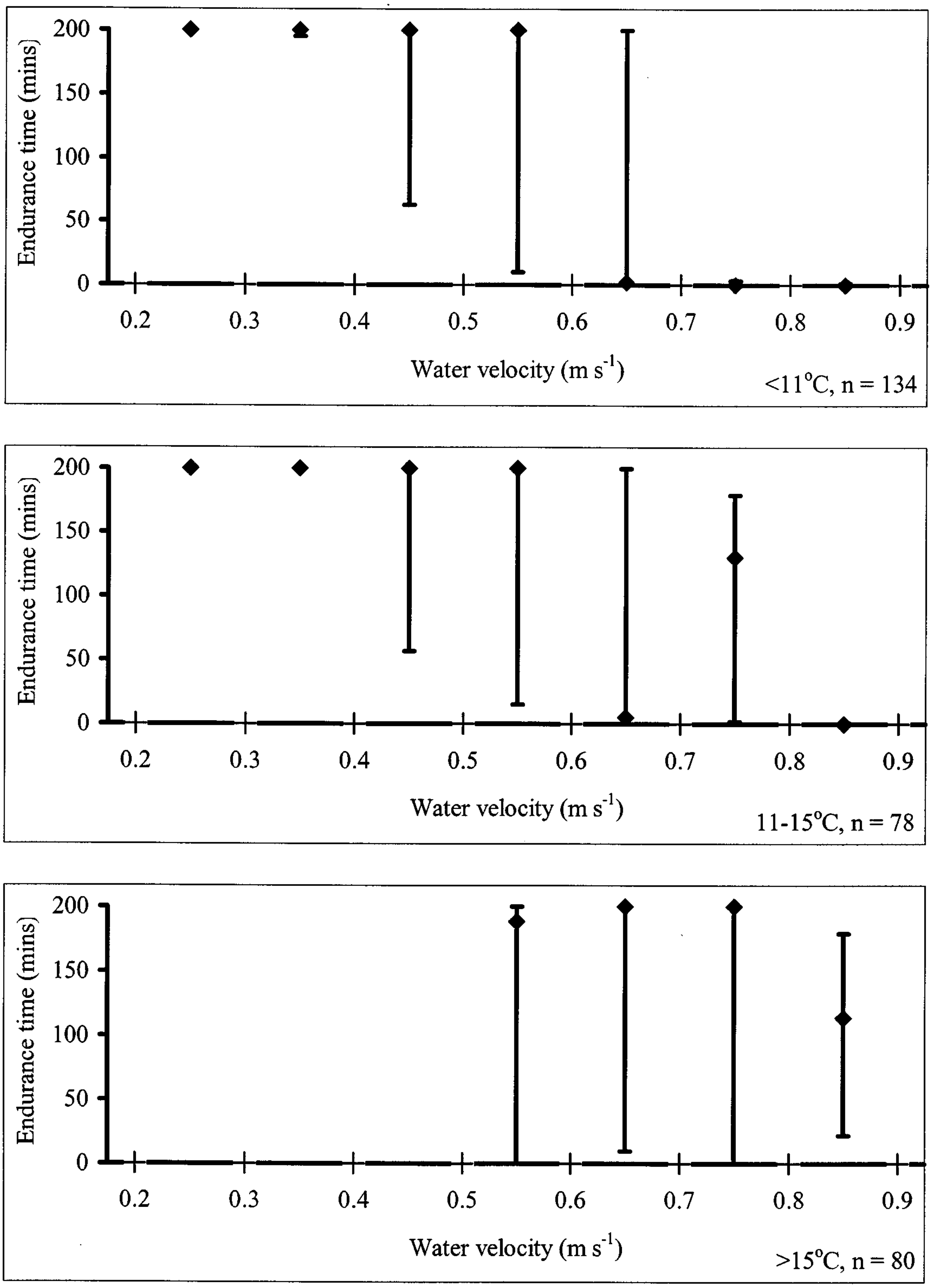


Figure A9 roach a. Median endurance of small roach in three temperature categories.

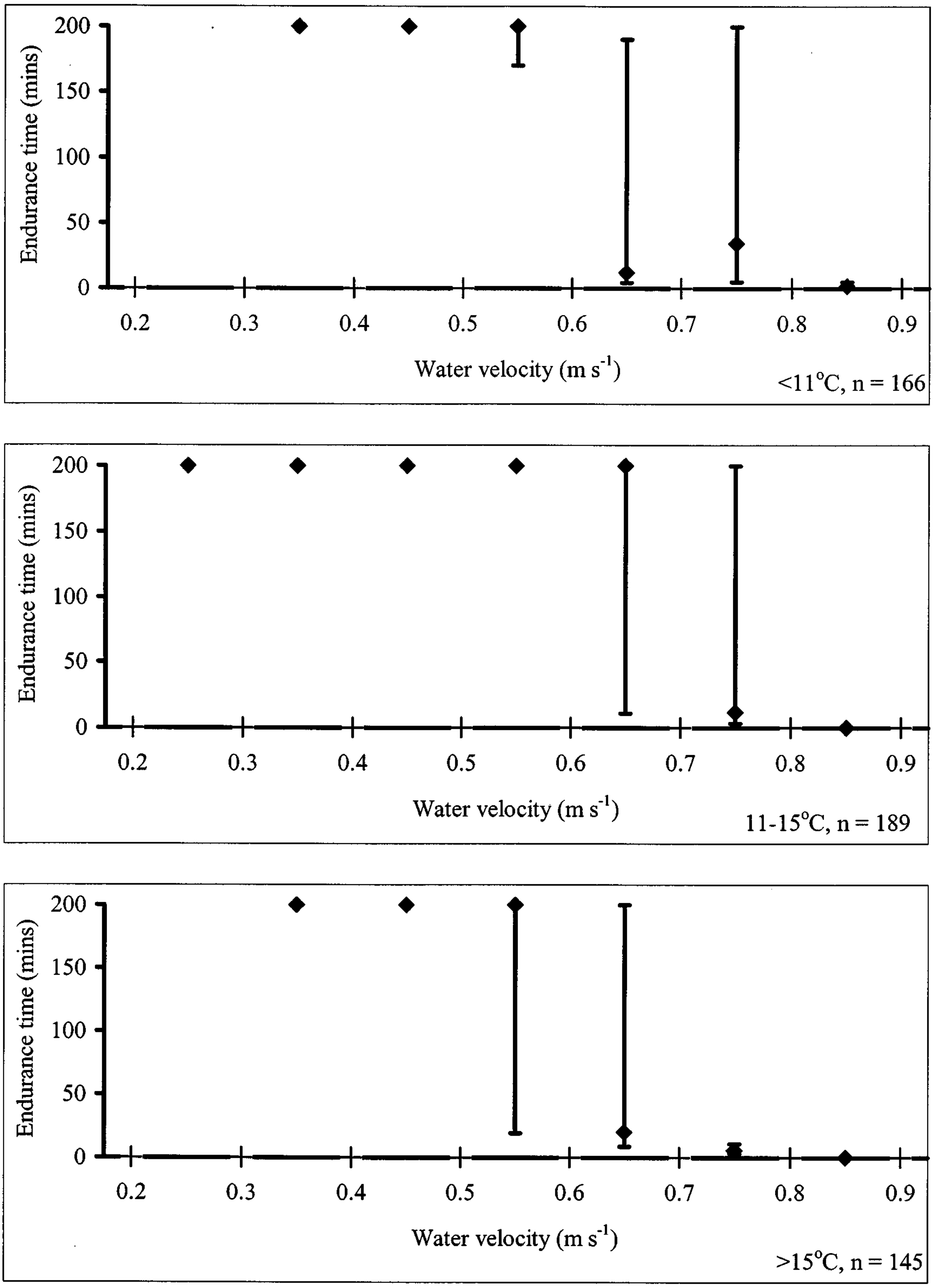


Figure A9 roach b. Median endurance of medium roach in three temperature categories.

