Environment Agency

Evidence

Field evaluation of combined gauging weir and fish passes

Report: SC070013

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Miranda Kavanagh

Director of Evidence

Executive summary

Under the Water Resources Act 1963, the Environment Agency is required to assess and manage water resources, including implementing hydrometric flow measurement schemes. The most common way of achieving this has been by using in-river, purpose-built flow measurement structures.

The Environment Agency operates a network of over 1000 flow gauging stations throughout England and Wales (Turnpenny *et al*., 2002a). Gauging structures are the most common method of river flow measurement in England and Wales. Of the 1500 flow measurement sites, over 1100 use a structure to act as flow measurement control. Of these, 200 are single crested Crump weirs (triangular profile, horizontal crested), 110 are compound (multi crested) weirs and 322 are triangular profile flat-V weirs. They are needed to enable accurate and reliable flow measurements, which are used to assess abstraction licence applications, discharge consents and ecological flows.

However, these weirs are thought to obstruct free fish migration, thus preventing access to spawning, feeding and sheltering areas vital for different life stages. There is therefore a conflict of interest between the requirements of hydrometry and the requirements of fisheries. As the Environment Agency is responsible for protecting the water environment, as well as assessing water resources, it has become increasingly apparent that both disciplines must work together to incorporate fish migration needs within the design of flow measurement structures, whilst still maintaining accurate and reliable flow data.

An earlier Environment Agency project (SC010027) undertook laboratory-based work to develop a low-cost design for improving fish passage over Crump-type flow gauging weirs. The solution comprised a series of slotted low baffles fitted to the downstream face of the weir, which was predicted to create a pathway up the weir face with sufficient water depth and low enough velocities to enable fish passage over a range of flows. The required velocities conducive to fish passage were estimated using the SWIMIT fish swimming speed calculation tool developed in earlier Environment Agency research (R&D note W2-026 and science report SC00005).

Science reports W6-084TR and SC020053SR2 examined potential impacts of the Larinier Super Active Baffle Fish Passes (LSABFP) on flow gauging structures.
The outputs from those projects enable a Larinier fish pass with 100mm high baffles to be used as a flow measurement device with comparable accuracy to a conventional gauging weir (Gauged flow <5 per cent deviation from theoretical rating). A calibration of the Larinier fish pass with 100mm baffles was determined, with the accuracy required by British and International Standards of less than 2 per cent variation in the coefficient of discharge, up to a head of 0.6m over the weir-crest, or the hydraulic invert of the fish-pass.

The purpose of this research project was to undertake a field evaluation of both the Larinier and low cost baffle solutions in terms of their effectiveness in facilitating fish passage and its impacts on flow gauging accuracy.

The first stage of this study was to provide an assessment of the impact of combined fish passage and flow gauging structures on flow gauging accuracy. Previous research has assessed the fish passage aids in a laboratory setting. This study examined impacts on flow gauging of the low-cost baffle solution at Brimpton compound Crump gauging weir on the River Enborne, Berkshire, whilst the impacts of a retrofitted

Larinier Super Active Baffle Fish Pass on a Crump weir were investigated at Louds Mill Weir on the River Frome, Dorset.

Hydro-Logic was commissioned to undertake analysis of the hydrometric impacts of aids to improve fish passage at flow measurement structures. The project sought to assess the impact on a range of operation and maintenance issues, including hydrometric accuracy, at both trial sites. The key objectives of this study included:

- rating analysis to quantify impact pre- and post-fish pass installation;
- comparison of fieldwork findings with available laboratory research and relevant published standards;
- review of operational concerns, including stage measurement and the impact of debris;
- assessment of impact on flow measurement uncertainties.

The key findings of this element of the study include:

Louds Mill Gauging Station LSABF:

- Excellent fit with laboratory-derived theoretical rating.
- Suitable approach conditions and installation of independent head measurement are critical to performance and should be in accordance with the relevant ISO guidelines.
- The LSABF was subject to debris snagging on the baffles resulting in limited observed impact in the stage record. Regular cleaning and maintenance visits are necessary, incurring additional operational costs.
- Due to the site-specific crest configuration at Louds Mill Gauging Station, the LSABF installation has resulted in an improvement in uncertainties under low flow conditions.

Brimpton Gauging Station Retrofit Baffles:

- The rating review revealed an existing bias in the gauging data relative to the theoretical rating. This remained consistent throughout the pre- and post-installation record.
- A limited range of flows were gauged in a critical area with a 200mm baffle, and there was no significant impact on the previous rating. 120mm baffles were also found to have no impact compared with historical gaugings.
- Available records suggest the baffle installation resulted in limited additional debris snagging.

The following general conclusions were drawn:

- The careful deployment of aids to improve fish passage at gauging weirs has been found to have limited impact on the hydrometric accuracy of the structures tested.
- If well designed and maintained, structures may improve measurement accuracy and uncertainty particularly at low flows.
- Costs of operation and maintenance are found to increase, both through clearance of weed and through operating and data processing costs in the case of an independent head measurement.
- It is believed that the LSABF can be used extensively with little impact on the hydrometric data quality, provided it is well installed and maintained. Care should be taken to ensure that approach conditions are in line with the relevant ISO guidelines. Further work is required to investigate hydraulic performance and modularity at high flows.

- Retrofit baffle arrangements appear to have limited impact on the hydrometric performance of Crump weirs, provided they are accurately installed and well maintained. Further work is required to provide a more comprehensive assessment of performance over the full flow range.

The effectiveness of these two fish pass options in enabling fish migration past these structures was evaluated by analysing the movements of PIT (Passive Internal Transponder)-tagged fish, translocated from upstream of the barriers into the weir pools downstream.

Results from the Brimpton study show that with the aid of the low-cost baffle pass, rheophilic species such as chub and dace and eurytopic roach were able to ascend the weir. Twenty-eight of the 45 chub translocated from upstream of the weir between them made 330 attempts to ascend. Fifteen of these 28 fish (54 per cent) ascended the weir. Many of these successfully ascended on their first attempt.

General levels of activity around the weir and numbers of attempts to ascend the weir were highest during periods of warmer temperatures and moderate flows. In contrast, the number of successful ascents was greatest during elevated flows with lower but still significant success at low flows. There is some suggestion that fish may have used the pass in different ways according to varying flow and conditions on the structure to negotiate what was previously almost certainly a barrier to upstream movement.

A similar exercise entailing capture, tagging and relocation of fish was undertaken around Louds Mill Weir in spring 2009. A minimum of 49 grayling (54 per cent of numbers tagged and released) and 143 trout (71 per cent) were judged to have successfully negotiated the pass.

There was some evidence that small grayling were less able to successfully ascend the pass than small brown trout. The vast majority of the fish that ascended did so within a few hours of release. There was no conclusive evidence that flow or temperature had any significant effect on fish movements.

This work provides clear evidence for the suitability of two solutions for reducing the environmental impact of gauging structures on fish migration and movement. This will enable the Environment Agency to begin to mitigate the impacts of its own activities, in support of its obligations under the European Water Framework Directive and the Salmon and Freshwater Fisheries Act 1975 (Environment Act 1995).

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Contents

1. Introduction

1.1 Obstructions to migration

Water is used for many applications, such as power, flow regulation, irrigation and flood defence (Cowx & Welcomme, 1998), and man-made structures that cause obstruction to fish migration is not a new problem. Since the beginning of the industrial revolution, many rivers throughout Europe have been increasingly subjected to impoundment and weir construction. More recently, weirs have been constructed specially for the purpose of measuring river flows, and some existing structures have been modified for this purpose. This is because accurate measurement of river flows (hydrometry) is necessary to help manage the water resource in order to meet the increasing demands of society and to protect the river environment.

The Water Resources Act 1963 requires the Environment Agency to assess water resources and undertake hydrometry. The Environment Agency operates a network of over 1500 flow gauging stations throughout England and Wales (Turnpenny *et al.,* 2002a). Historically, the most common way of gauging river flow has been to use purpose-built in-river flow measurement structures. These remain the most common method of river flow measurement in England and Wales. Of the 1500 or so flow measurement sites, over 1100 use a structure to act as flow measurement control. Of these, 200 are single crested Crump weirs (triangular profile, horizontal crested), 110 are compound Crump (multi crested) weirs and 322 are triangular profile, flat-V weirs – comprising more than 50 per cent of all structures in use. To ensure consistent, reliable and accurate data, the weir and approach channel must be constructed to produce certain geometrical properties, conforming to BS ISO 3680 standards (Turnpenny *et al.,* 2002a).

The precise physical characteristics of gauging structures are associated with a number of adverse environmental impacts. By altering the hydraulic conditions of the river, they may affect the diversity of habitat and reduce the morphological and ecological status of the river. There is scientific evidence that some of these weirs have a detrimental effect upon freshwater fisheries, by preventing access to spawning, feeding and over-wintering areas vital for different life stages (Pinniger, 1998; Lucas & Frear, 1997). Although such evidence is not available for the majority of individual weirs, it is widely felt that many obstruct free fish migration at a wide range of flows (Turnpenny *et al*., 2002a).

As the Environment Agency is responsible for protecting the water environment (including fish populations) as well as hydrometry, there can be a conflict of interest between the two requirements. Recently it has become increasingly apparent that both disciplines must work together to incorporate fish migration needs within the design of flow measurement structures, while still maintaining accurate and reliable flow data.

1.2 Fish passage past obstructions

River obstructions in Australia have been shown to cause local extinctions and dramatic population declines in migratory percid populations (Harris & Mallen-Cooper, 1994), and have been identified as a cause of population declines of lithophilous and rheophilic cyprinids in European rivers (Baras *et al*., 1994; Ovidio *et al*., 2007; Lucas *et al.,* 1998) with consequences for the performance of recreational fisheries (Axford, 1991). Any new obstructions should ideally be avoided whenever possible, as it is ecologically important for the longitudinal and lateral connectivity of a river system to be maintained. When in-river constructions are unavoidable, the problem can be partly mitigated by constructing a fish pass. Armstrong *et al*. (2004) define a fish pass as:

"Any form of conduit, channel, lift, other device or structure which facilitates the free passage of migrating fish over, through or around any dam or other obstruction, whether natural or man-made, in either an upstream or a downstream direction."

Essentially, these are structures that provide hydraulic conditions that enable fish to pass. The field of fish pass design and construction is now well advanced (Beach, 1984; Clay, 1995; Larinier, 2002; Travade & Larinier, 2002; Armstrong *et al*., 2004). Typical solutions are normally expensive, purpose-built structures either within or circumventing an existing structure or impediment. The Environment Agency National Fish Pass Manual (Armstrong *et al*., 2010) provides design details for all the fish passes currently used by the Environment Agency. Some of the most problematic obstructions for providing fish passage solutions are flow gauging weirs, since incorporation of fish passes into the structures clearly has the potential to compromise gauging accuracy.

The Water Framework Directive is a key driver for improvements in fish passage. It is intended to introduce new legislation; the Environment Agency, the Department for Environment, Food and Rural Affairs (Defra) and the Welsh Assembly Government are in consultation over new regulations that will improve access to spawning, nursery and feeding grounds to all fish species (not just migratory salmonids), by way of fish passes at barriers and screens over intakes/outfalls. This legislation also includes an order on obstructions and screens under section 5.2.2 of the European Communities Act 1972.

Armstrong *et al*. (2004) categorise fish passes as follows: pool passes, baffle fishways, easements, culverts and other river crossings, tidal flap gates and eel passes. The majority have been developed for migratory salmonids, especially salmon and sea trout, due to their economic value and their obvious migratory life cycle. The alleviation of in-river obstructions for populations of coarse fish species has received little attention, despite their ecological and economic importance (Axford,1991). However, there has been a growing understanding of the diversity and extent of coarse fish passage (Aprahamian, 1973; Ovido & Philipart, 2002; Lucas & Frear, 1997; Clough & Ladle, 1997; Lucas *et al*., 1998; Lucas *et al*., 1999a). Some of the most extensive research has been carried out on the River Meuse, Belgium, which concentrates on the influence of river canalisation and damming on the population ecology and migration of barbel (*Barbus barbus* L.) (Philippart *et al*., 1988; Baras *et al*., 1994). It is now evident that many coarse fish undertake migrations to find microhabitats suitable for spawning, feeding and refuge (Lucas *et al*., 1998*)*. This realisation, combined with the popularity of coarse fishing as a recreational pursuit, highlights the importance of making provisions for coarse fish passage within fish pass design criteria.

1.3 Impact of fish passage facilities on flow gauging

An active research and development area within the Environment Agency studies fish swimming behaviour and ability, and design of fish passage facilities that can be incorporated into flow measurement structures. The studies that have been undertaken in recent years are included in the table below:

Table 1.1 Environment Agency reports related to fish passage.

Reference	Date	Authors	Title
C5200	1995	National Rivers Authority	Hurn weir gauging station: re-appraisal of options to facilitate the upstream migration of Dace.
Exeter Enterprises Ltd	1996	Walters	Hydraulic model tests on the proposed fish pass structure for Hurn gauging weir, Dorset.
W2-026/TR1	2001	Clough, S.C. & Turnpenny, A.W.H.	Swimming speeds in fish: Phase 1.
W2-026/TR2	2001	Turnpenny, A.W.H. *et al*.	Literature review of swimming speeds of freshwater fish.
W6-029/TR1	2002a	Turnpenny, A.W.H. *et al*.	Fish passage at flow gauging stations in England and Wales. Stage 1: Literature review and regional survey.
W6-029/TR2	2002b	Turnpenny, A.W.H. *et al.*	Fish passage at flow gauging stations in England and Wales. Stage 2: Fish pass physical model evaluation and field studies.
SC020053/SR1	2003	White, W.R. & Woods-Ballard, B.A.	The investigation and specification of flow measurement structure design features that aid the migration of fish without significantly compromising flow measurement accuracy, with the potential to influence the production of suitable British standards.
W2-049/TR1	2004	Clough, S.C. *et al.*	Swimming speeds in fish: Phase 2.
Joint Hydrometry And Fisheries Fish Passage Group.	2004	Armstrong, G. & Iredale, R.	Guidance on the design and construction of Crump and flat-V gauging weirs in relation to fish passage.
W2-049 TR3	2004	Clough. S.C. *et al.*	Swimming speeds in fish: Phase 3.
SC020053/SR2	2005	White, R., Bowker, P. & McGahey, C.	Flow measurement structure design to aid fish migration without compromising flow data accuracy.
SC030230/SR	2005	Zaidman, M.D., Lamb, R., Mawdsley, J., Lawless, M.R., Archer. D.R. & Melching, C.S.	Non-invasive techniques for river flow measurement.
PhD Thesis Cranfield University, Shrivenham	2006	Servais, S.A.	Physical modelling of low-cost modifications to the Crump weir in order to improve fish passage: Development of favourable swimming conditions and investigation of the hydrometric

Reference	Date	Authors	Title
			effect.
SC010027	2008	Rhodes, D.G. & Servais, S.A.	Low cost modifications of the Crump weir to improve fish passage.

The earliest of these studies was carried out in search of a solution for passage of dace at a weir in South West England The flat-V weir at Hurn, on the Moors River in Dorset (NRA, 1995; Walters, 1996) is an example of modifications made to an existing structure. A number of solutions were investigated before a baffled solution, known as the Hurn-type baffle system (Armstrong *et al*., 2004), was installed on site following laboratory trials. A series of baffles with slots and notches have been fixed to the downstream apron of the weir (Walters, 1996). Although anecdotal evidence suggests that this fish pass is successful at least for salmonids, conclusive results have yet to be published and there is currently no evidence that coarse fish can successfully use these structures.

Turnpenny *et al*. (2002a & b) began to look more systematically for solutions that would be accepted both hydrometrically and environmentally. Phase one provided a technical review of the subject and looked at the extent and importance of fish passage problems associated with flow gauging stations in England and Wales. Phase two dealt with identification of possible solutions by modelling several fish pass designs for new and existing structures in the laboratory. Three types of fish pass were investigated: the plain-baffle Denil pass, the Larinier ('super active baffle') pass and the pool-and-traverse pass. The field investigations showed that all three types of fish pass would potentially be capable of meeting the accuracy criteria for flow measurement, other than at low flows (that is, below the normal minimum design flow for a fish pass). Removal of the two topmost baffles in either the Denil or the Larinier passes was expected to improve gauging performance. This could however potentially reduce fish pass efficiency as the velocities would be increased by 11-13 per cent.

White & Woods-Ballard (2003) and White *et al* (2005) looked specifically at how standard hydrometric structures could be adapted to aid fish migration without significantly compromising flow measurement accuracy. The report reviewed the problems of trash build-up at fish passes, and ways to minimise it. It also made several key recommendations in relation to both low-cost retrofits of fish passage facilities such as the low cost baffle solution (Servais 2006) at gauging weirs using 'baffle'-type easements, and technical, new build solutions. New build solutions were addressed by White *et al.* (2005), and included the modelling and design for a combined flow gauging and fish pass structure as recommended in White *et al.* 2003, and identified the Larinier design as the most promising approach. The report provides guidance on site selection, necessary installation conditions, and assesses different gauging and fish pass structures detailing specific design parameters, and provides a hydrometric standard discharge relationship for the 100mm high Larinier fish passes, later adopted as the BS ISO standard BS ISO 26906.2009.

The studies of swimming speeds in fish (Clough & Turnpenny, 2001; Clough *et al.,* 2004) were also an integral part of this work. These studies created a fish swimming speed database, SWIMIT, which provides information on both burst and endurance (sustained swimming) speeds of a total of nine species of fish, as well as a description of the techniques associated with obtaining them. The swimming performance of fish depends on many factors, including:

- species;
- individual size and ability;
- water temperature;
- water depth;

• water velocity;
• water quality;
• turbulence;
• motivation.

Clearly the effectiveness and efficiency of a fish pass structure will be intrinsically linked to the swimming capabilities of the fish species attempting passage, both in terms of swimming velocity and endurance. Successful ascent of passage facilities is dependent on achieving a fast enough speed relative to the riverbed for a sufficient length of time.

1.4 The low-cost baffle solution.

Concurrently to work by White *et al.*, a PhD study by Servais (Servais, 2006; Rhodes & Servais, 2008) undertook laboratory-based research to develop a retro-fit fish passage solution for a Crump gauging weir. The study focused on the hydrometric effect generated by the placement of baffles on the downstream slope, which provided favourable swimming conditions (Clough & Turnpenny, 2001; Turnpenny *et al.,* 2004) thus improving fish passage.

Brimpton Weir on the River Enborne near Reading was chosen as a suitable site on which to base the laboratory modelling tests of the low-cost baffle solution, as a very similar weir on the River Loddon had been previously shown to obstruct coarse fish migration (Pinniger, 1998). The preferred arrangement was found to be a series of baffles fitted on the downstream slope of the Crump weir. Each baffle contained a slot with the slots arranged in a 'rotated-V' layout, which helped form a path of ascent for fish. The baffles effectively acted as mini-weirs each with a free gap, creating lower velocity and retaining depth at low flows, and creating roughness elements important at high flows (Servais, 2006). This design required that the baffle closest to the crest be set at the same height as the crest, as this led to optimum low velocities in the slots on the downstream slope.

In response to the results obtained from the studies above, the current project intends to further the work carried out by Servais (2006) and Rhodes and Servais (2008), by undertaking field trials of the rotated-V baffle arrangement at Brimpton Weir on the River Enborne.

1.5 A Larinier Super Active Baffle Fish Pass

Loud's Mill Weir on the river Frome in Dorset was chosen as an example of a retrofitted Larinier fish pass onto an existing gauging weir. Full-scale field trials are essential for producing evidence to support the lab-based study, not least because models cannot account for full-scale effects such as aeration. Larinier fish passes are suitable for a wide range of weir types other than flat-V and Crump gauging weirs, and so field assessment of their efficacy is particularly valuable.

1.6 Objectives

The overall objectives of the project are to assess:

- Whether an obstruction to migration, a small gauging weir on the River Enborne, can be alleviated by installing low-cost baffles, without compromising gauging integrity.

a) Whether a Larinier Super Active Baffle Fish Pass is effective in enabling passage of the full range of fish species and sizes present in the Frome around Dorchester and what impact the structure has upon flow gauging activity at the weir.

Field trials were carried out in order to:

- Undertake a study of the hydrometric features of the modified structures and assess the impact of the installed baffles on gauging accuracy and operational performance of the weir.
- Analyse movements of fish at each weir, to determine whether they are able to use the passes. This was carried out using PIT tag detection equipment and cameras to monitor the movements of fish translocated to the area immediately downstream of the weir.
- Provide an assessment of the effectiveness and efficiency of the two fish passes. Efficiency was assessed by comparing the number of fish attempting to ascend the weir with numbers eventually successful. Where possible, inter-specific differences and differences between fish from different locations were also analysed with regards to attractiveness and usage of the fish passes.
- Provide an assessment of the effects of environmental variables (temperature, flow and photoperiod) upon the stimulation of fish movement and passage through the weir structures.
- Produce an overall assessment report that makes recommendations on the effectiveness of this approach for both gauging and overcoming an obstruction to fish movement.

2. Field evaluation of impacts on flow gauging of aids to fish passage

2.1 Introduction

For some years, the Environment Agency has been concerned about the conflict between flow measuring structures and the movement of fish. This has resulted in the Environment Agency commissioning a considerable amount of research into the installation of aids to assist fish passage at gauging structures.

The research work undertaken to date has been primarily theoretical and laboratory-based. The practical application of these structures in the field may differ considerably to lab-based models, and the uncertainties and impact of natural variables such as debris and algal growth may alter the hydrometric performance of the gauging station following the construction/installation of any fish passage aid. Measurement of downstream head for periods of drowned flow is also much more difficult in the field compared to controlled laboratory conditions.

This project seeks to assess the impact of aids to fish passage on the hydrometric performance of flow monitoring structures at trial sites and also the potential impacts relating to operation and maintenance requirements.

Two sites were identified by the Environment Agency for investigation:

- Louds Mill Gauging Station on the River Frome (Dorset) (NGR: SY708903):

The Louds Mill structure incorporates two existing Crump weirs: a main weir and side weir. Informal broad-crested abutments flank the main structure. A Larinier fish pass, situated adjacent to the left bank, was completed in autumn 2008. It is believed to have been designed largely in accordance with the laboratory-based theory (White *et al*., 2006; BS/ISO 26906:2009). The exception to this is length of approach which, at 3.9m, does not meet the requirement for a minimum approach quoted in BS / ISO 26906:2009 of ‘at least five times the width of the fish pass, with greater lengths for approach through a bend or at an angle’ – that is, a minimum of 9m.

- Brimpton Gauging Station on the River Enborne (Berkshire) (NGR: SU568648):

The Brimpton structure is a compound Crump weir, with low flow and high flow crests separated by a formal divide pier. The structure was retained in its existing form and a low cost baffle fish pass installed on the downstream face of the low flow crest in March 2008. Replacement baffles were subsequently installed in February 2010.This site was previously the subject of a detailed study of baffle placement as part of a research PhD on the hydrometric effects of fish passage (Servais, 2006). The subsequent baffle configuration and installation was based on this theoretical design.

2.2 Background

The overall objective of the project is to confirm, or otherwise, the results of the earlier theoretical work and laboratory research and investigate whether or not aids to fish passage have a detrimental impact on the performance of flow measurement structures in situ. White *et al.* (2006) reported on this initial research, undertaken to inform future environmental measures to improve the movement of fish while maintaining the integrity and measurement quality of flow measurement structures.

Previous research has focused on the:

- desk-based study of combined uncertainties;
- a review of the problems of trash;
- laboratory tests to provide accurate hydrometric calibration of Larinier Super-Active Baffle Fish pass (LSABF);
- laboratory research into the baffle arrangements close to the crest of measurement structures;
- laboratory testing of a LSABF set alongside a hydrometric structure.

Initial research was based on technical theory and laboratory work while only limited research has been conducted on in-situ fish pass and flow measurement structure combinations.

The current project seeks to develop this research to include performance checks on a LSABF and a low cost baffle solution, as implemented at existing flow measurement structures.

This report outlines the findings of this analysis work and provides a series of recommendations for future maintenance of these sites and for subsequent applications of fish passes at other flow measurement structures.

2.3 Louds Mill Gauging Station

2.3.1 Site description

Louds Mill is located on the outskirts of Dorchester and consists of two Crump weirs, one on the main channel and one on a side channel. The main weir is constructed at right angles to the flow in the main channel, effectively forming a spillway on the left bank of the channel, and is flanked by informal broad-crested abutments. The side weir is located to the right of the main crest, immediately before the side channel passes under a mill building. A Larinier fish pass (LSABF) has been constructed adjacent to the left bank of the main weir crest and cutting through the left abutment (see Figures 2.1, 2.2 & 2.3).

The catchment of the River Frome above Louds Mill is predominantly rural and mainly on chalk bedrock. However, the upper catchment includes some Greensand and Gault that may contribute to a flashy response following intense and sustained rainfall events, largely dependent on the catchment condition.

The total flow for the River Frome at this location is reported as a summation of the Louds Mill weirs and a further weir located at Stinsford gauging station, this is on a separate side channel of the main River Frome that rejoins shortly downstream of Louds Mill Gauging Station. This gauging station is located on the far side of the flood plain (NRFA, CEH data holdings website) (see Figure 2.4). The site will now incorporate a further summation of the fish pass, treated as a separate gauging station.

Figure 2.1 Louds Mill main weir and Larinier fish pass

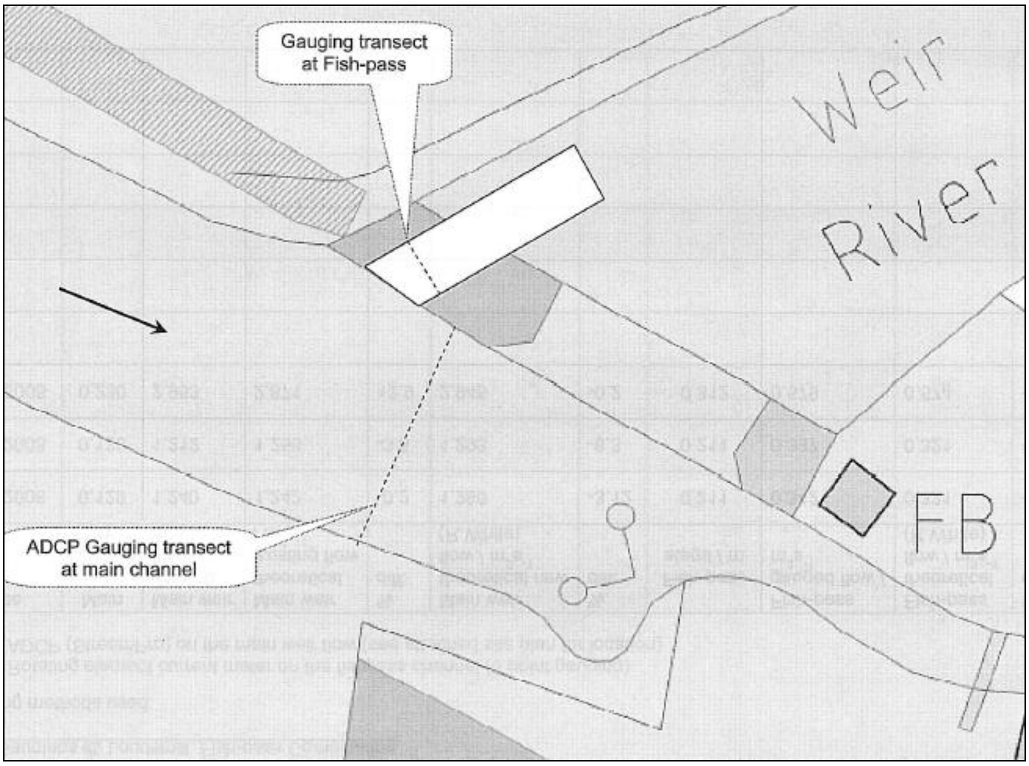


Figure 2.2 Relative site layout at Louds Mill (following construction of fish pass)

Figure 2.3 Arial view of the Louds Mill site

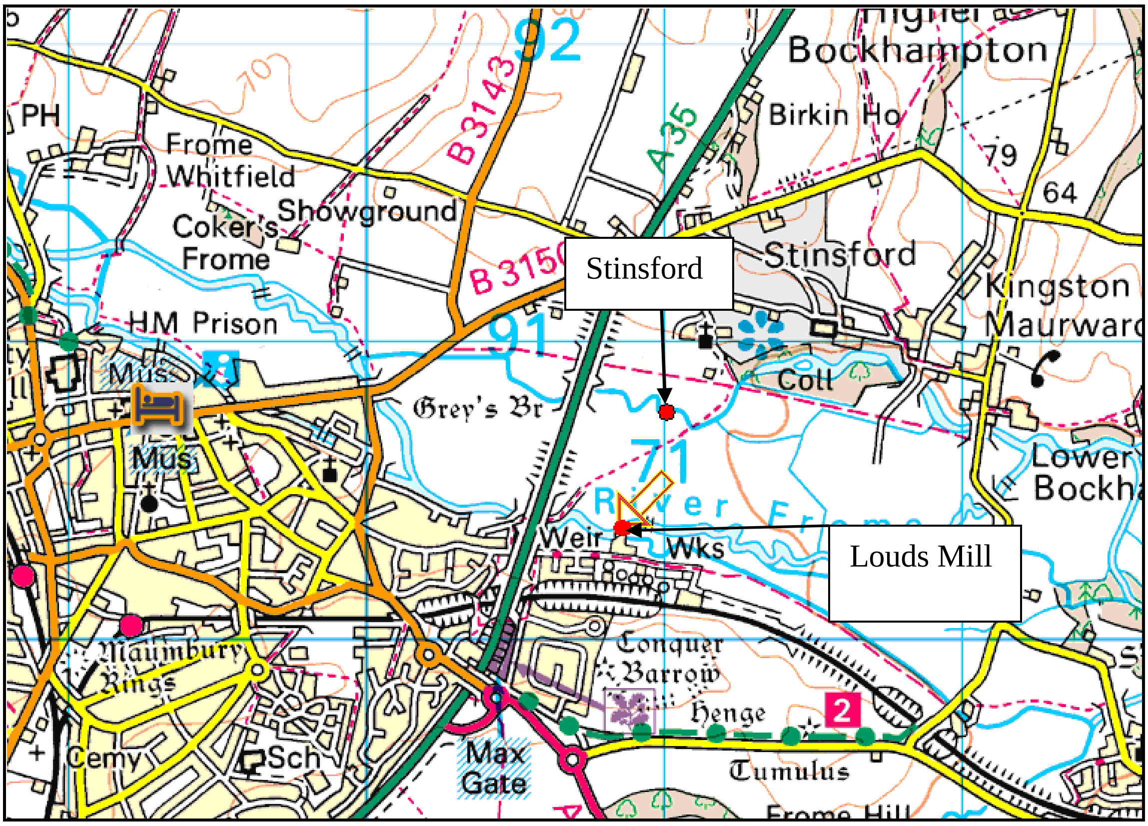


Figure 2.4 Site location (indicating Louds Mill and Stinsford)

2.3.2 Initial site survey: Louds Mill

Construction of the main structure at Louds Mill was completed in 1969 and the fish pass subsequently added in autumn 2008. A full cross-sectional survey was undertaken by the Environment Agency in August 2008 and made available for the project. As-built dimensions were gained for the fish pass, together with check measurements for the other control structures. Further spot levels were measured as part of the calibration work. This incorporated a number of dip points to assess the potential impact of local hydraulics around the structures. Post-construction access to the uppermost fish pass baffles is limited by safety grids and the associated support beams and railings. This constrained the extent of post-installation surveying that could be undertaken, although some checks were possible in the approach channel where the safety grids can be lifted for access.