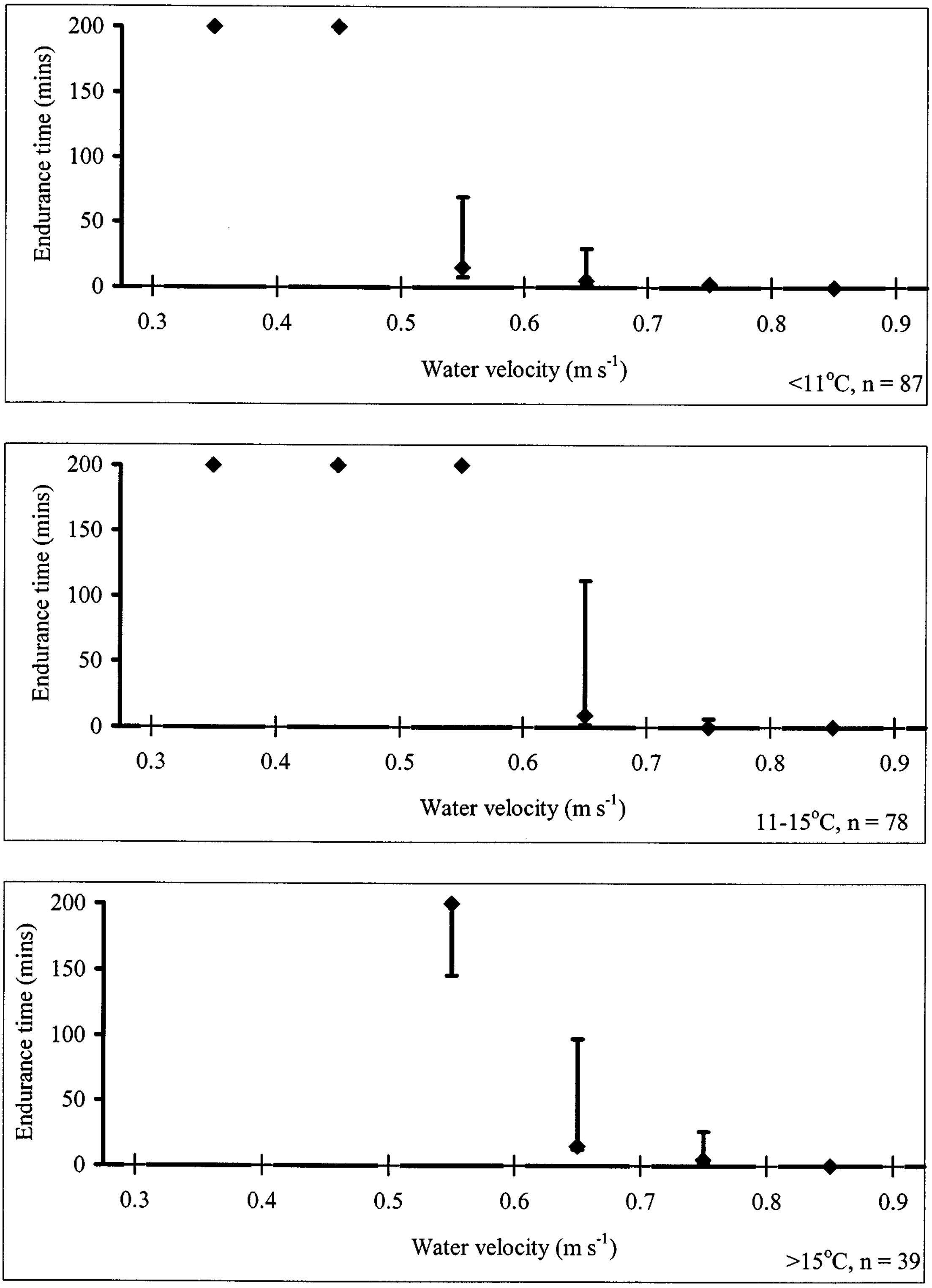


Figure A9 roach c. Median endurance of large roach in three temperature categories.

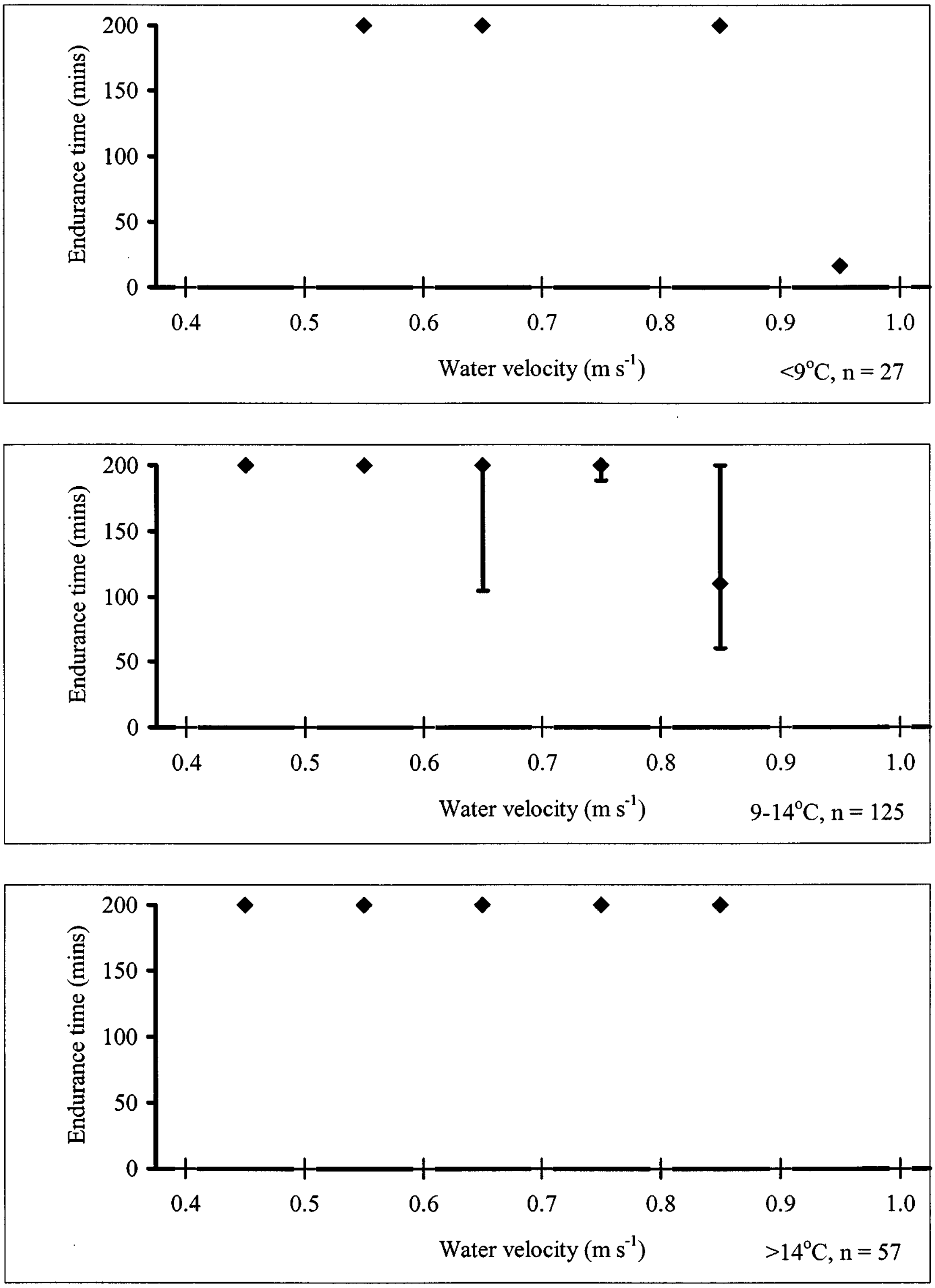


Figure A9 trout a. Median endurance of small trout in three temperature categories.

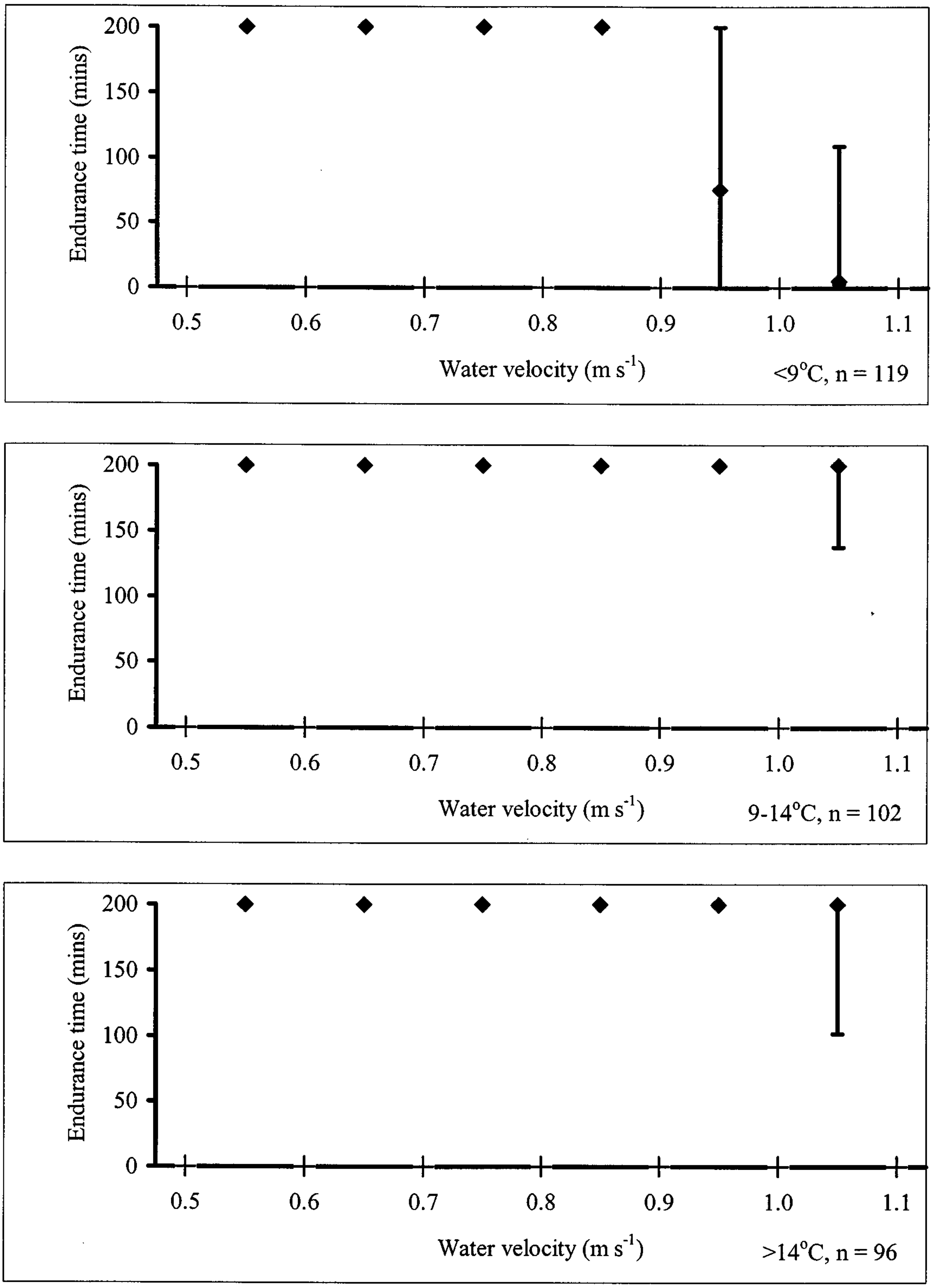


Figure A9 trout b. Median endurance of medium trout in three temperature categories.

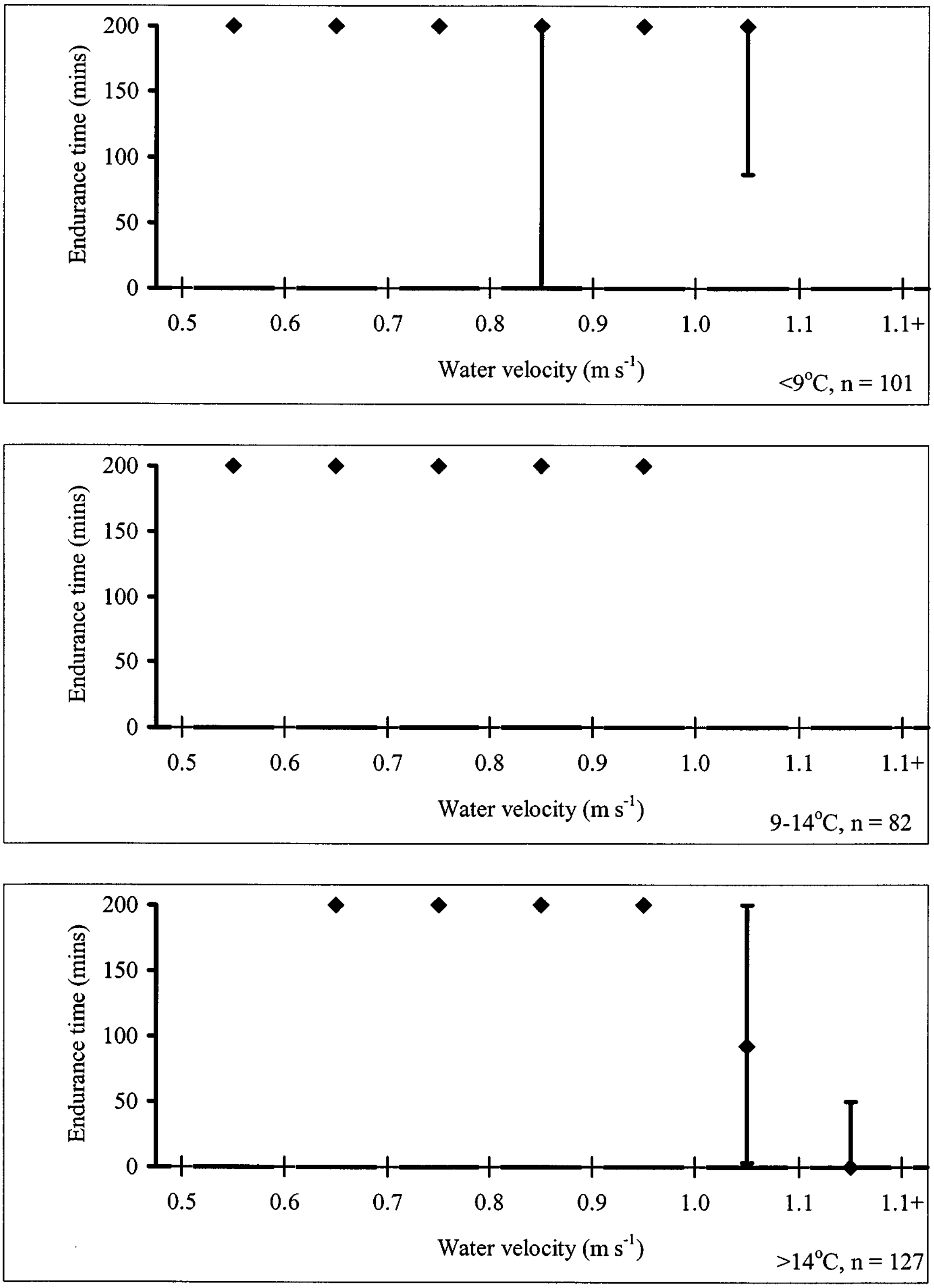


Figure A9 trout c. Median endurance of large trout in three temperature categories.

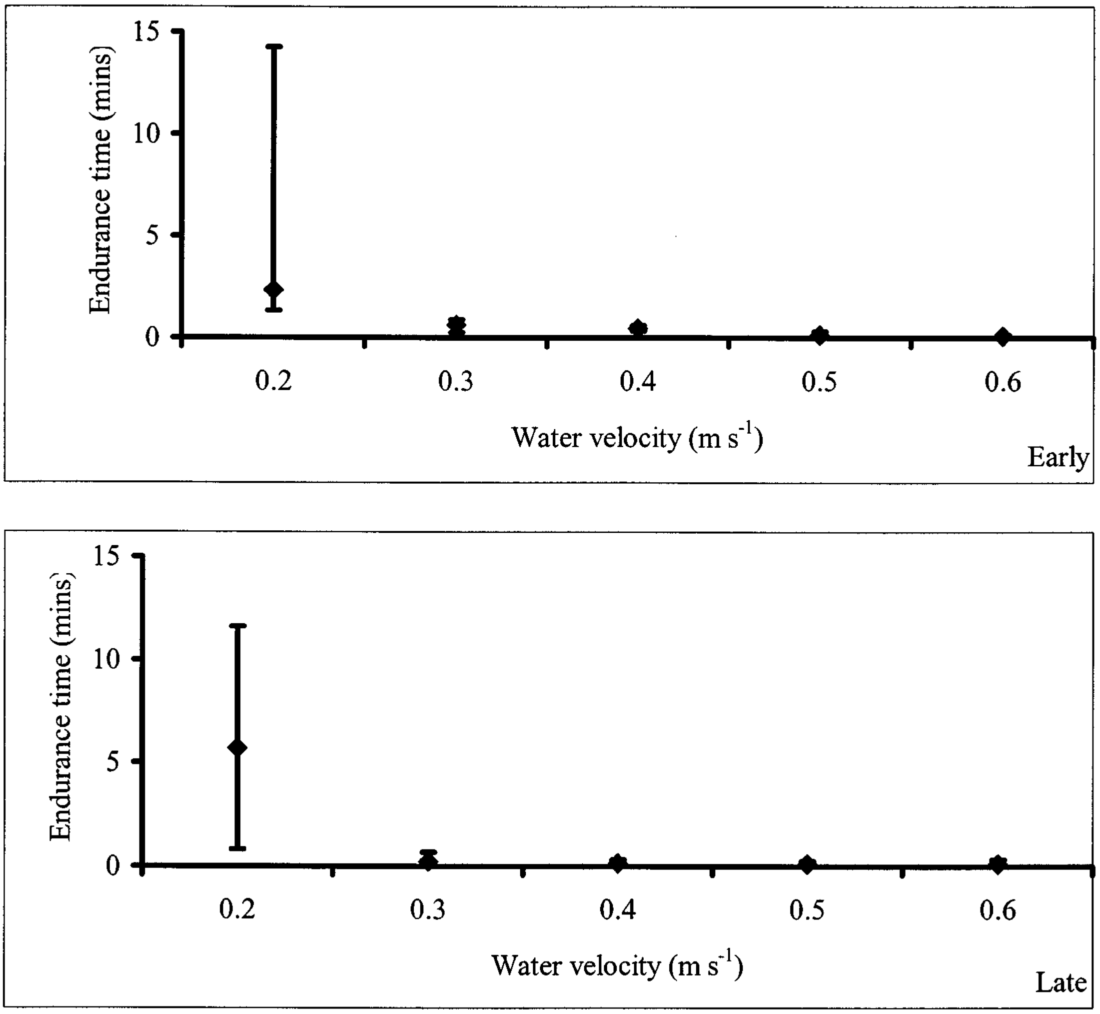


Figure A9 elver. Median endurance of elvers early and late in the season.

Appendix 10 – Median endurance swimming data in three temperature categories, with water velocities given in body lengths per second. Error bars represent upper and lower quartiles. None visible error bars are hidden behind the data point.