The initial walkover survey was undertaken by Graeme Peirson, Geoff Hardwicke, Richard Iredale and Owain Wynne-Jones of the Environment Agency, together with Nik Whalley and Martin Dibley of Hydro-Logic. The walkover survey familiarised the consultant with the site layout and informed the requirement for verification/calibration work and additional information. The survey also provided an opportunity to discuss the available data and review the site history with Geoff Hardwicke (Area Team Leader, Hydrometry and Telemetry).

A brief health and safety risk assessment was undertaken and compared with the health and safety constraints and requirements already in place at the site. Access routes to the instrumentation kiosks and the gauging locations were identified. Access via the agricultural merchants was assessed and confirmed as suitable and safe.

The site visit also provided an opportunity to review the potential for bypass and further elements where there may be concern, such as level measurement for the main crest. This provided valuable context for the detailed monitoring stage and helped to focus subsequent visits to ensure a comprehensive record of the areas of concern could be achieved.

2.3.3 Data collation

In summary, a relatively comprehensive historic data record is available for Louds Mill, providing a useful resource for comparison of the current and historical records pre- and post-fish pass construction.

Table 2.1 provides a summary of items requested prior to the completion of this report to enable a full assessment of the fish pass to be undertaken. An indication of whether these were available/received and comments on the level of detail and the relevance of each item are provided.

Table 2.1 Summary of data availability for Louds Mill

Relevant data requested	Received	Comment
Design drawings of the original structures and the aids to improve fish passage, and as-built dimensions, where they exist	Yes	Full survey and a record of historical surveys including detailed measurements
Instrumentation details including set-up and historical records e.g. maintenance, replacement	Part	No full record of instrumentation and datum points. Good records of maintenance but no full record of equipment types and setup dates
Gauging station histories	Yes	Full station history file provided in good order with all relevant information and problems in the station history outlined
Stage-discharge and rating history	Yes	Good historical record of previous ratings and dimensions of both weir structures. Relevant checks against gauging
Current and historic ratings, how they have been derived and any supporting information	Yes	New rating report provided with details of survey and available check gaugings
Maintenance schedules/logbooks	Yes	Full record of station logs in good order. Comprehensive notes made available
Photographs of the structures, preferably over a wide range of conditions, particularly at extreme low and high flows which may not be experienced during the study period	Yes	Could be more digital images available and covering a range of flow conditions. Need to confirm at what point does it bypass and where are the spill points. More of fish pass including debris. Possible disposable camera kept with diary in kiosk ?
Any additional anecdotal evidence regarding the operation of the structure prior to and following the installation of aids to improve fish passage, e.g. noticeable changes in velocisty distribution, debris accumulation, geomorphological impacts	Yes	Excellent record of debris accumulation both on station notes and through on-site diary filled out by ops and other site personnel. Record of velocity distribution would be valuable through ADCP ASCI outputs. Flow directions could be derived in a similar way

Historical data from the site, including previous surveys and analyses, was collated and assessed to determine what further information was required. The data for the site was found to be comprehensive with a good level of detail on historical ratings and reviews of flow data. Subsequently detailed design drawings of the Larinier fish pass were also available and used to inform the detailed analysis.

The CEH National River Flow Archive (NRFA) provides station summary data including summary flow statistics for the site. The station is reported to have a mean flow of 3.07 cumecs (m^3s^{-1}) , a Q10 of 6.116 cumecs and a 95 per cent exceedance of 0.866 cumecs. However, it should be noted that this is recorded as a Dorchester total and includes not only the two weirs at Louds Mill but also a further Crump weir at Stinsford. Analysis at Louds Mill is therefore not directly comparable to these statistics. The high flows record also indicates some concern over bypass at high flows. This was confirmed by the area hydrometry and telemetry team leader and is likely to impact on uncertainty at the upper limits of the rating.

The NRFA lists a peak flow of 32.5 cumecs for the station. However the main weir is detailed as having a modular limit of 10 cumecs and the site survey and analysis of historical photos reveal that the site is subject to considerable bypass during high flow events. A note in the station history file indicates that in January 2002 a number of small channels and hatches were observed as feeding an upstream offtake and that consent exists to divert water into these at high flows. This may artificially reduce the hydrograph peak of a high flow event at Louds Mill.

The station was constructed in 1968 and data is available from January 1969. It appears a good standard of data is available up to the present day, though data is missing for 1975. The daily mean flow data provides an excellent resource and is invaluable in assessing the lower limits of the site and informing uncertainties during the preliminary assessment.

2.3.4 Work undertaken

Analysis at Louds Mill included a desk-based study to form a working knowledge of the site, followed by field-based data collection and analysis to assess the potential impact of the fish pass.

The station history was assessed alongside the previous rating work at the site and the fish pass design.

The fieldwork sought to confirm the theoretical ratings for the site. Spot flow gaugings were undertaken at the fish pass structure and on the main channel upstream of the two original weir structures. These gauged flows were used to assess the suitability of the theoretical ratings for each of the three structures.

The analytical work included assessment of the uncertainties at the site, further assessment of the ratings, and analysis of the operational constraints on the site, including debris, modularity and head measurement.

2.3.5 Rating review

Historical rating analysis

The initial rating for the site appears to plot relatively accurately and a review of the theoretical flow plotted against the gauged flows shows a reasonable correlation. The station history files indicate that the offset of the lower mill offtake crest below the main weir crest caused some initial calibration issues but later surveys have shown correlation within expected parameters.

Theoretically, the main Crump weir at the site does not strictly conform to British/International Standard as it is located at right angles to the direction of flow in the approach channel. Velocity distributions in the upstream channel appear relatively uniform at low flows and therefore the weir is likely to perform quite well through low to medium flows. At higher flows the angle of approach causes the flow to exhibit considerable skew and the rating is likely to underestimate flow as the head of water is not even across the crest of the weir. This appears to be confirmed by the apparent deviation in the gauging at high flows, shown in Figure 2.5. Difficulties in stage measurement may also contribute to this problem.

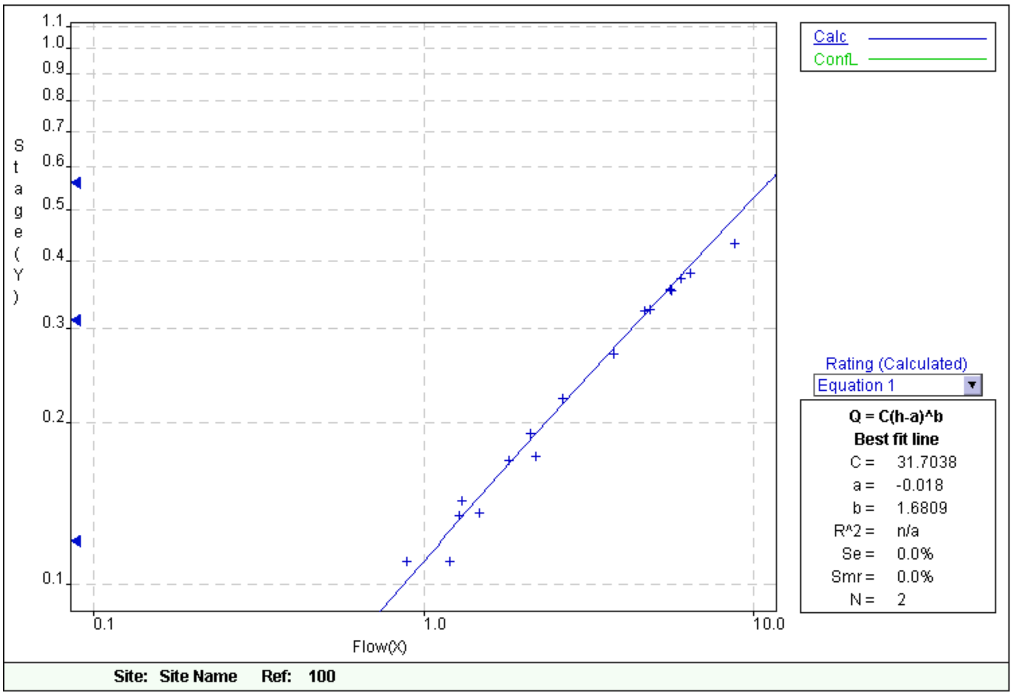


Figure 2.5 Rating and available gaugings prior to fish pass construction

N.B. – Please note that 'ConfL' refers to confidence limits that can be displayed on the graphs, these have been removed to improve the clarity of the graph.

Deviation plots of the rating from the gaugings relative to stage and date of the historical data prior to fish pass construction are shown in Appendix A.

The existing rating for the site appears to plot relatively well with a fair to good relationship with the gaugings over the past eight years. Scatter is generally within +/-10 per cent with some outliers at 15 to 18 per cent deviation, most notably at lower flows.

It appears only one gauging was undertaken between 2001 and 2007. It is generally recommended that, even once calibrated, a minimum of two gaugings per year are undertaken for verification purposes, ideally at different flows.

Fish pass rating analysis

The new LSABF has a separate crest and level measurement facility. As such the fish pass should be treated as a separate structure and individual gauging station. This is of particular note as the floating trash boom is observed to create a change in stage between the main channel and the fish pass approach channel, together with some additional turbulence. HR Wallingford produced a rating table for the site applicable to a separate level measurement. Operating a separate head measurement point also reduces uncertainty, as the level does not need to be transposed.

The crest of the fish pass is treated as the invert of the lateral section of the top baffle. This was surveyed as an element of the post installation checks. Whilst a variation of up to 5mm across the baffles was found, it is possible that this may be a function of the accuracy with which it is possible to survey a complex structure. The variation was not found to be incremental across the lateral width of the baffle.

The fish pass rating has been based on the theoretical rating work carried out on Larinier baffle fish passes (White *et al.,* 2006). This has provided the basis for the theoretical background for parts of the international standard (British Standard, 2009).

A rating table has been provided by HR Wallingford for use in the water management information system WISKI to gain derived flow values. This has subsequently had a rating curve fitted as an element of the analysis phase. The fitted line is within +/-0.5 per cent of the theoretical data points throughout the stage range. This rating will hereafter be referred to as the 'HR/Environment Agency existing theoretical rating'.

As part of the uncertainty analysis it was necessary for flow to be calculated by hand from the relevant standard. These calculations revealed a discrepancy of around 1 per cent from the HR/Environment Agency existing theoretical rating, following a full 20 iteration calculation. To accurately reproduce the flows provided in the HR Wallingford report an additional 100mm is required on top of the surveyed p-value – the difference between the upstream bed in the head measurement section and the cease to flow point on the control. If it is assumed that the baffle height has been double counted, the recalculation creates an almost perfect match. Although the current difference only creates an impact of approximately 1 per cent, which would be lost in gauging uncertainty, it is recommended that the rating be revised to correct the current error and minimise uncertainties as far as possible.

In light of this recalculation, a full theoretical rating was produced using the as-built survey dimensions and a line subsequently fitted through the points to display the theoretical rating. It is recommended that the Environment Agency migrate to this recalculated rating to minimise uncertainty in flow measurement. This rating has been used to analyse the gaugings and is referred to throughout as the 'proposed theoretical rating'.

This fitted rating curve is within 0.5 per cent of the theoretical rating for most of the stage range and within 3 per cent below a stage of 30mm. At these very low stages there is greater uncertainty and it would be expected that there would be a change in the relationship due to boundary friction effects. This is also lower than the theoretical threshold, below which the rating for either a Crump weir or rectangular thin plate weir has not been tested and is therefore not covered by the relevant standard.

The figures below show the theoretical points calculated by Hydro-Logic compared to the proposed theoretical rating curve and the associated percentage deviation in flow between each dataset. The slightly elevated deviation below 0.1m is a product of the change points required to gain an accurate rating fit to the theoretical data points.

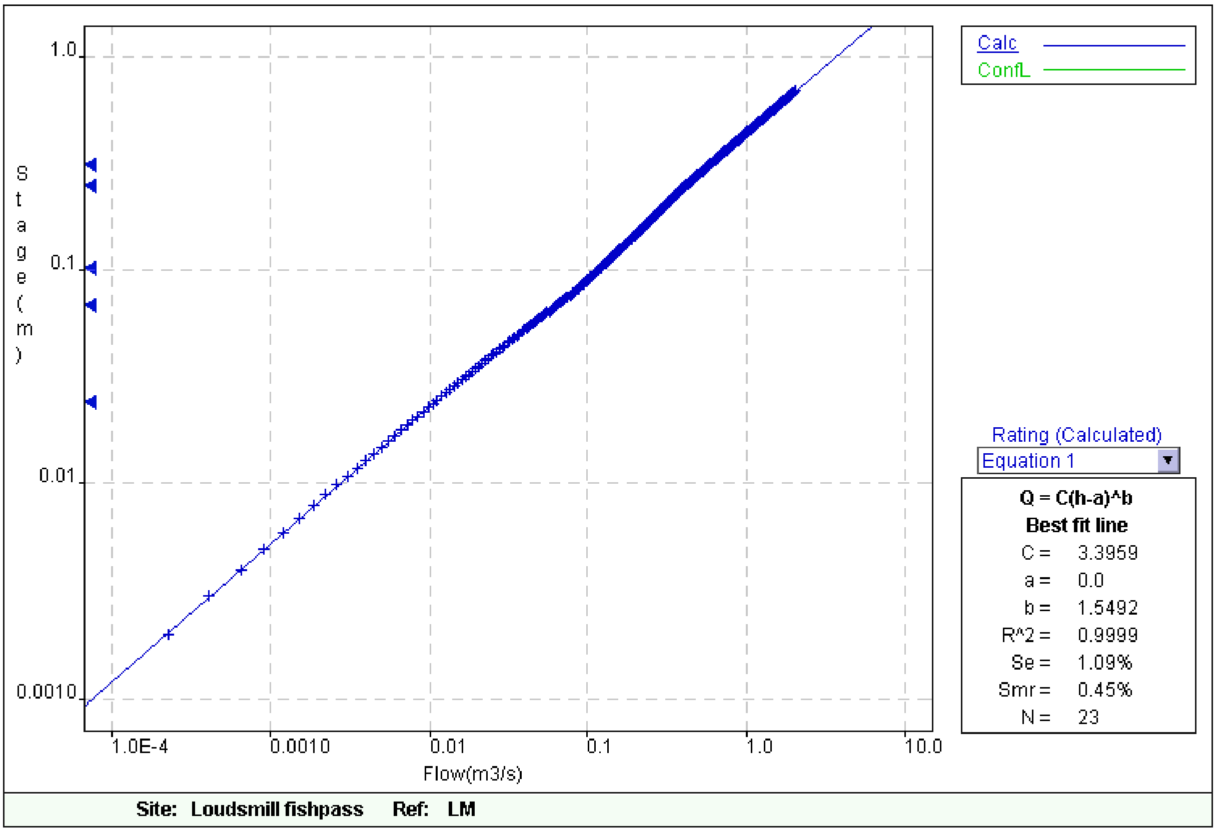


Figure 2.6 Theoretical values with proposed theoretical rating curve

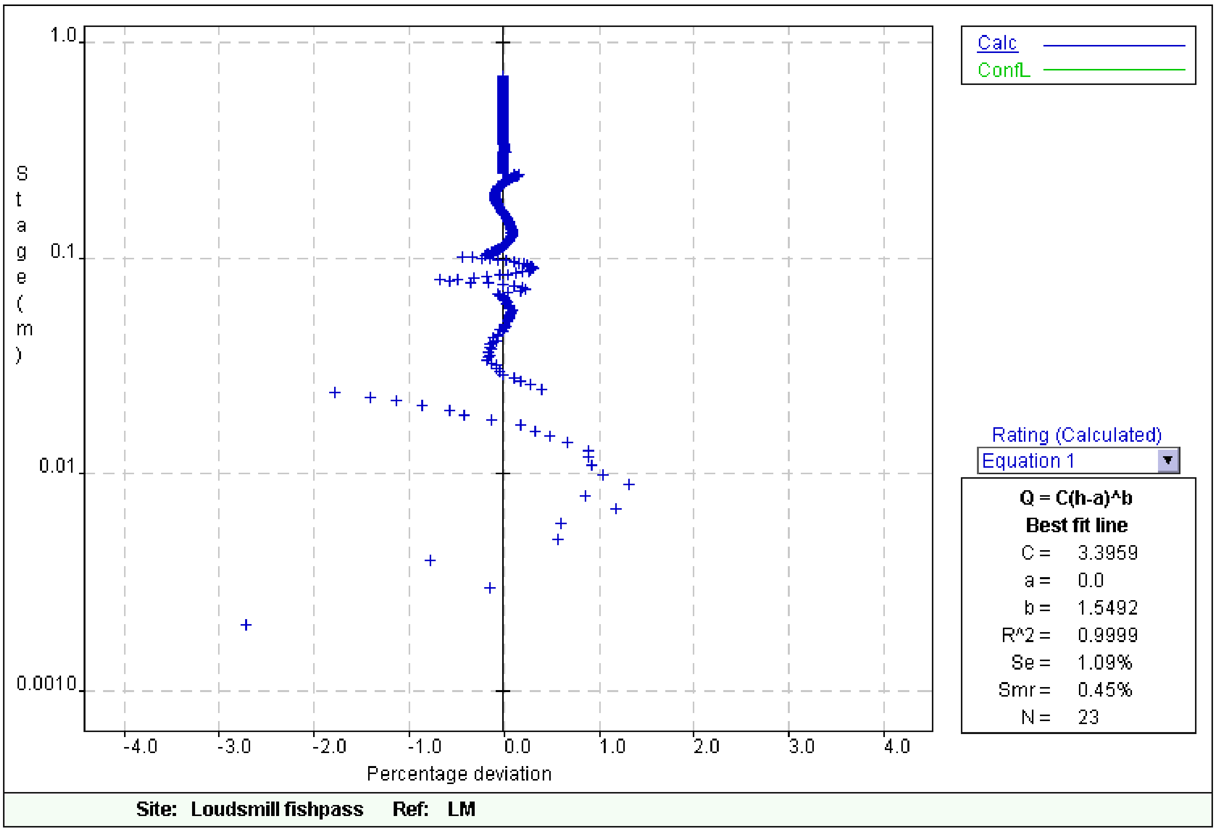


Figure 2.7 Theoretical values deviation from proposed theoretical rating

The gaugings undertaken within the fish pass approach plotted against the proposed theoretical rating for the site are shown in Figure 2.. The analysis reveals an excellent fit with the theoretical rating, performing very well throughout the majority of the gauged range. This is a particularly strong relationship considering the potential for turbulence in the relatively short approach to the gauging section. A slight deviation occurs towards the upper stages, which is discussed in more detail below. However, generally deviation is within +/-8 per cent, which is within the expected tolerance of current meter gauging, and shows no evidence of bias.

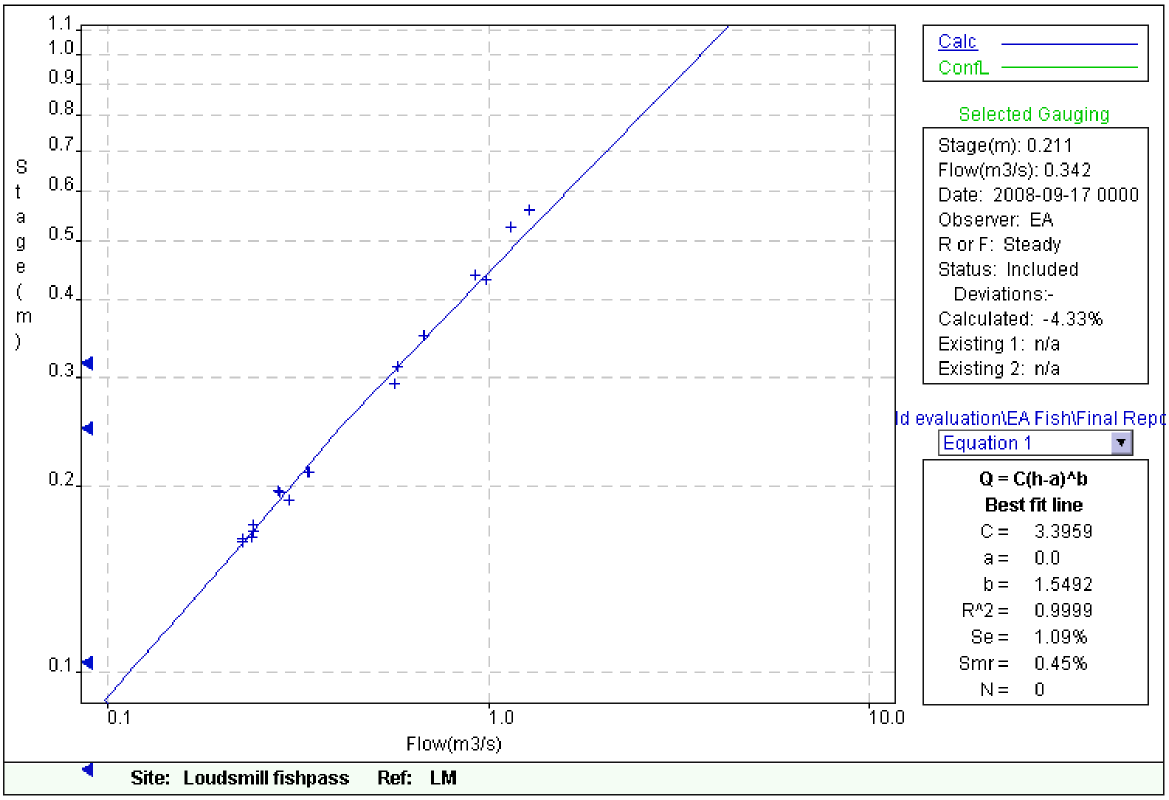


Figure 2.8 Proposed theoretical rating compared to gaugings

The plot of deviation of the proposed theoretical rating from the gaugings in relation to stage illustrates a poorer fit for the highest two gaugings, but reveals no other potential problems. The deviation by date also does not appear to show any significant patterns. The potential issue with the two highest gaugings is discussed in greater detail at the end of this section.

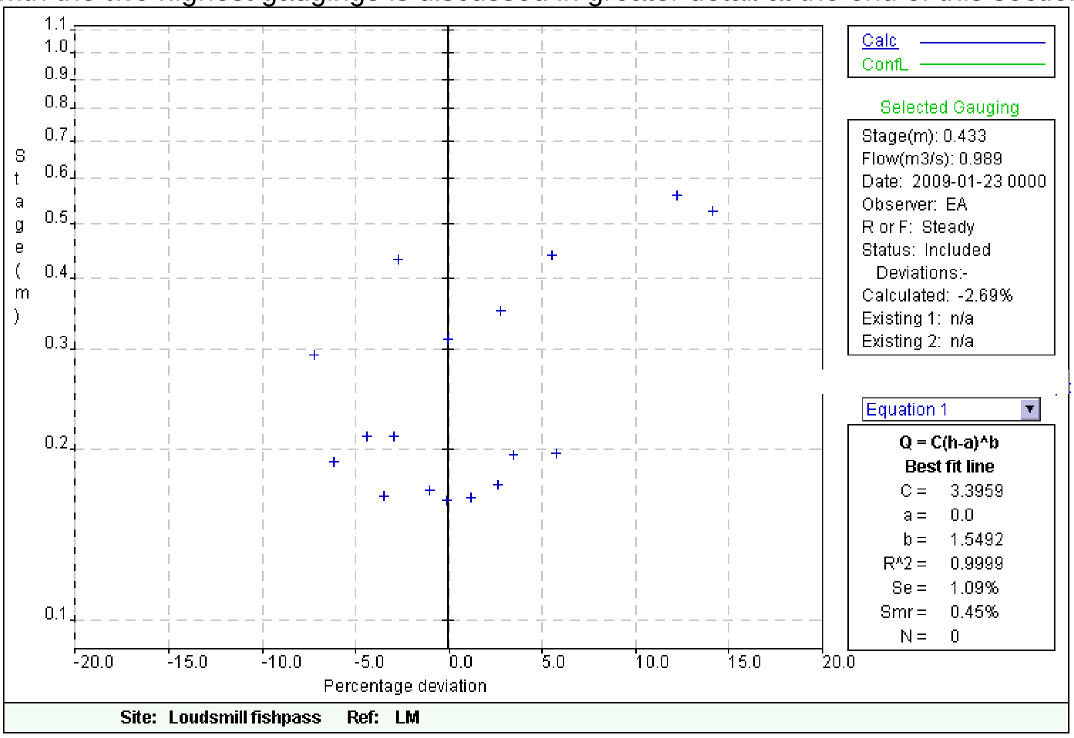


Figure 2.9 Proposed theoretical rating percentage deviation of gaugings against stage

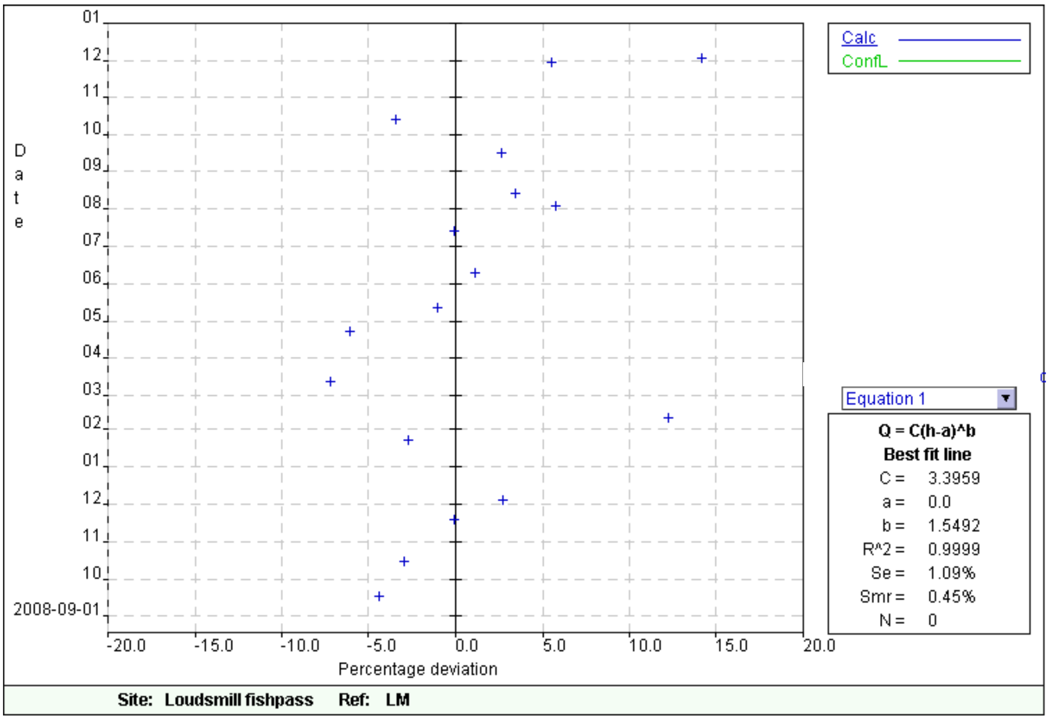


Figure 2.10 Proposed theoretical rating percentage deviation of gaugings against date

The table below provides the set of rating curves that Hydro-Logic have fitted to the calculated theoretical points, this will give values to approximately 0.5 per cent of the theoretical relationship for stages greater than 30mm. A tabulated form of the Hydro-Logic theoretical rating, showing flow associated with stage at 1mm increments, is provided in Appendix B.

Table 2.2 below provides ranges and limits for the proposed theoretical rating equation in the form:

$$Q=C(h-a)^\beta$$

Where:

Q = Flow
h = Stage
C,a, β = Constants dependant on stage

H_{min}	H_{max}	C	a	β
0.000	0.024	3.395913	0.000	1.549158
0.024	0.069	9.009191	-0.005	1.900940
0.069	0.103	1.116080	0.040	0.808239
0.103	0.248	2.555513	0.014	1.265264
0.248	0.316	3.516580	-0.008	1.583282
0.316	0.700	3.517262	-0.013	1.605091

Table 2.2 Proposed theoretical (fitted) rating for fish pass

The difference between the HR/Environment Agency existing theoretical rating and the proposed theoretical rating are very slight (see Figure 2.11). Both fitted lines are shown against the gaugings with a barely discernable difference, the proposed rating is shown in blue and the

HR/Environment Agency existing theoretical rating is in red. For consistency with the published standards, and as an example for future sites, it is recommended that the proposed theoretical rating be adopted.

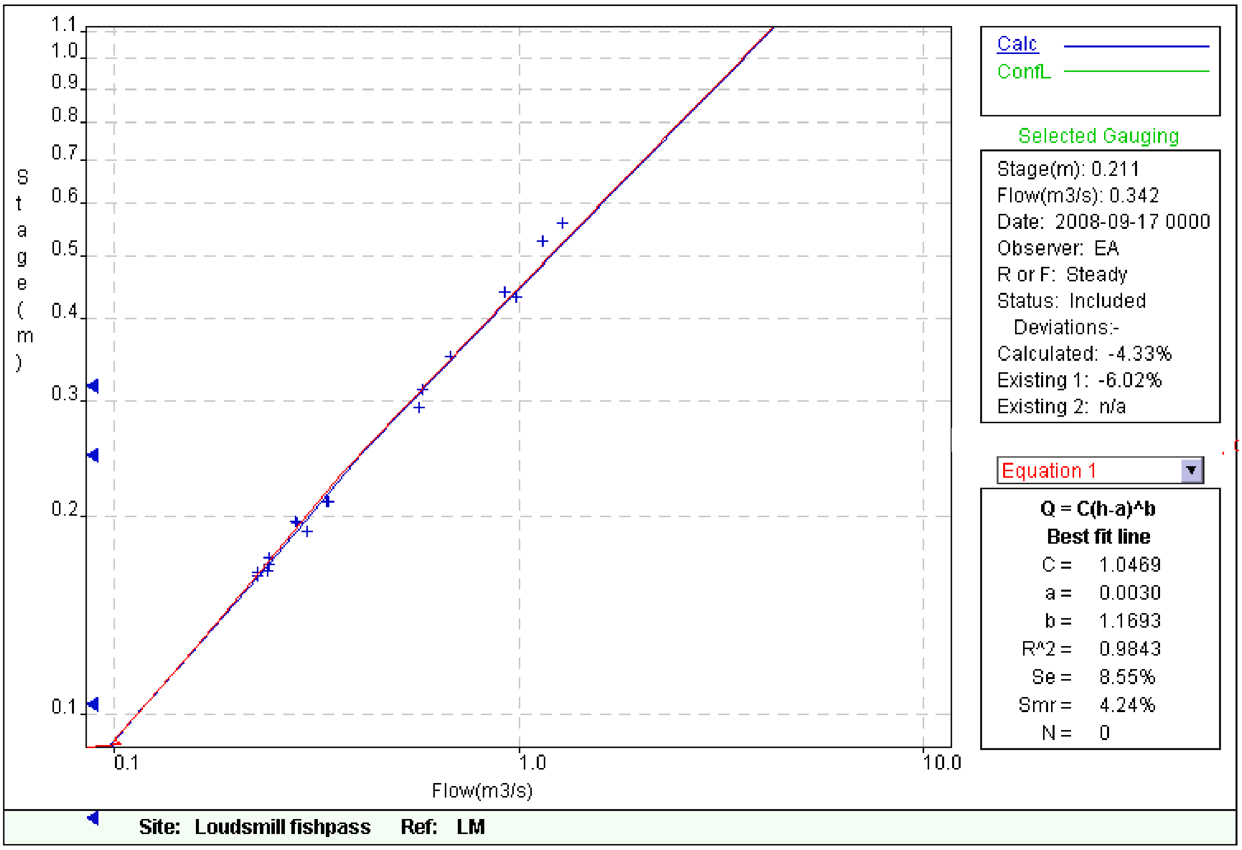


Figure 2.11 Comparison of theoretical ratings

While the Larinier fish pass is designed to assist fish passage it is also vital that where it is deployed at flow monitoring stations, it provides an accurate record of flow. Table 2.3 provides a record of the percentage deviation of the gauged flows from the proposed theoretical rating. The two gaugings marked with an asterisk show the greatest deviation and occur at the highest stages.