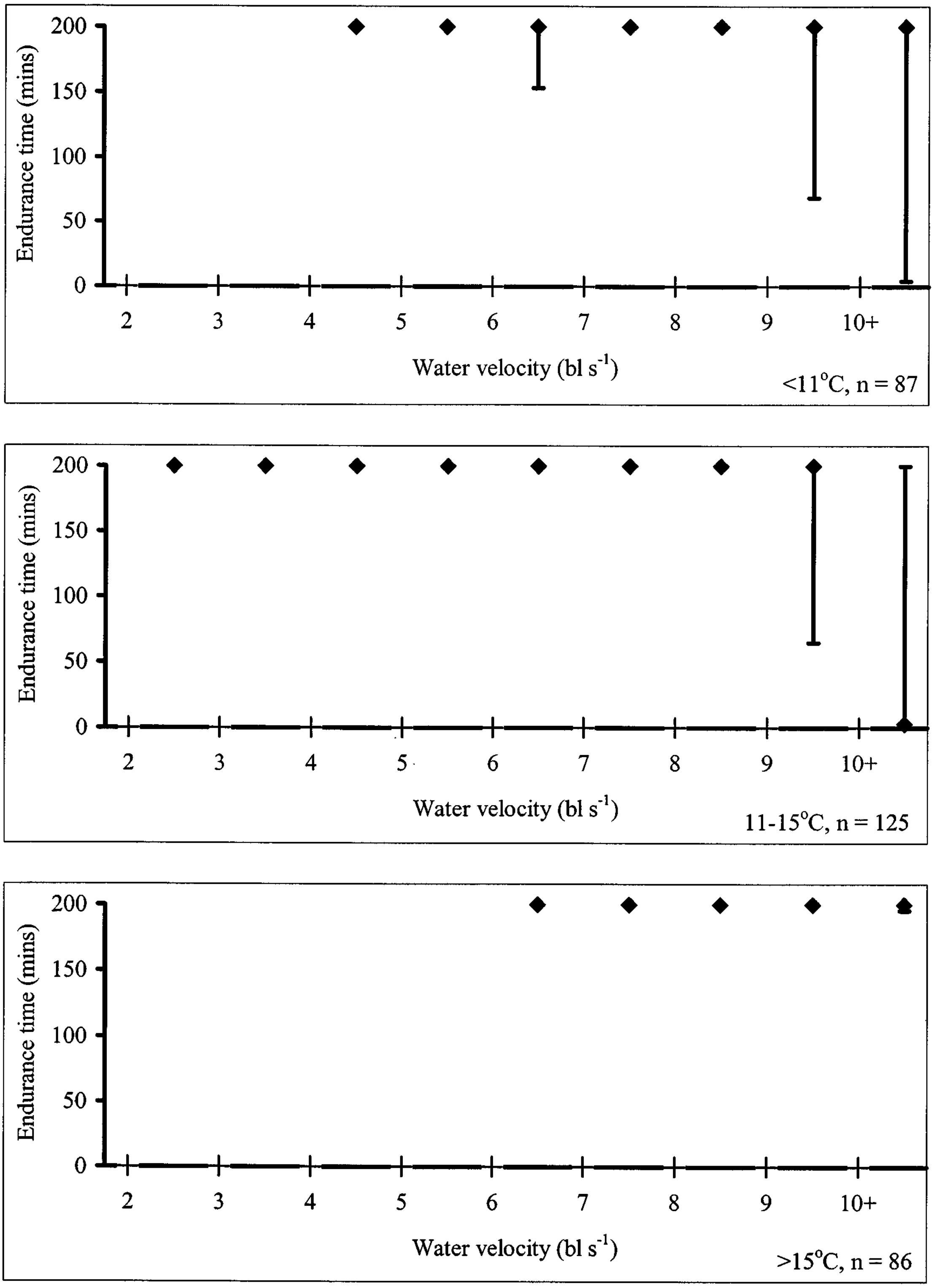


Figure A10 chub a. Median endurance of small chub in three temperature categories.

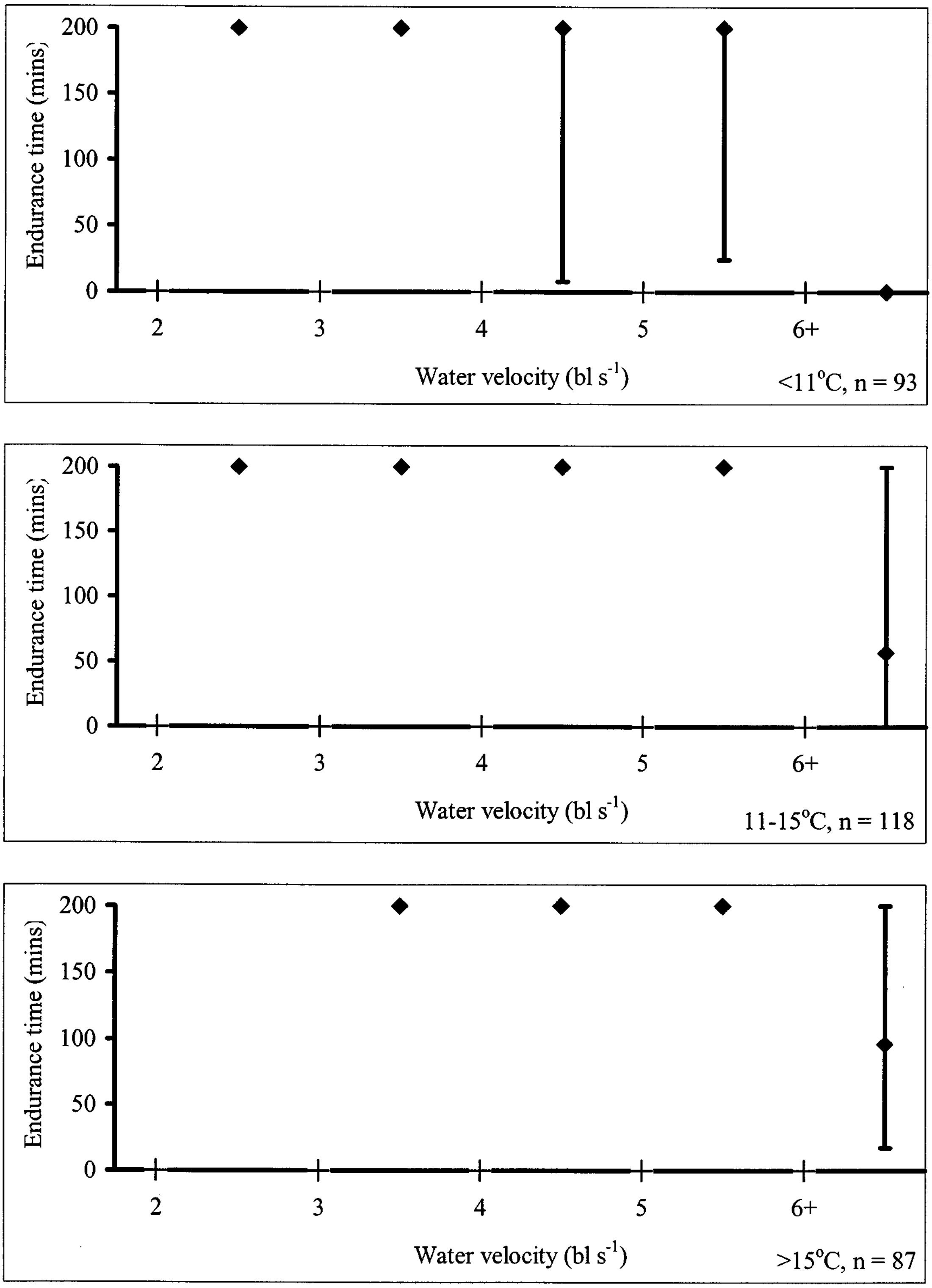


Figure A10 chub b. Median endurance of medium chub in three temperature categories.

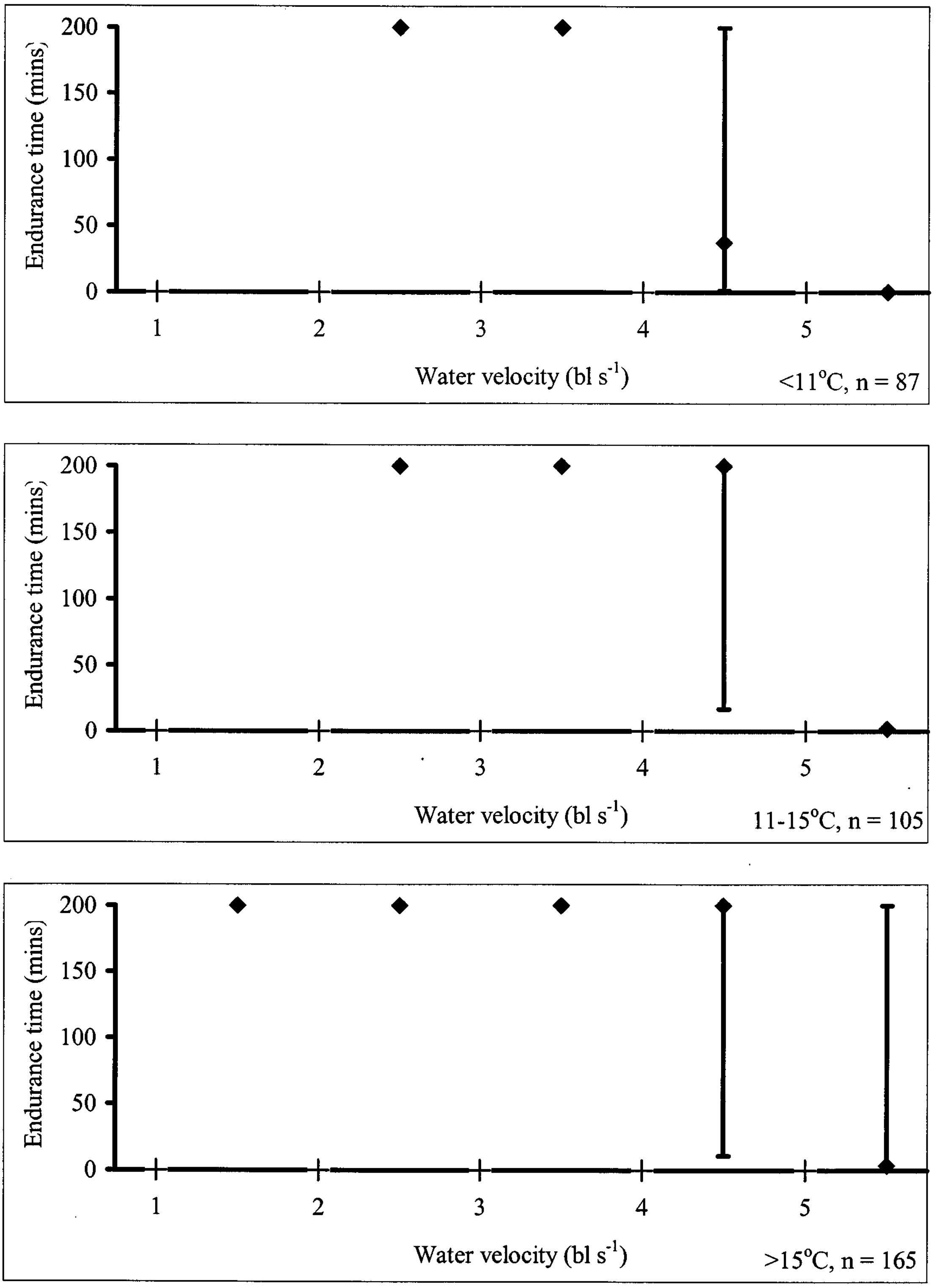


Figure A10 chub c. Median endurance of large chub in three temperature categories.