Date	Stage (m)	Gauged flow (m^3s^{-1})	Theoretical flow (m^3s^{-1})	% difference
17/09/2008	0.211	0.3420	0.3274	4.46
15/10/2008	0.211	0.3370	0.3274	2.93
19/11/2008	0.312	0.5790	0.5789	0.01
05/12/2008	0.352	0.6787	0.6977	-2.72
23/01/2009	0.433	0.9890	0.9624	2.76
10/02/2009	0.562	1.2890	1.4469	-10.91*
12/03/2009	0.294	0.5690	0.5282	7.72
22/04/2009	0.190	0.3020	0.2839	6.36
12/05/2009	0.169	0.2440	0.2416	0.98
10/06/2009	0.164	0.2290	0.2318	-1.19
14/07/2009	0.162	0.2280	0.2278	0.07
04/08/2009	0.197	0.2817	0.2983	-5.56
14/08/2009	0.196	0.2860	0.2962	-3.46

16/09/2009	0.173	0.2430	0.2496	-2.63
14/10/2009	0.165	0.2420	0.2337	3.54
30/11/2009	0.439	0.9313	0.9833	-5.29
03/12/2009	0.527	1.1455	1.3082	-12.44*

Table 2.3 Percentage deviation in flow in the fish pass channel

Due to the turbulence in the approach it is recommended that, where possible, a longer approach channel should be included when designing LSABF at other monitoring sites. It is recognised that at many sites this will be constrained by the existing site layout. The inclusion of a boom in the design at Louds Mill appears to help reduce debris snagging, but appears to increase the hydraulics in the approach channel. In particular, a drawdown affect is observed immediately downstream of the boom. Any such impacts will be specific to the configuration of each site. As such, the assessment of the potential impact of the boom at Louds Mill was not included as part of this study.

The application of the Larinier fish pass in the field introduces the potential issue of non-modularity. It is not practically feasible to measure the downstream head within the fish pass and therefore correct the data from periods when the structure may be non-modular. The two highest gaugings (Table 2.3) indicate an increased head for the corresponding flow, suggesting that the theoretical rating may be overestimating flow at this point. The earlier of these gaugings was taken while the wooden beam was in place and in contact with the water. It was initially assumed that this was raising the stage reading for the same flow. The second of these gaugings was undertaken once the beam was removed and yet appears to exhibit the same elevated stage.

Photos taken during the later gauging also indicate a potential change to non-modular conditions (Figure 2.12). It is suggested that the theoretical rating be used for stages up to 0.45m. Between 0.45m and 0.5m it is believed that the structure begins to drown and a separate rating should be derived using the gaugings undertaken at higher flows.

It should be noted that these observations are based on only two gaugings, one of which was affected by the wooden beam, which might have contributed to the observed deviation from the rating. Whilst other supporting information is available, the gaugings in themselves are not conclusive and it is therefore recommended that further gaugings targeted at higher stages, particularly those greater than 0.45m, are undertaken as the opportunity arises.

In order to gain an improved understanding of the hydraulics at higher stages, one possible option would be to visually assess the location of the algal profiles on each of the vertical sides of the fish pass. Unfortunately it was not possible to make this assessment using the photographic information collected during the study period.

Figure 2.12 Louds Mill fish pass showing potential non-modularity

Main weir complex

To assess the impact of the fish pass on uncertainty in the overall measurement at Louds Mill, the existing weir complex at the site has been reviewed in further detail.

A difference in elevation of 73mm exists between the crest of the lower mill leat offtake weir and the crest of the main weir. There is a further 10mm difference between the invert of the mill leat offtake weir and the minimum crest level of the top baffle on the fish pass. The reference water level for the main complex uses the stage in relation to the main weir. The fish pass has a separate water level measurement point, located in the approach channel.

The latest Environment Agency rating was provided for the main weir complex and assessed against the combined rating provided by HR Wallingford and a rating calculated by Hydro-Logic using the consultants' in-house Hydrolog 4 software. While all the ratings appear to plot fairly similarly throughout most of the stage range (see Figure 2.), significant variation was found between flows derived at the upper limits of the weir structures, taken at a stage of 0.6m. The original Environment Agency rating also deviates notably from the others at lower stages.

The ratings will be referred to by the key below for clarity.

Key:
A = Rating provided by HR Wallingford as an appendix to the initial rating report.
B = Rating created using the survey existing in the H&T data holding.
C = Rating created in HLOG 4 using the parameters in the HR report (approach width not listed).
D = Original Environment Agency rating.
E = New Environment Agency Rating.

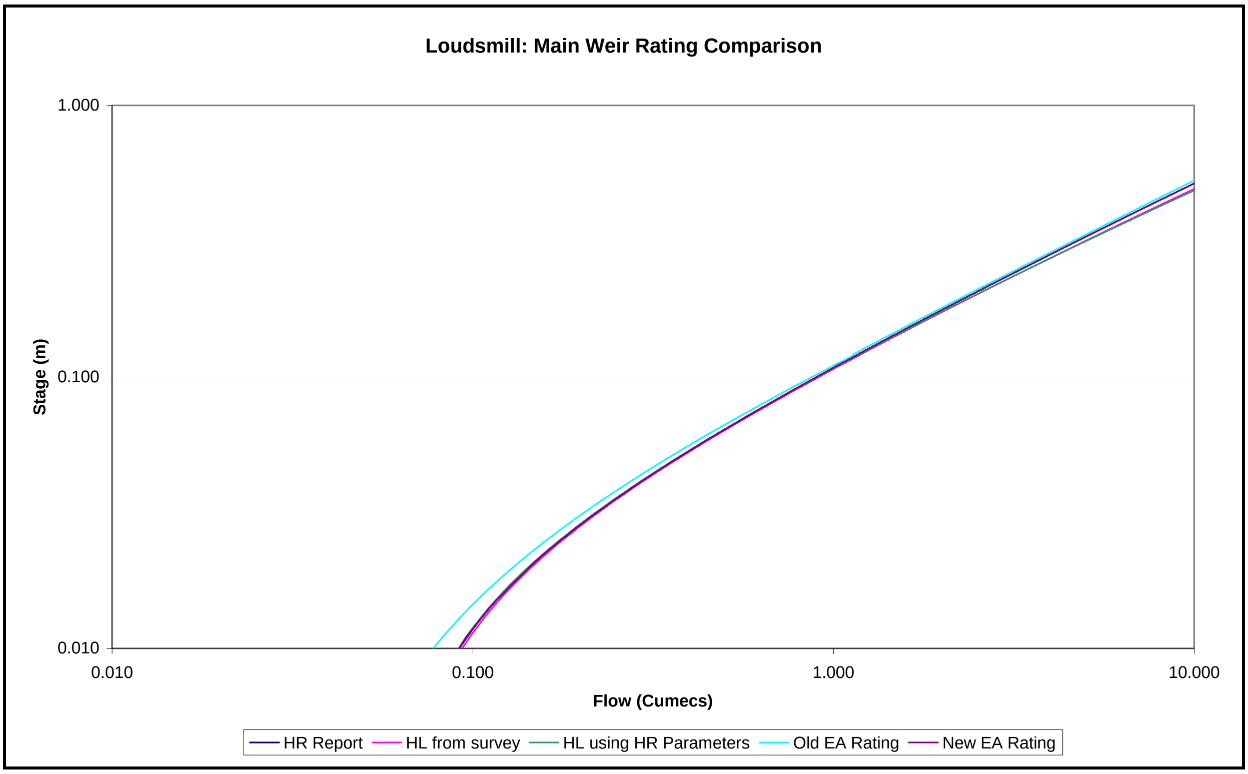


Figure 2.13 Comparison of ratings for Louds Mill main weir complex

The parameters listed within the HR Wallingford report indicate that the crest breadth of the main weir was taken to be 10.7m. Subsequent surveys provided by the Area Hydrometry and Telemetry team responsible for the site indicate a width of 10.67m. A discrepancy of 11mm also exists between reported p-values, and no approach channel width is detailed in the HR Wallingford report. The crest breadth used on the side channel is also listed as 1.50m rather than the surveyed 1.52m. It would appear that these values have been rounded, possibly automatically, which introduces an unnecessary error and associated increase in uncertainty.

The new Environment Agency rating was provided during the analysis and is the rating currently in use. It is essentially the rating produced by HR Wallingford with some additional rounding at higher stages.

The discrepancies in flows derived for a given stage between each of the ratings are summarised in Table 2.4 and Figure 2.13. Flows are shown up to a stage of 0.6m, above which flows start to spill over the flanking concrete abutments on the main weir.

Stage (m)	Flow (m^3s^{-1}) from : A	B	C	D	E
0.020	0.1443	0.1460	0.1431	0.1300	0.1440
0.050	0.3681	0.3713	0.3661	0.3457	0.3680
0.100	0.8992	0.9125	0.9035	0.8730	0.8990
0.150	1.5846	1.6219	1.6111	1.5402	1.5800
0.200	2.3983	2.4791	2.4712	2.3374	2.4000
0.400	6.7609	7.1938	7.2905	6.5571	6.7600
0.500	9.5380	10.2431	10.4805	9.1932	9.5400
0.600	12.7690	13.7082	14.1759	12.3310	12.8000

Table 2.4 Difference in produced flows

Key:
A = Flows provided by HR Wallingford as Appendix B to the report 'Larinier Fish pass at Louds Mill post construction calibration data', flow tabulation to the main weir complex (1mm head increments).
B = Flows produced using the survey existing in the H&T data archive.
C = Flows produced in HLOG 4 using the parameters in the HR report (approach width not listed).
D = Flows produced using the original Environment Agency rating for the main weir complex.
E = Flows produced using new Environment Agency Rating for the main weir complex.

The theoretical rating currently used by the Environment Agency is shown in Figure 2.14 with a line fitted for illustration purposes. This is only shown from the site datum zero on the main weir crest. However, a tabular form of the rating is provided in Appendix C, extended downwards to a stage of -0.073m, the cease to flow point of the Crump weir on the mill offtake.

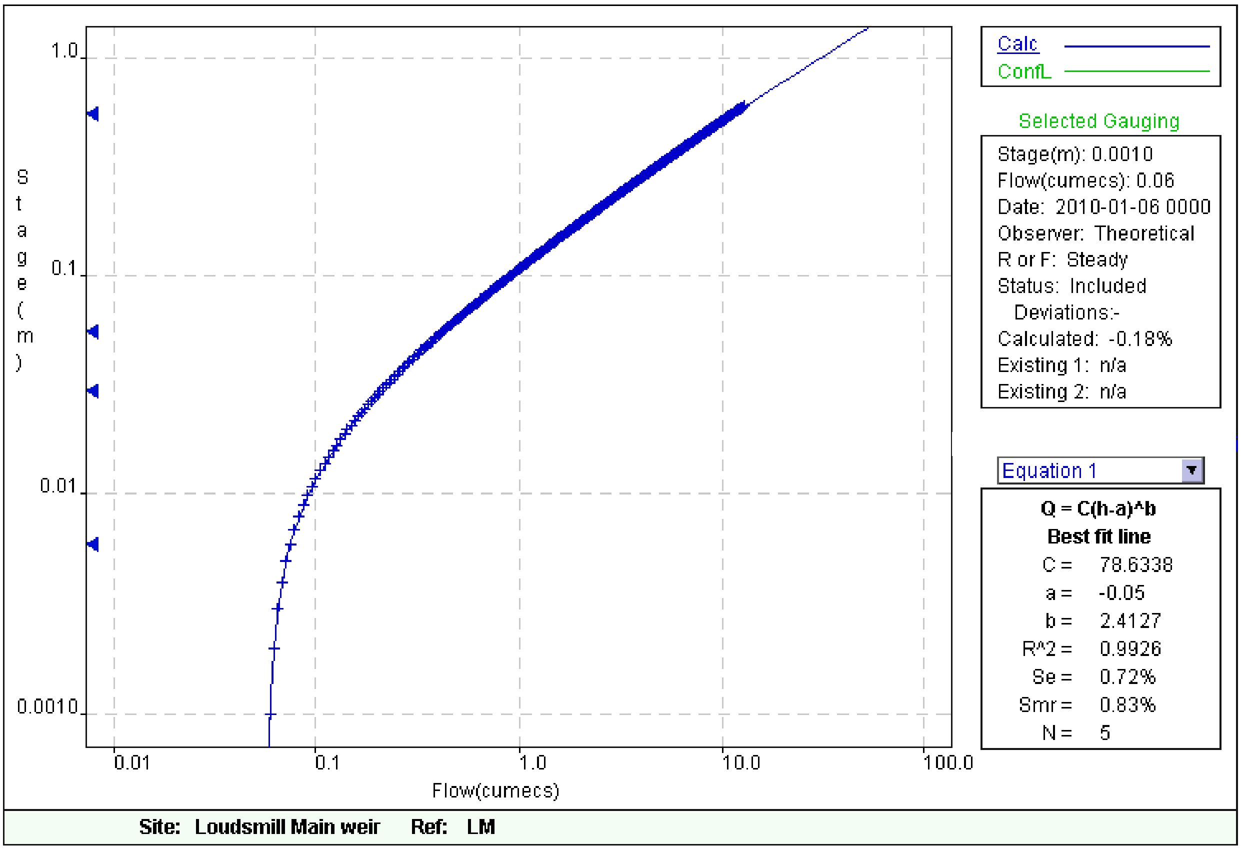


Figure 2.14 Current post-fish pass Environment Agency rating (E)

Despite the discrepancies between ratings, the lower end of the current post-fish pass Environment Agency rating is observed to fit relatively well. Due to the size of the main structure and its alignment at right angles to the line of flow, it is considered that the majority of the difference will be lost within the inherent measurement uncertainty. The rounded figures mean that the HR rating and the Hydro-Logic rating plot differently, with the HR rating giving lower flows and the Hydro-Logic rating providing higher flows for the same stage.

While the location of the stilling well, effectively in line with the main flow, leads to the potential for elevated head measurement for the main weir complex, the proximity of the inlet pipe to the main weir crest may lead to a reduction in measured stage due to drawdown effects, particularly at higher flows. This may explain why a rating curve fitted to the gauging data alone would fall between the two ratings. In light of this, it is recommended that the rating currently in use by the Environment Agency and based on that derived by HR Wallingford continues to be used, with consideration given to correcting the rounding of flow values at higher stages.

The initial analysis using the original Environment Agency rating for the site is shown in Figure 2.15. While the rating appears reasonable, with the majority of gaugings falling within 10 per cent of the theoretical rating, some bias is clearly visible with an underestimation of flow throughout the majority of gaugings. As the dimensions of the structures and head measurement location have not changed, it is unknown why this rating does not appear to fit the post-fish pass gaugings as well as the pre-fish pass gaugings. However, the migration from the original rating appears justified. It is possible that this is a statistical anomaly due to the relatively small sample size, and is within the usual gauging uncertainty associated with spot flow gauging.