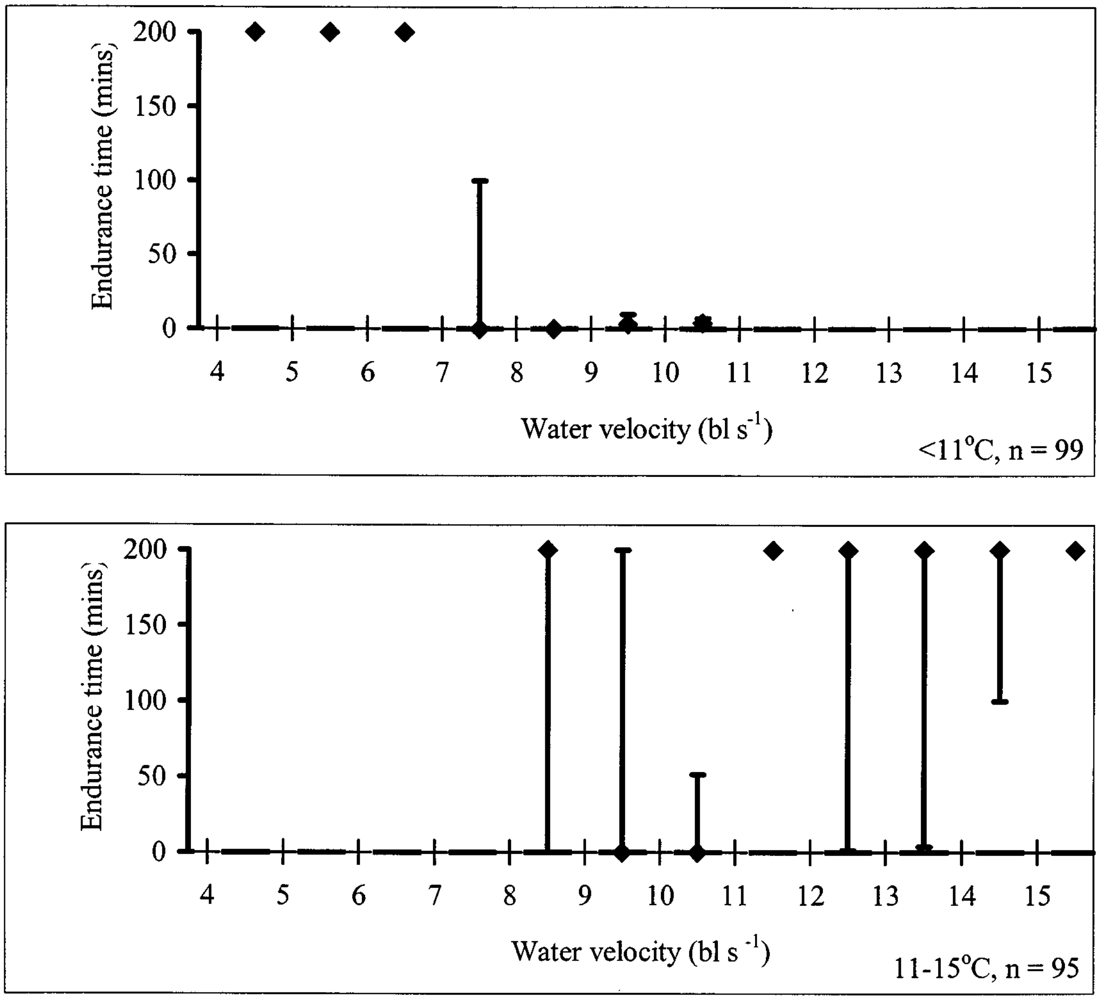


Figure A10 dace a. Median endurance of small dace in three temperature categories.

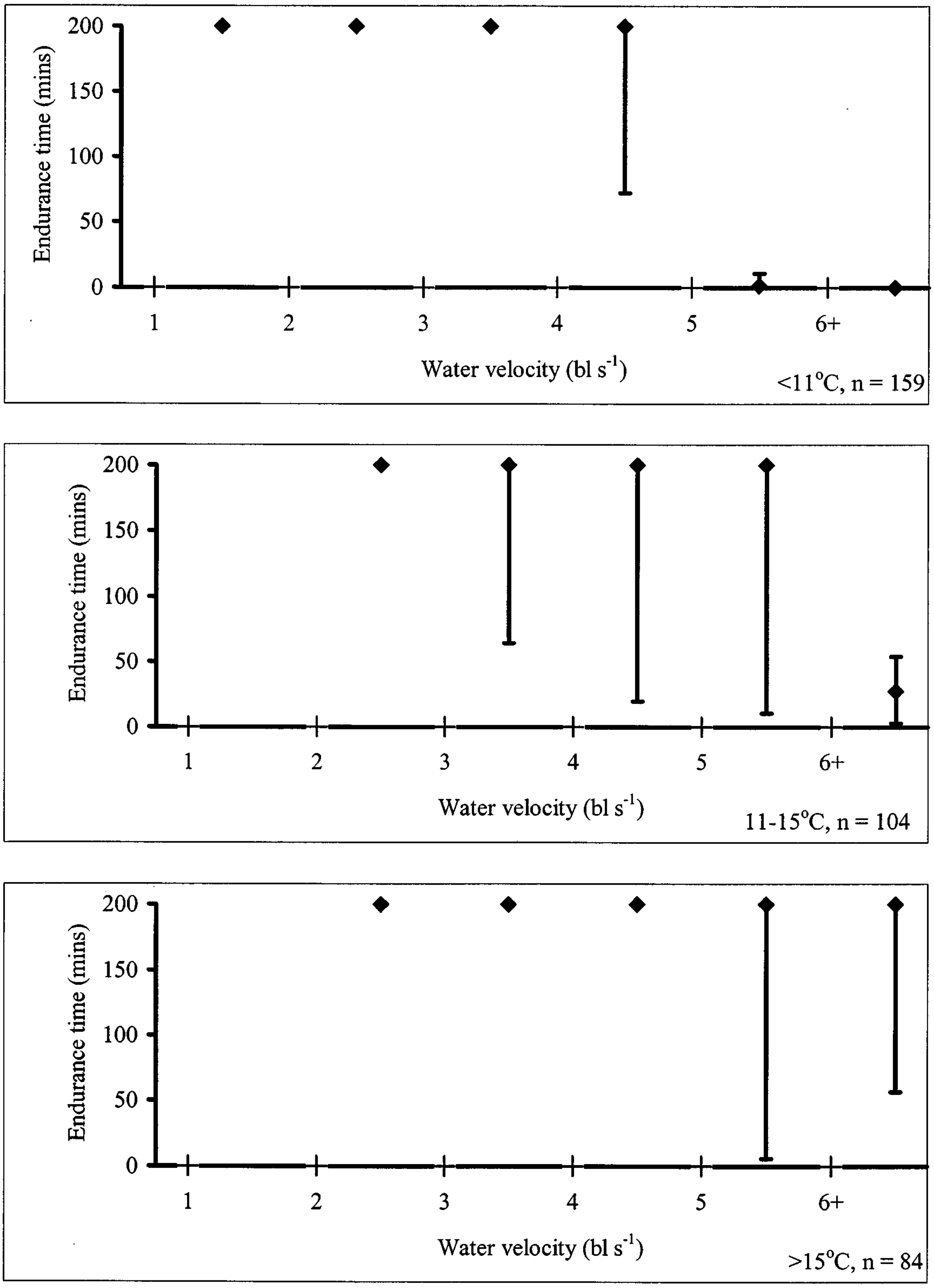


Figure A10 dace b. Median endurance of medium dace in three temperature categories.