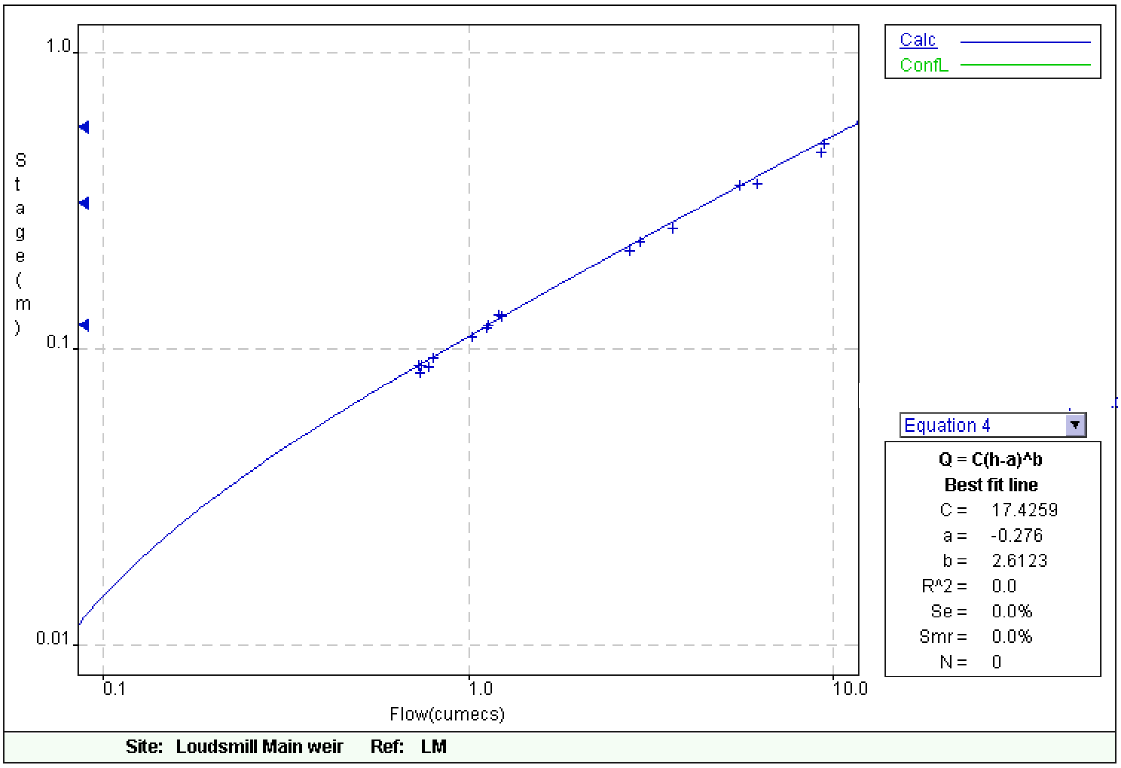


Figure 2.15 Original Environment Agency rating (D) plotted to gaugings

The deviation at the upper stages shown in Figure 2.15 is similar to the pre-fish pass plot, where the rating appears to under estimate flow.

The original rating used in WISKI (rating D) was migrated when the fish pass was constructed. Since construction of the fish pass, the rating produced within the HR report (rating E) has been applied, with an additional constant added for the 73mm offset to the lower mill weir crest. The values were plotted and a line fitted for comparison purposes. The rating and deviation is displayed in Appendix D.

Figure 2.16 displays the gaugings against the new Environment Agency theoretical rating (rating E), which shows a more even fit with less bias. All of the gaugings fall within +/-10 per cent, which is reasonable given the 'non-standard' hydrometric conditions in the approach to the site.

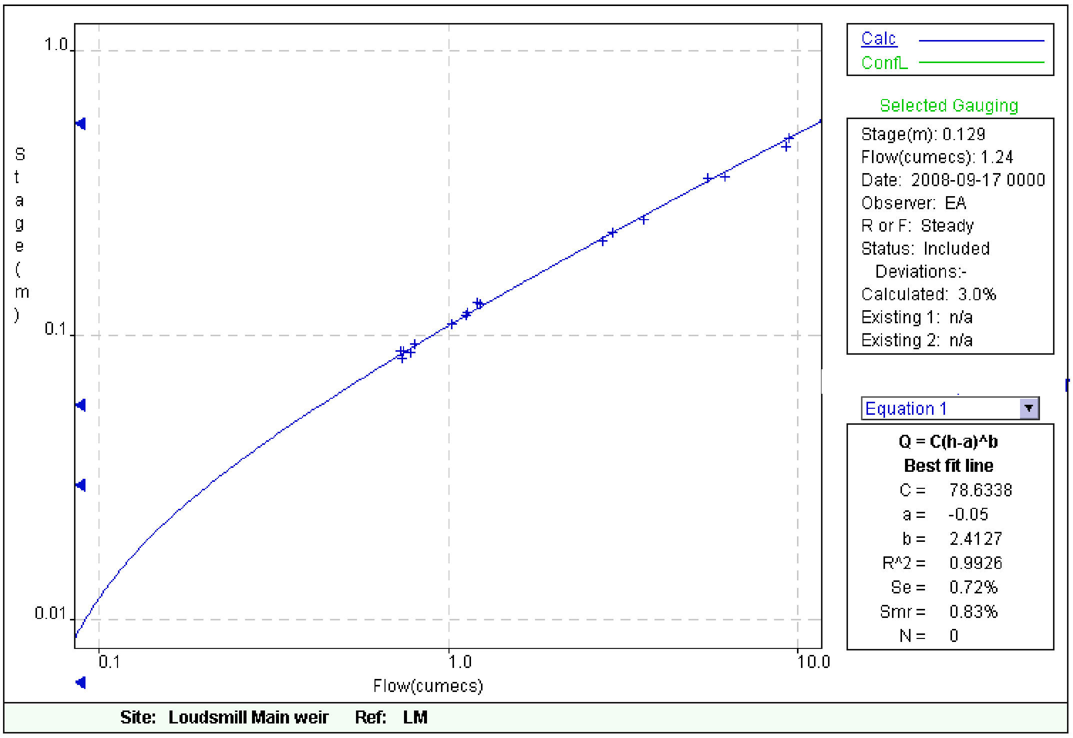


Figure 2.16 Post fish pass Environment Agency rating (E) against gaugings

Deviation is shown with stage and date in Table 2.5 below. These values relate to the fitted line, which is within +/-0.5 per cent of the look-up table values provided by the Environment Agency Hydrometry and Telemetry team.

Date	Stage (m)	Gauged flow (m^3/s)	Flow (m^3/s) from rating	% difference
17/09/2008	0.129	1.24	1.277	3.00
15/10/2008	0.13	1.212	1.291	6.50
19/11/2008	0.23	2.953	2.945	-0.30
05/12/2008	0.257	3.648	3.473	-4.80
23/01/2009	0.356	5.535	5.67	2.40
10/02/2009	0.493	9.412	9.321	-1.00
12/03/2009	0.215	2.773	2.666	-3.90
22/04/2009	0.11	1.032	1.023	-0.80
12/05/2009	0.088	0.732	0.756	3.30
10/06/2009	0.088	0.751	0.756	0.70
14/07/2009	0.083	0.742	0.7	-5.70
04/08/2009	0.12	1.144	1.154	0.90
14/08/2009	0.118	1.129	1.128	-0.10
16/09/2009	0.093	0.805	0.814	1.20
14/10/2009	0.087	0.786	0.745	-5.20
30/11/2009	0.361	6.191	5.791	-6.50
03/12/2009	0.461	9.257	8.409	-9.20

Table 2.5 Percentage deviation between gaugings and Environment Agency theoretical rating (E)

The Hydro-Logic theoretical rating (B) derived using the survey data is shown in Figure 2.17, with stage and date deviation plots in Appendix E. This shows a good fit, with all gaugings falling within +/- 9 per cent of the rating.

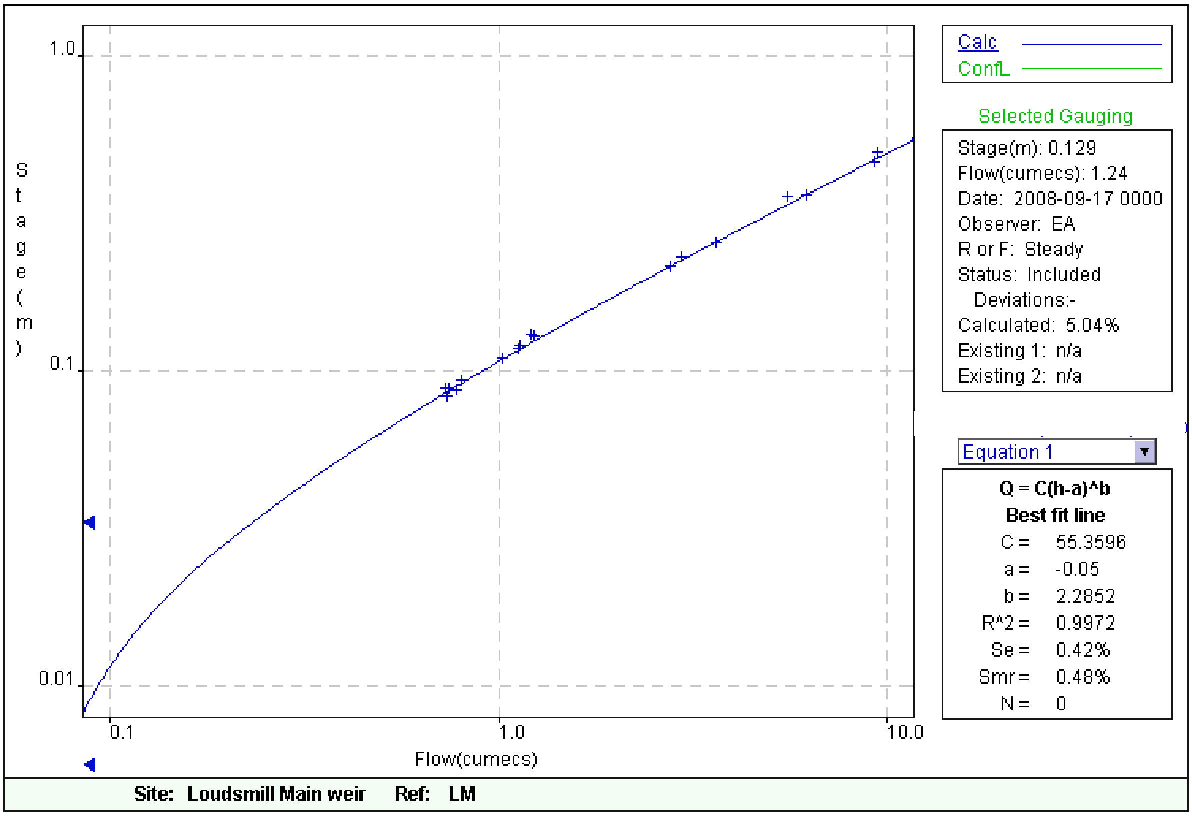


Figure 2.17 Gaugings displayed with Hydro-Logic theoretical rating (B)

The current rating applied by the Environment Agency (E) shows a discrepancy of up to 7 per cent from the values derived by Hydro-Logic using the latest survey dimensions (B). Gauged flows appear to largely fit between the two theoretical lines as shown in Figure 2..

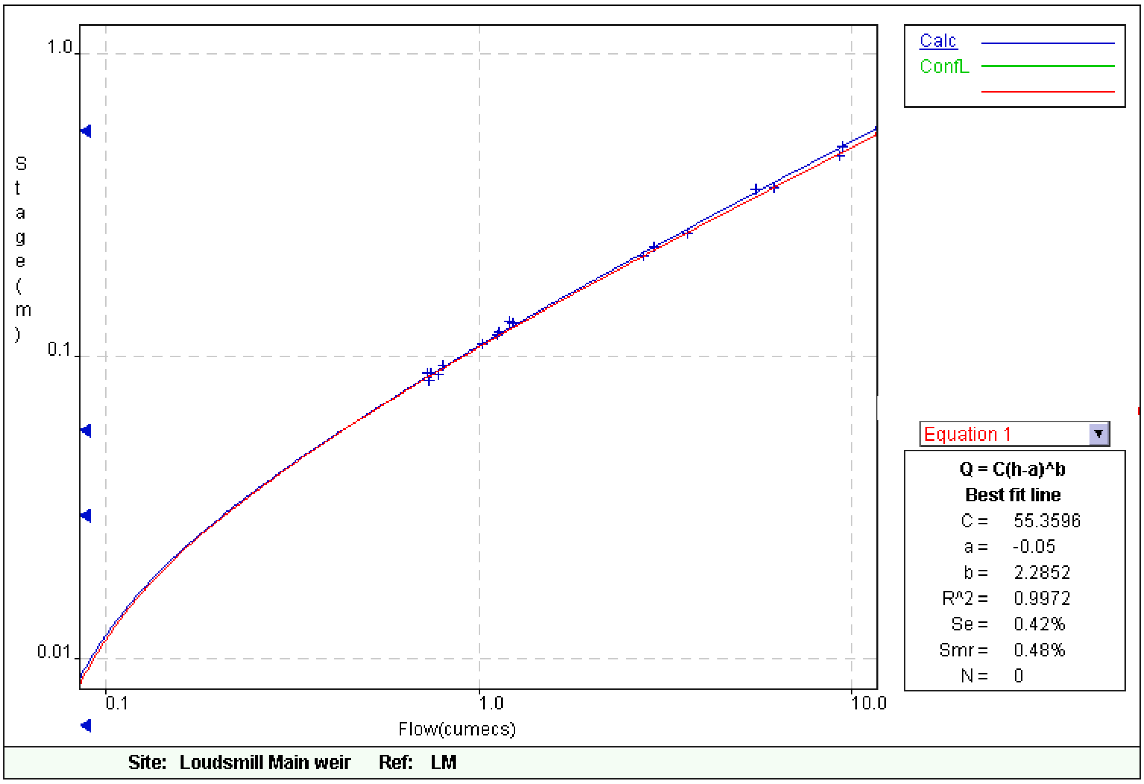


Figure 2.18 Environment agency new and Hydro-Logic plots

It is not known why the rating would change following the commissioning of the fish pass, as the change in stage should have been the only impact. However, the ratings produced both by HR Wallingford (A), adopted by the Environment Agency in WISKI (E) and Hydro-Logic (B) appear to show a much more concise fit to the observed flows. The Environment Agency's existing rating based on the HR Wallingford report findings will give a reasonable determination of flows. However, it is recommended that the Hydro-Logic theoretical rating (B) be adopted as this is considered to best reflect the structural dimensions and minimise rounding errors in the calculations.

2.3.6 Uncertainty analysis

Combined analysis

The project specification included a requirement to assess the uncertainty associated with the three independent structures that make up Louds Mill Gauging Station. To undertake this analysis, flows and uncertainties were calculated for each structure and combined to provide an estimate of uncertainty throughout the full range of the structures. The uncertainty associated with flow measurement at each of the two original Crump weir crests was combined by algebraic summation, as they are both dependent on the same water level measurement. The total uncertainty for the weir complex was then combined with that calculated for the fish pass by adding in quadrature (the square root of the sum of the individual uncertainty values squared, for the separate structures) as the fish pass has an independent stage measurement.

Parameters

The parameters used in the calculation of flows and uncertainties for the two Crump weir structures are shown in Appendix F. Flow calculation and uncertainty calculation for the fish pass was undertaken in accordance with ISO 26906:2009 (British Standard, 2009).

An offset was applied for each control structure (crest). To summarise, the level of the baffle invert on the fish pass is 10mm below the crest of the mill offtake weir, which in turn is 73mm below the main weir crest. A variation of 5mm was observed in the fish pass crest level at the time of the post-installation survey. However, as this appears to be a result of general scatter in the values, it is assumed that this is largely related to the difficulty of accurately surveying the crest once the infrastructure for the handrail and protective grille were in place.

The calculation of total uncertainty requires a weighting on the division of flows based on the percentage of total river flow over the two weirs and the fish pass. The percentage total flow over the fish pass is displayed in Figure 2.19. For the first 0.01m the fish pass is accommodating all of the flow in the river. Uncertainties at this stage and flow are too high to allow flow to be measured accurately, and it is very unlikely that these conditions would ever occur. During the 1976 drought, water levels reduced to 18mm above the main weir crest, based on the mean daily flows provided and the migrated rating for the weir. The lowest mean daily flow in 1976 was 0.120m^3/s. If this flow were to occur again, with the fish pass in place, this would result in a stage of 0.074mASD; that is, 9mm below the main crest.