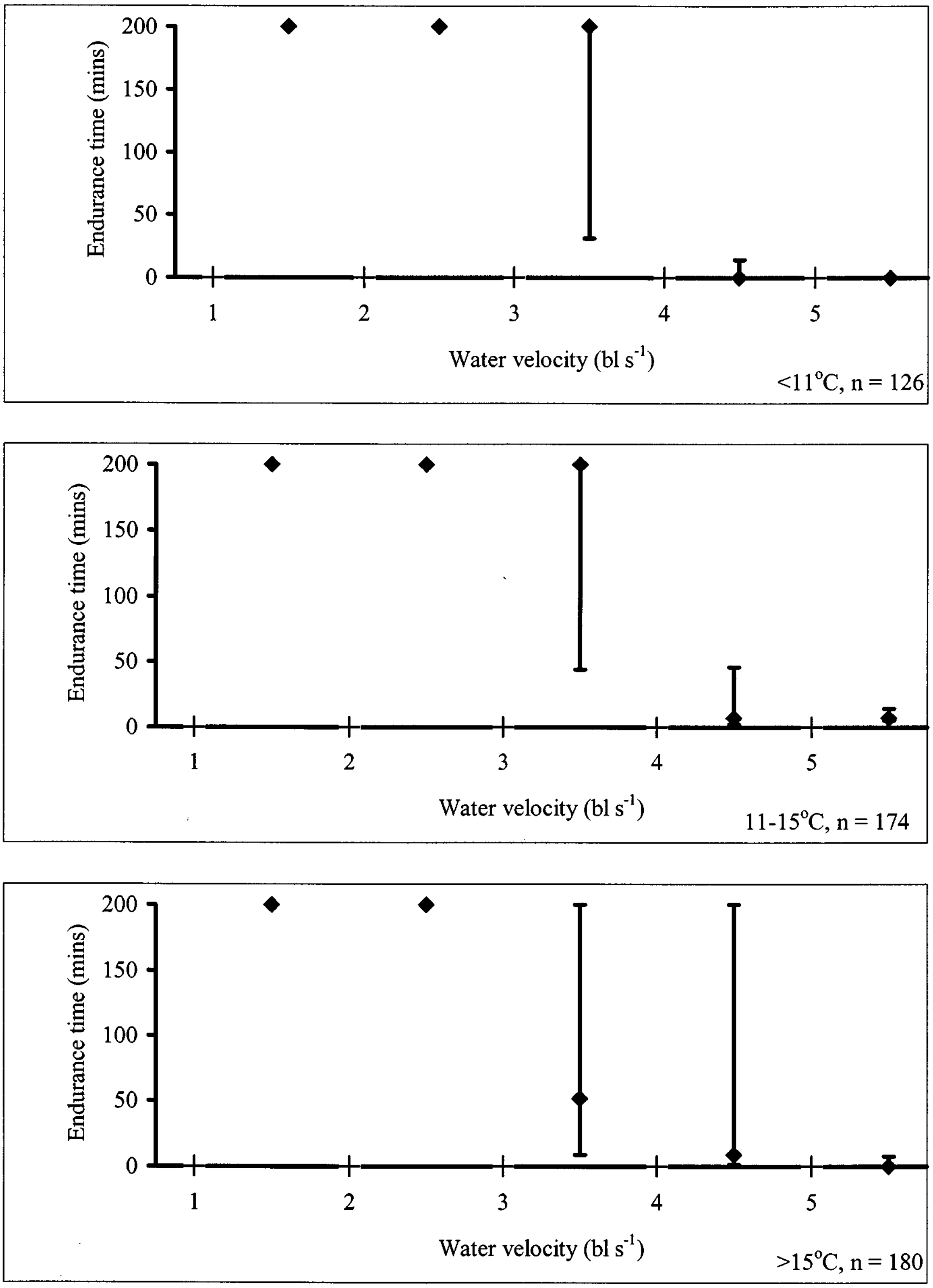


Figure A10 dace c. Median endurance of large dace in three temperature categories.

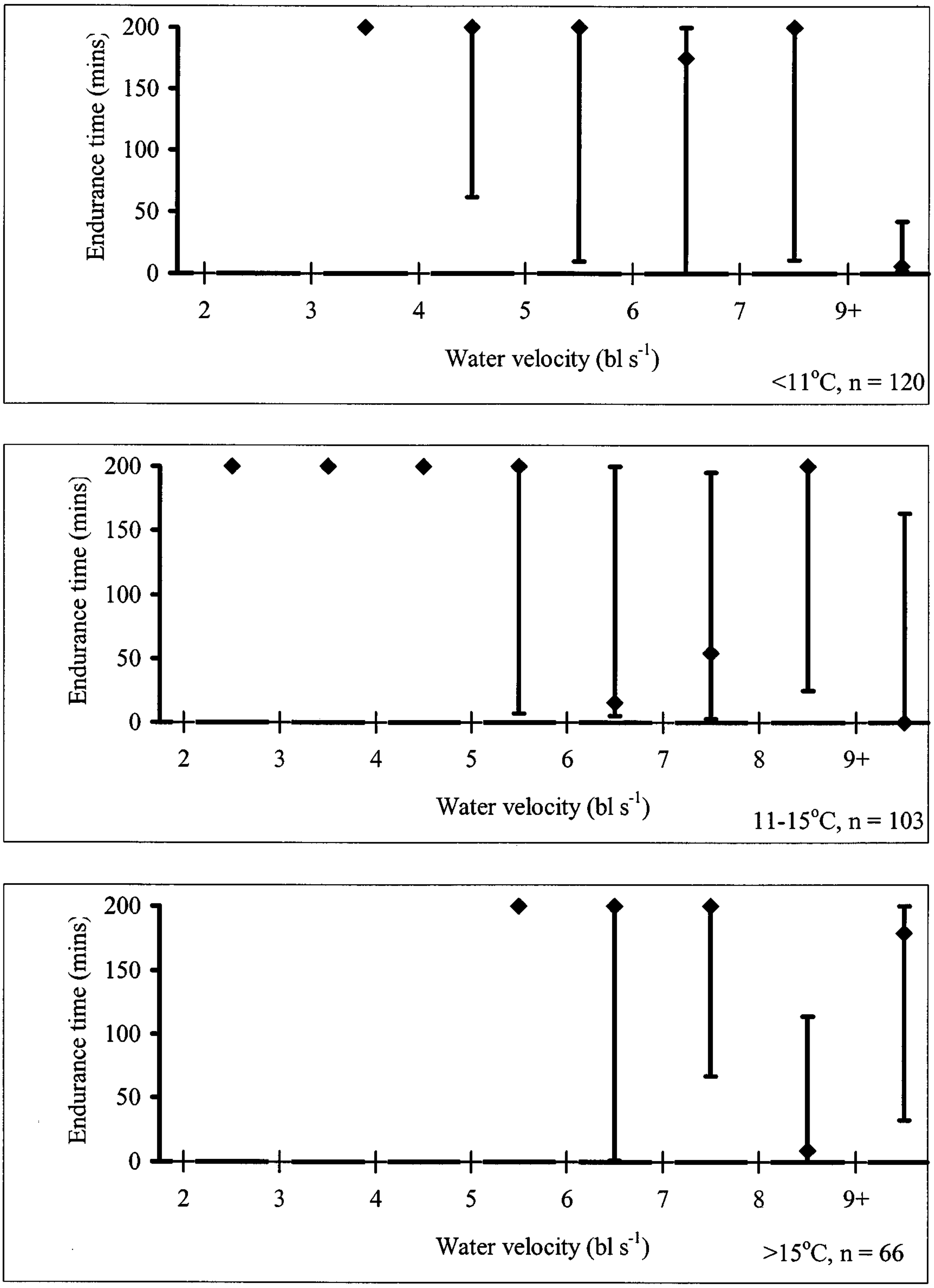


Figure A10 roach a. Median endurance of small roach in three temperature categories.