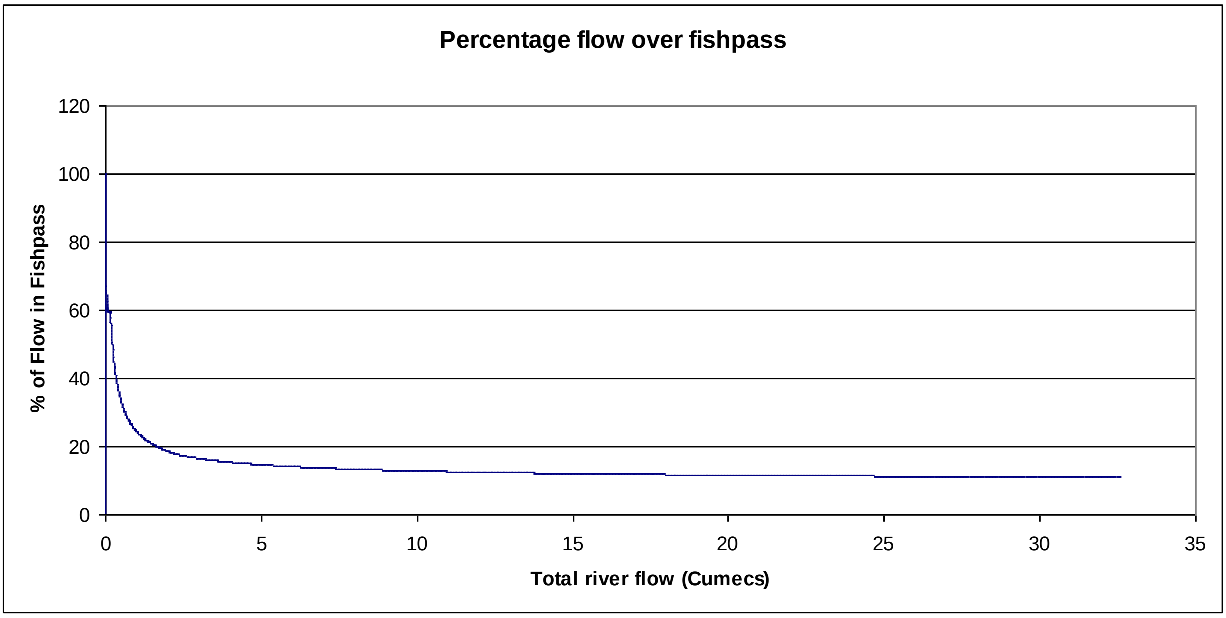


Figure 2.19 Percentage flow over fish pass

Figure 2.20 illustrates the combined uncertainty for all three structures with increasing stage. A marked increase in uncertainty will occur at 0.01m where the mill crest begins to spill. However, the increase in uncertainty here is not significant as the uncertainties at the fish pass measurement are still very high. This is also well below the lower stage threshold of 0.03m for either Crump or thin-plate weirs, as stated in the International Standard.

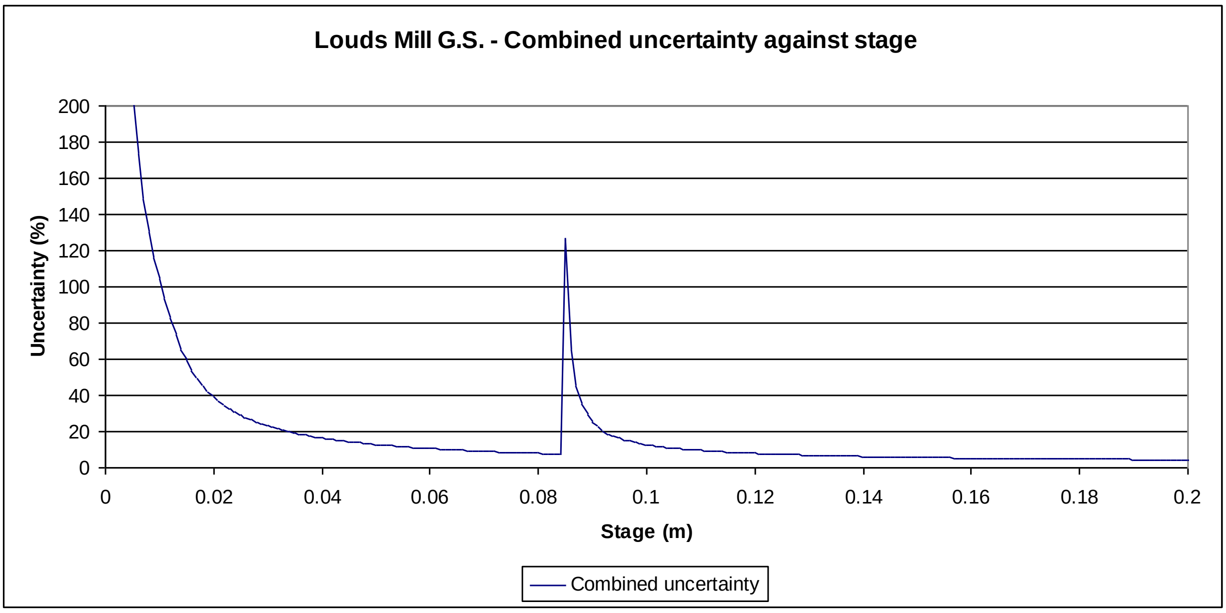


Figure 2.20 Combined uncertainties against stage

Flows for each stage are provided in Appendix B and C for reference.

Historical records indicate that, based on available flows, the main weir has been dry for just three days (in 1976) and at this low stage the sensitivity over a structure of this width will lead to very high uncertainties. In theory, the fish pass offtake will lower the stage over the weir for a given total flow, but it is not thought this will cause the head over the main weir to reach the cease to flow level on a regular basis. When the fish pass was opened, the stage over the main weir is recorded to have fallen by 22mm. Should the main weir go dry during a major drought event, a combination of the mill weir and fish pass would provide greater sensitivity and therefore reduced uncertainty in total flow measurement at very low flows.

During the data collection phase for this project, very low flows were not reached. It is recommended that further gauging be undertaken under low flow conditions to enable the lower end of the rating to be confirmed. The relative uncertainties pre- and post-installation of the fish pass are displayed in Figure 2.21.

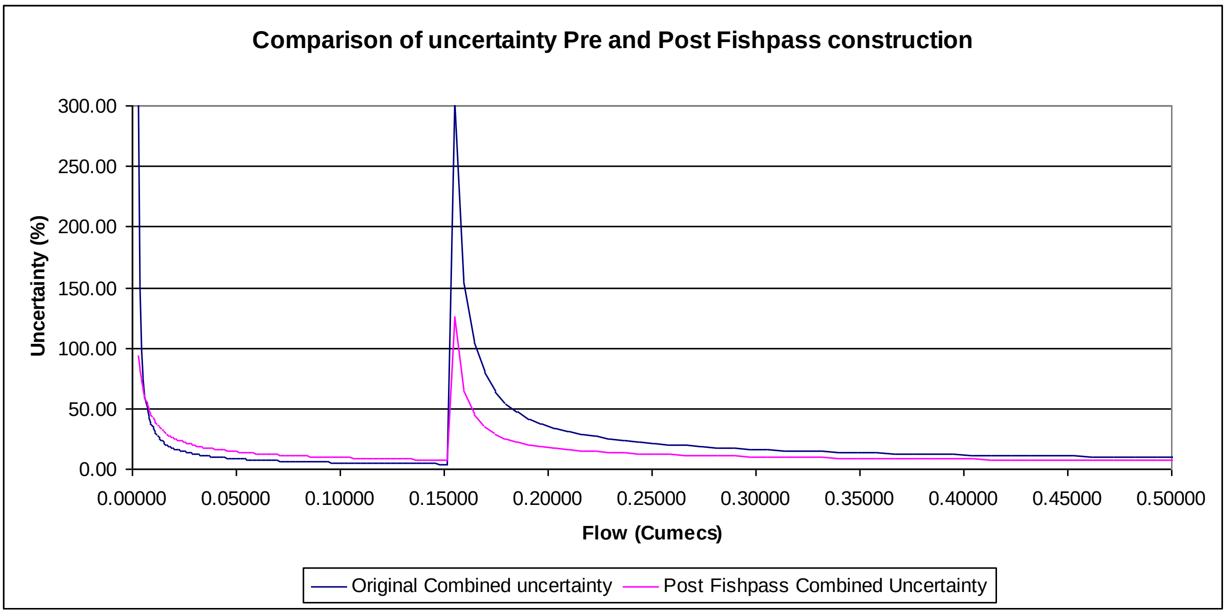


Figure 2.21 Pre- and post-uncertainty comparison against flow

2.3.7 Stage measurement

There is some concern over the ability to measure water level accurately for the main weir complex. The positioning of the stilling well on the downstream end of the main weir crest, effectively facing the flow, is likely to lead to an increased velocity head component and the potential for the head to be overestimated. A discrepancy across the weir, between the dip point and the gaugeboard, of up to 50mm has been observed. This degree of inaccuracy would lead to very high uncertainties in the data. For example, a 50mm increase in stage at 0.3m would lead to an approximately 38 per cent increase in derived flow. In reality, a number of variables impact on stage measurement and the stage difference appears to balance out across the crest of the weir (that is, it is elevated on the right of the crest and depressed on the left of the crest).

Significant turbulence has been observed in the approach to the main weir at higher flows, with a notable trough forming in the approach section to the left of the main crest and associated turbulence adjacent to the gaugeboard on the left side of the main weir, as shown in Figure 2.2.

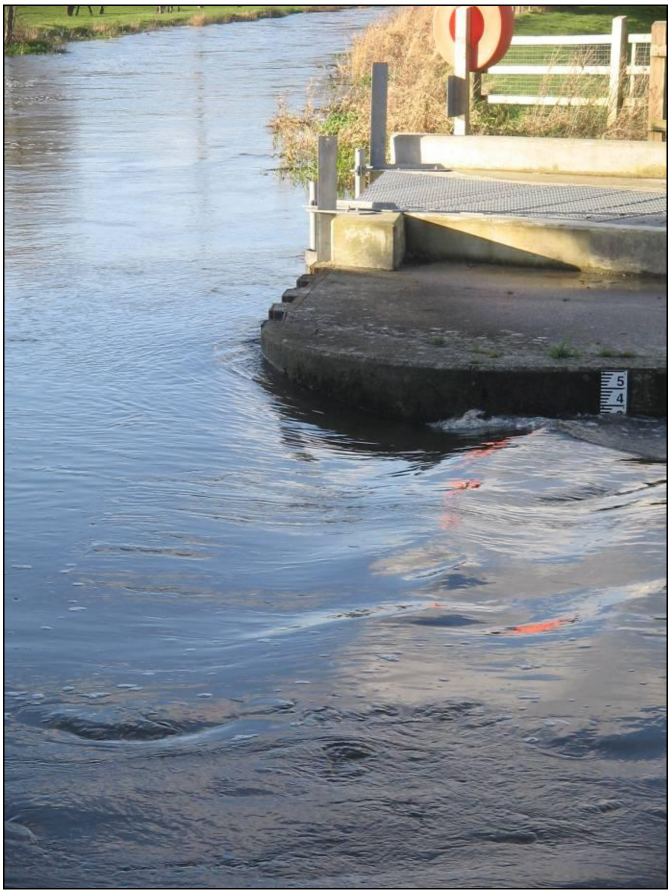


Figure 2.22 Turbulence on main weir at higher flows

The potential impacts of these effects were investigated during the project. Dips were undertaken at a number of different points around the complex, when safe access allowed, to assess if a reliable relationship could be determined using the existing head measurement location.

Under low flow conditions the correlation in head measurement across the main weir approach was found to be good. At higher flows the correlation was found to be less consistent, with significant variation most likely as a result of the unusual hydraulics in the approach. Whilst the additional dip data has identified that the variable approach conditions appear to have a significant impact on accurate stage measurement at high flows, it has not been possible to gain a consistent adjustment with the limited data available.

Stage is taken relative to the internal dip plate located in the Environment Agency instrument kiosk. This recorded a higher level at low to medium flows but a lower level than the key dip adjacent to the fish pass at higher levels noted at a stage of 0.461mASD. At this stage a distinct trough is formed on the left side of the weir approach.

To gain a better appreciation of the potential impact of the stage measurement location, a second gaugeboard was installed on the right of the channel, opposite the main weir structure (Figure 2.23). This was in place for the visit of 30 November 2009.

The location provided a means of gaining water level measurement in a location with minimal turbulence (outside the immediate hydraulic influence of the weir structure).

Figure 2.23 New gaugeboard in situ

During both subsequent high flow visits on 30 November 2009 and 1 December 2009, readings from the gaugeboard were significantly higher, at 21mm and 38mm respectively, than those recorded on the main weir. This is contrary to what was expected due to pressure head effects. It is possible that as flows increase, the inlet for the stilling well is affected by drawdown in the approach to the weir.

Historical drawings in the station folder indicate that the inlet to the stilling well is placed relatively close to the weir, at 0.762m from the crest. The maximum head over the weir (H_{max}) of the main crest is 0.607m, indicating that the inlet is less than twice the H_{max} upstream and therefore does not meet the relevant standards. On this theoretical basis, and through assessment of high flow photos, it is possible that the measured stage is affected by drawdown in the approach to the weir, from a stage of approximately 0.36mASD.

Analysis of gaugings to date, and the stage value taken from the logger and stilling well dip, indicates that the majority of gaugings lie within +/-8 per cent of the Environment Agency's existing rating. It is possible that the drawdown in the approach to the weir is balancing the increase due to velocity head and resulting in a stage flow relationship in line with established hydraulic theory.

In conclusion, it is not recommended that an adjustment to the historical record or current rating (for example, stage correction) is applied to reflect the impacts of velocity head or drawdown effects in the head measurement section. It is unlikely that any adjustment would result in a significant improvement in the quality of the data and may even introduce a further potential source of error.

2.3.8 Operational considerations

Approach conditions

To accurately calibrate the fish pass and independently assess the weir complex, gauging needs to be undertaken between the fish pass offtake and the main weir. There is a very limited reach of channel available and the hydrometric conditions are not ideal for accurate flow measurement.

The location of the Larinier fish pass and the main weir perpendicular to the channel creates some unusual hydraulics in the measurement section. Debris (such as leaves and particles) floating down the main channel moves towards the fish pass orifice before straightening into a linear path before again moving to the left bank to be taken over the main weir. Following initial gaugings, the measurement section was moved slightly further downstream of the fish pass opening. The variation in velocity direction is now largely seen on the right bank away from the weir and is most likely caused by weed growth in the channel margins.

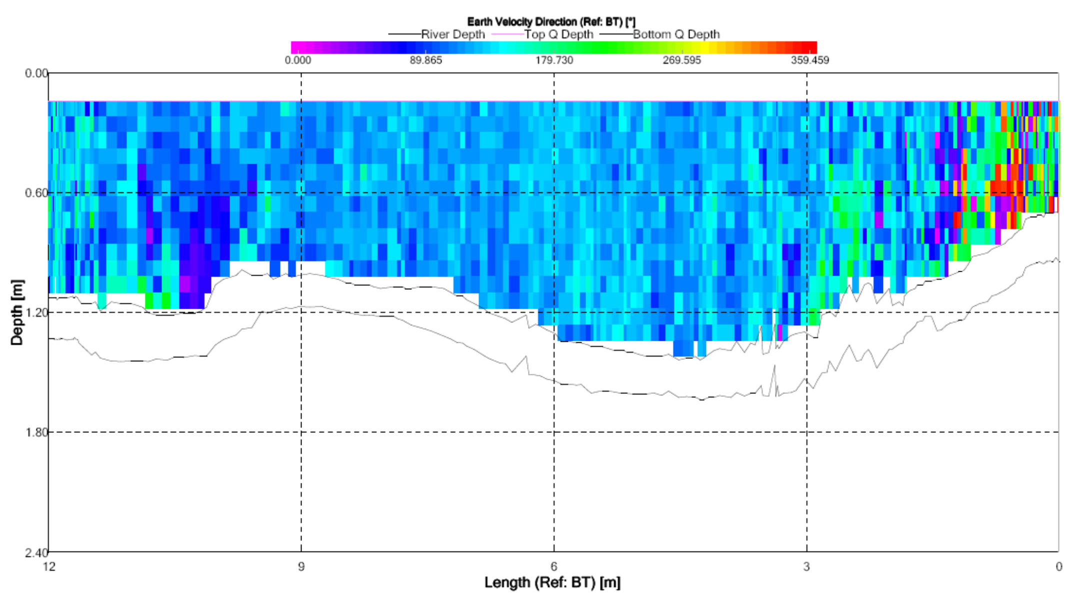


Figure 2.24 Velocity directions at ADCP gauging section (downstream view)

At high flows the short approach to the fish pass crest also exhibits some considerable turbulence. The floating trash boom creates turbulence, particularly at the surface. As velocities increase there is significant turbulence and eddies throughout the water column in the approach to the fish pass. The image below provides an example of the turbulence observed at the fish pass entrance.