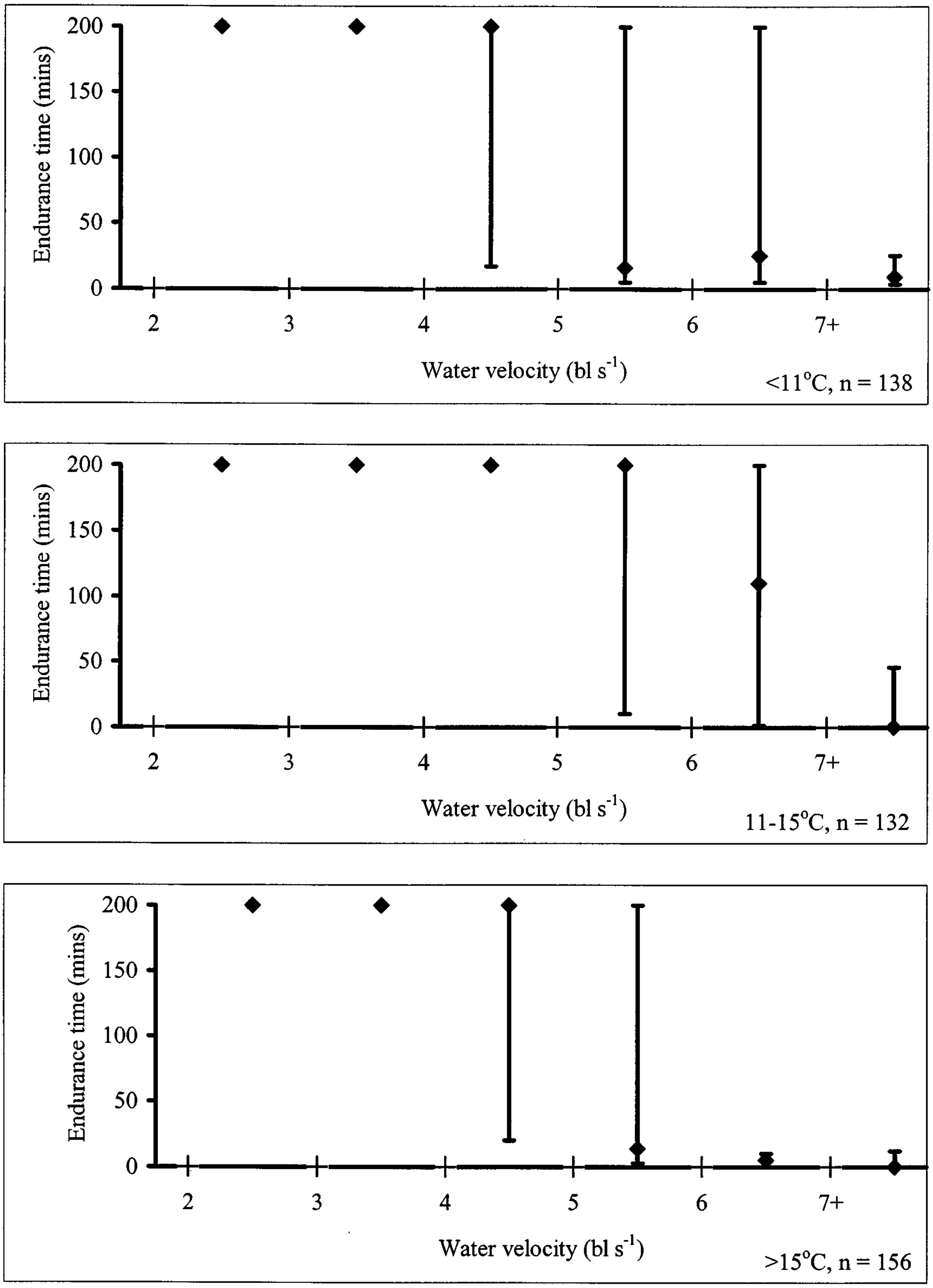


Figure A10 roach b. Median endurance of medium roach in three temperature categories.

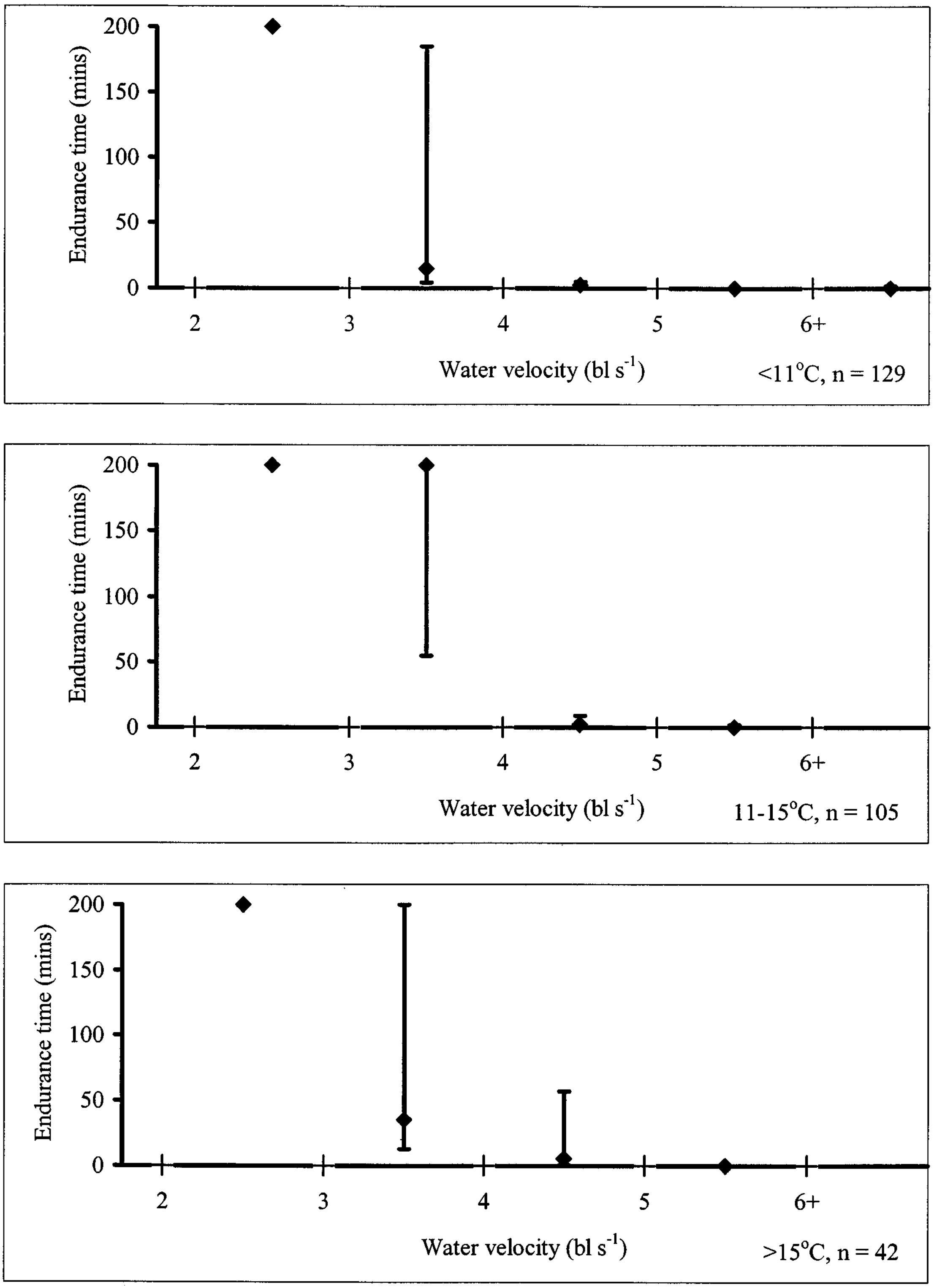


Figure A10 roach c. Median endurance of large roach in three temperature categories.

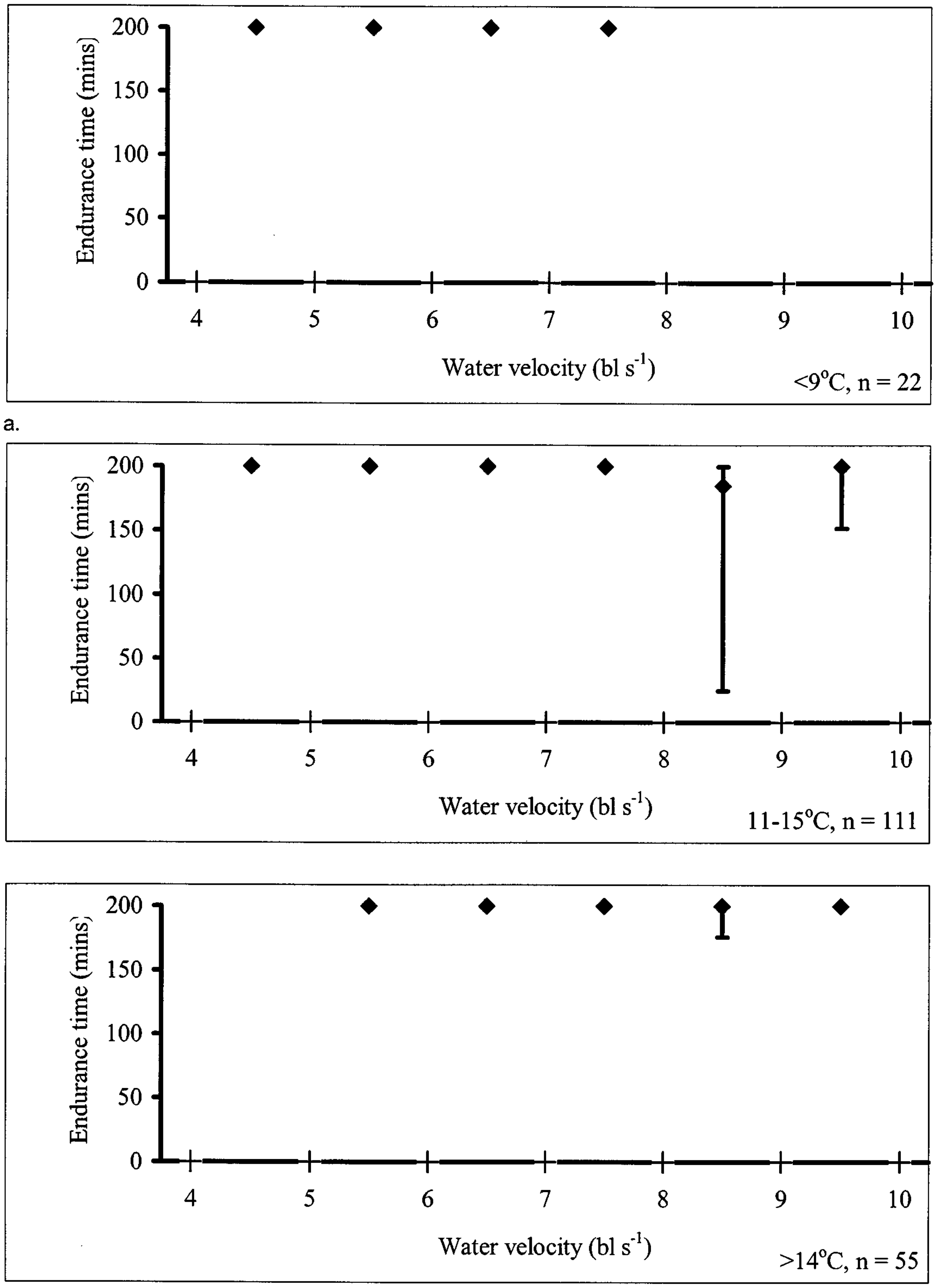


Figure A10 trout a. Median endurance of small trout in three temperature categories.

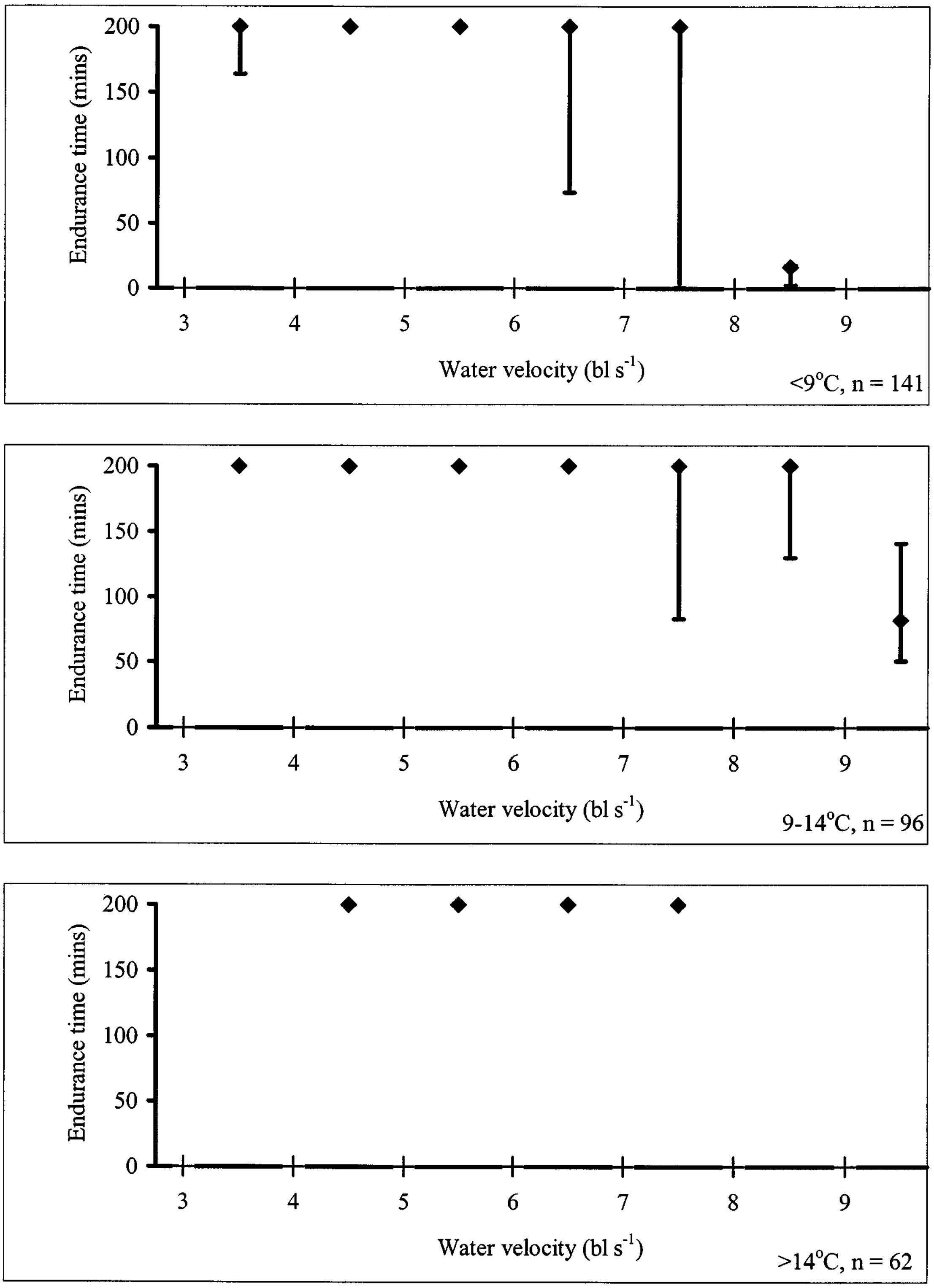
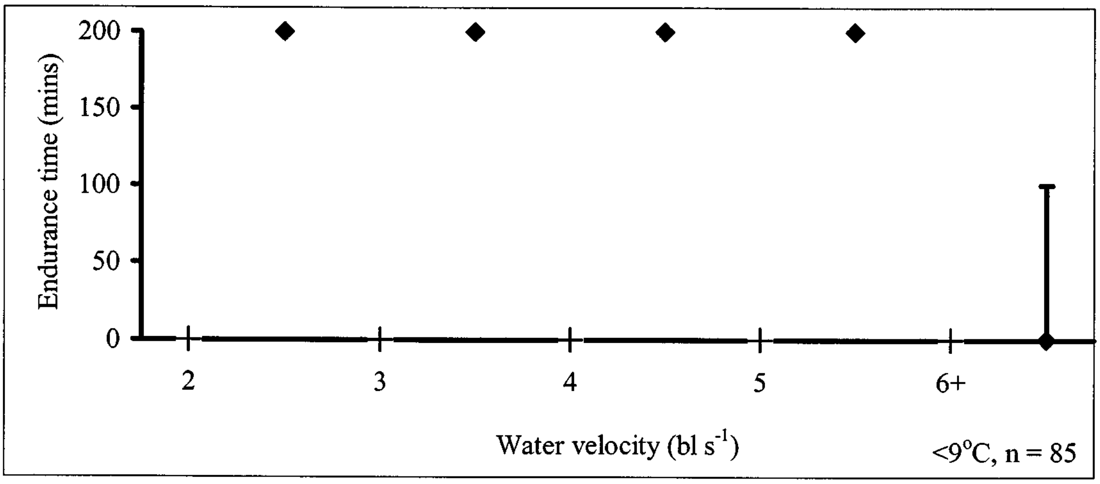
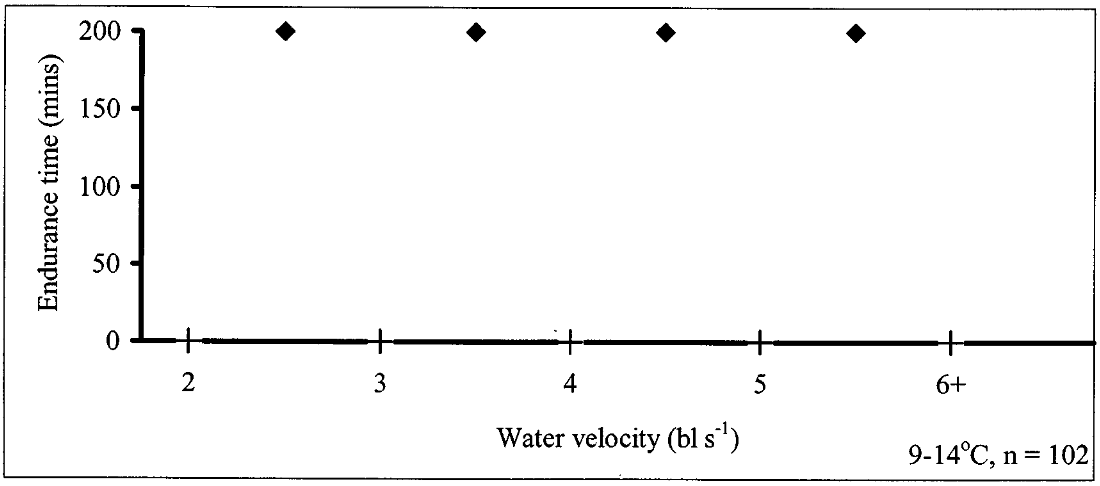


Figure A10 trout b. Median endurance of medium trout in three temperature categories.





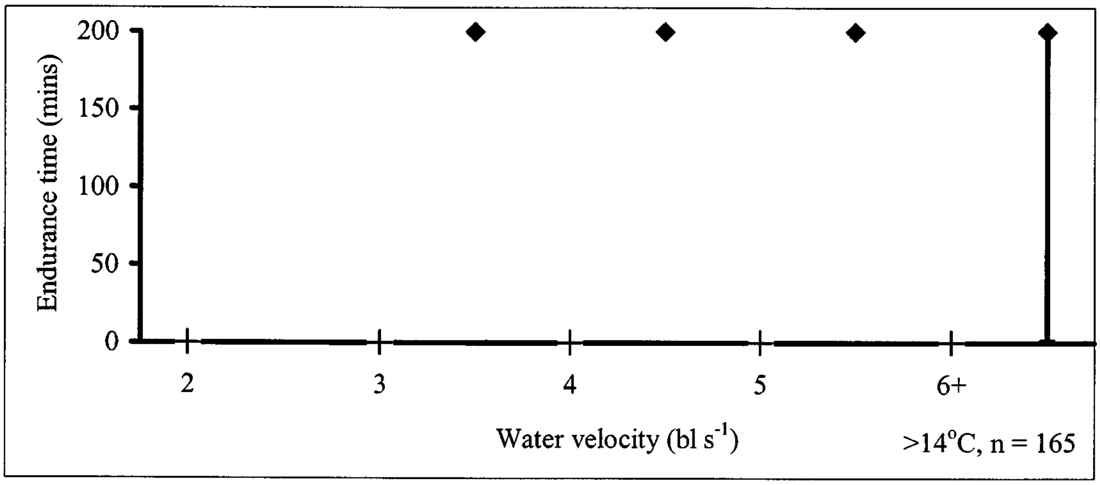


Figure A10 trout c. Median endurance of large trout in three temperature categories.