Figure 2.25 Turbulence observed in the fish pass approach

Debris and obstructions

Throughout much of the calibration period, a wooden beam was mounted within the approach to the fish pass, approximately adjacent to the gaugeboard. It is understood that the beam is required for HDX monitoring of trout and grayling and needs to be within certain proximity of the water to allow the system to function correctly. The beam was removed in late 2009, and is unlikely to return as it was a temporary installation for the fish monitoring element of the project.

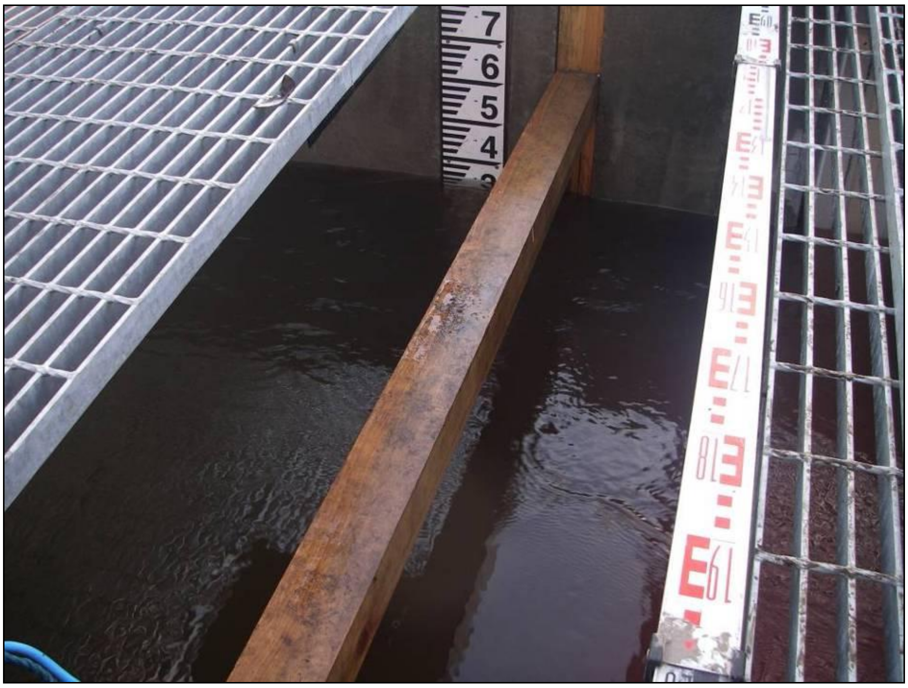


Figure 2.26 Potential high flow obstruction within fish pass

The baffles are subject to a build up of weed and debris due to the configuration of a Larinier pass (pointed upstream). They are regularly cleaned during routine work at the site and a record kept. A concise table of the maintenance record is shown below (Table 2.6). In summary, the records held at the site indicate that although weed, twigs and plastic debris (such as carrier bags) do catch on the baffles, their removal rarely results in a significant change in stage.

The records generally indicate a change in stage of less than 2mm, with minimal weed clearance generally creating no change in stage. In the 20-month period for which a record of debris exists (17 September 2008 to 12 May 2010), the stage on the gaugeboard fell by 1 to 2mm after the top baffles were cleaned on only three occasions., Notably these observations all fell within a two-month period in August and September 2009, when weed growth in the channel was likely to be at its most vigorous and weed cutting/clearance most likely.

Notes relating to the boom suggest that it is effective in preventing some of the trash from reaching the fish pass structure at this site. However, this may also be aided by the fact that the boom runs at 90 degrees to the main flow of the channel. The separate head measurement downstream of the boom means that debris caught on the boom will not impact on stage measurement.

Cleaning and maintenance of the fish pass structure does incur an additional maintenance cost. The frequency is of particular note, with weed recorded shortly after cleaning on a number of occasions (for example, November 2008 and August 2009). Further longer-term records would be valuable to assess the impact of weed on stage measurement at very low flows and in relation to any seasonal impact, such as leaf fall in autumn or chalk stream seasonal weed clearance for improvement of fish habitat during the summer.

Date:	Staff:	Comment:
17/09/2008	CAG/TP	Weed cleared from boom and fishpass second set of baffles at 09:30. No change recorded.
15/10/2008	CAG / KH	Boom and 1st 3 baffles cleared 10:00 - 10:10
22/10/2008	AM	14:50 - 17:08 Cleaned fishpass top baffles
12/11/2008	RG / JB	Weed cleared
19/11/2008	CAG	Top 3 baffles cleared of debris leaves and twigs. Weir crest cleaned no debris on Boom
04/12/2008	JB	Camera work top baffles were clear
05/12/2008	CAG	Cleaned no change. No rubbish on boom
17/12/2008	JB	No need to clean baffles and boom clear.
10/02/2009	Martin Dibley	Boom clear, high flow can't inspect baffles, small debris taken in flow
12/03/2009	CAG/KH	Accessed fish pass to perform CMG from 10:20 - 11:10. Cleaned a small amount of debris from front of boom
15/04/2009	?	09:30 cleaned fish pass lightbox and camera housings
22/04/2009	CAG/KH	cleaned fish pass and swept weed away from front of the boom from 09:30 to 09:33
06/05/2009	CAG	onsite at 07:30 to remove stone from fish pass. No change in level. Weed removed from upstream side of the boom at 07:25. No change in level (=0.172m)
	Jon B	16:55 Cleaning fish pass light box possible level disturbance.
12/05/2009	CAG/KK	onsite for QA and gauging. Cleaned debris from fron tof boom and cleaned f/pass from 09:12 - 09:20. No change in level. Gauged 0930 - 10:08.
19/05/2009	JB	cleaned fish pass light box & perspex camera housing
20/05/2009	CAG	swept small amount of debris (reeds etc) from in fron of boom at 14:55 - no change in level (0.171m)
10/06/2009	CAG/KH	Swept some weed from front of boom & cleaned weir. 09:37 - 09:40: no change in level @ 0.164m
17/06/2009	JB/RG	clean fish pass light box
30/06/2009	JB	10:55 cleaned fish pass lightbox & perspex sides
14/07/2009	CAG	11:00 - 13:00 UTC. Gauged flow. Cleaned fish pass weir and removed debris from front of boom
04/08/2009	Martin Dibley	Some weed cleared from baffles. No change in stage, gauging undertaken.
13/08/2009	GH	weed removed from top baffle @ 10:00 GMT. Level fell by 1-2mm
14/08/2009	CAG/OB	Onsite for QA and gauging. Swept boom and scraped weir. Level fell by 1mm.
27/08/2009	JB	08:30 GMT. Cleaned top baffles on fish pass. No weed on top baffle.
03/09/2009	JB	cleaned fish pass light box
16/09/2009	CAG/KH	cleaned weir and baffles at top; swept debris off boom @ 09:00. No significant change in level.
28/09/2009	GH	A lot of weed (& plastic) removed from baffles (mainly 2nd & 3rd tier) @ 12:00-12:10 GMT. No change in level.
14/10/2009	Fisheries	Baffles cleaned AM level fell 2mm
14/10/2009	CAG	Debris from Boom cleaned no change in level
22/10/2009	CAG	Snagged debris cleared baffles and boom, Level rose. Rising stage
05/11/2009	JB	Cleaned FP and weed from top baffles
25/11/2009	CAG	No debris, cable caught.
30/11/2009	H-L	High flow cannot see baffles
03/12/2010	H-L	High flow gauging no debris
12/01/2010	CAG	No Debris comments. Concerns over inlet tube.
22/03/2010	CAG	Modem reset scan ok
25/03/2010	CAG	Modem reset scan ok
26/04/2010	CAG	Weir and GB cleaned no significant change in level.
12/05/2010	JB	Cleaned light box and cameras and top of fishpass some level disturbance.

Table 2.6 Debris and maintenance record

The photo below indicates weed caught on the baffles. It is not known if weed or debris catching on the baffles impacts on the attractiveness of the pass to fish. It is important that regular maintenance is maintained, particularly on the uppermost baffles, which are most likely to have an impact on the hydrometric performance of the fish pass.

Figure 2.27 Weed caught on fish pass baffles

Remote monitoring

The camera situated on the main instrument housing provides a valuable source of up to date visual information for the site. This is particularly useful in ascertaining any impact from debris build-up. The alternative camera angle on the gaugeboard does not currently archive images, though provides a valuable resource for checking levels on a reactive or ad hoc basis. A further camera provides a view of the baffles of the fish pass. This is useful identifying debris on the fish pass baffles and has been used to respond to weed issues at the site.

2.4 Conclusions and recommendations: Louds Mill Gauging Station

Fieldwork and subsequent analysis has led to the following conclusions and recommendations relating to the on-going operation of Louds Mill Gauging Station, and broader observations relating to the future use of Larinier fish passes at flow measurement structures.

- The performance of the Larinier fish pass at Louds Mill, as judged by the fit of the gauged data to the theoretical stage discharge relationship, is considered excellent throughout the majority of the stage range. The existing Environment Agency theoretical rating could be slightly improved by correcting for an error in the p-value used in the original calculation. The difference between the existing Environment Agency theoretical rating and the proposed theoretical rating is less than 1 per cent throughout the full stage range.

- Above a stage of approximately 0.45mASD, two gaugings were observed to deviate from the theoretical relationship. While one of these gaugings may have been affected by the presence of a beam in the approach channel, the second suggests that non-modular conditions are present. This appears to be validated by observation and photographic evidence. It is therefore recommended that the proposed theoretical rating be applied up to a stage of 0.5mASD. Further gauging should be undertaken above this stage to confirm, or otherwise, the modularity of the fish pass. If the fish pass is confirmed as non-modular, or no longer conforming to the hydraulic theory, then the rating should be extended using the available gauging data.

- The ratings for the main weir complex were also assessed. The existing Environment Agency theoretical rating, based on the HR Wallingford report findings, is thought to give a reasonable determination of flows. However, it is recommended that the Hydro-Logic proposed theoretical rating be used in future as this is considered to provide a more accurate reflection of the structural dimensions and minimise the impact of rounding errors within the calculations.

- It has been demonstrated that the construction of the fish pass at Louds Mill will improve sensitivity and reduce uncertainty in total flow measurement at the site, based on the historical flow range.

- During the monitoring period, weed and debris (plastic bags, twigs, and so on) were observed to accumulate on the fish pass baffles. While removal of the weed and debris is recorded to have limited impact on the stage measurement, it is important that regular maintenance is maintained, particularly on the uppermost baffles where potential impact on the hydrometric performance of the fish pass is likely to be most significant.

- Installing cameras to monitor the main weir complex and the approach to the fish pass provides a significant benefit in the successful operation and maintenance of the site. Remote observations allowed the timely clearance of weed accumulations in the fish pass, targeted spot flow measurements, and a general check of conditions and the integrity of the gauging station as an Environment Agency asset.

- The wooden beam temporarily installed in the approach to the fish pass for fish monitoring purposes was observed to be interfering with accurate stage measurement at high flows. To maintain favourable hydrometric conditions, it is recommended that in future, the beam be positioned as high as possible above the water and deployed for the minimum period required to fulfil the fisheries monitoring requirements. During this period, the accuracy of the high flow data record at stages greater than the minimum beam height should be treated with due care and labelled accordingly.

- It is recommended that, where possible, the approach to the fish pass structure should be longer than that constructed at Louds Mill. The International Standard (BS/ISO 26906) recommends a minimum of five times the channel breadth at the crest. This value should be further increased for skewed or angled flow or if a baffle arrangement is in place.

- The installation of the Larinier fish pass at this location does not appear to have had any detrimental impact on the overall monitoring accuracy of the gauging station. It is likely that the installation of the Larinier fish pass at this site has actually improved the sensitivity of the structure under low flow conditions.

- The installation of Larinier fish passes to improve fish passage at hydrometric structures can be undertaken with some confidence that they will have little or no negative impact on flow measurement performance, provided they are designed appropriately and operating within the specified range.

- Additional costs are incurred by the Area Hydrometry and Telemetry team in terms of the installation and operation of an additional flow monitoring site. Costs incurred include the level sensor and outstation, cameras, maintenance and data processing. Additional costs may also be incurred by Area Operations and Fisheries teams.

2.5 Brimpton Gauging Station

2.5.1 Site description

Brimpton Gauging Station (Figure 2.8) is situated on the River Enborne two kilometres upstream of its confluence with the River Kennet (NGR: SU568648). The position of the gauging station is important to minimise the impact of the backwater effect from the River Kennet. The station is located about one kilometre east of Brimpton, just after Shalford Bridge (Figure 2.9). The structure is a purpose built asymmetrical compound Crump weir with high and low crests designed to enable relatively accurate measurement over a wide range of flows (Figure 2.30).

The catchment area of the River Enborne is 147.6km^2 and consists mainly of impervious tertiary clays, with some chalk and upper greensand in the upper catchment.

The gauging station became operational in 1967. In 1992, a tail level recorder was installed to correct the data for non-modular flow conditions. It should be noted that high flows prior to this are therefore likely to be significantly overestimated. The quality of the tail water record in recent years has been raised as a potential issue by the Environment Agency and is further investigated in Section 2.5.8.

Figure 2.28 Brimpton Gauging Station (view from downstream)

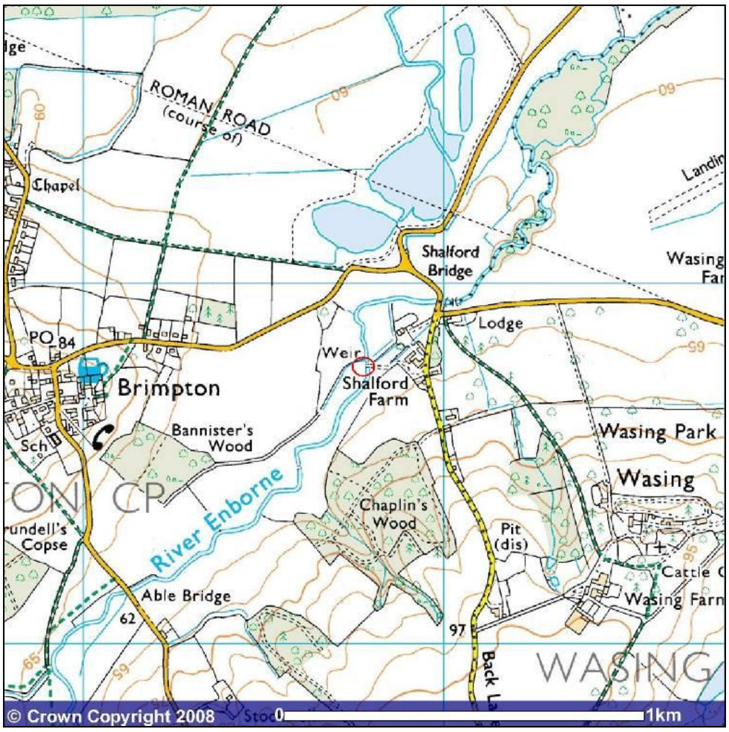


Figure 2.29 Brimpton G.S. location map

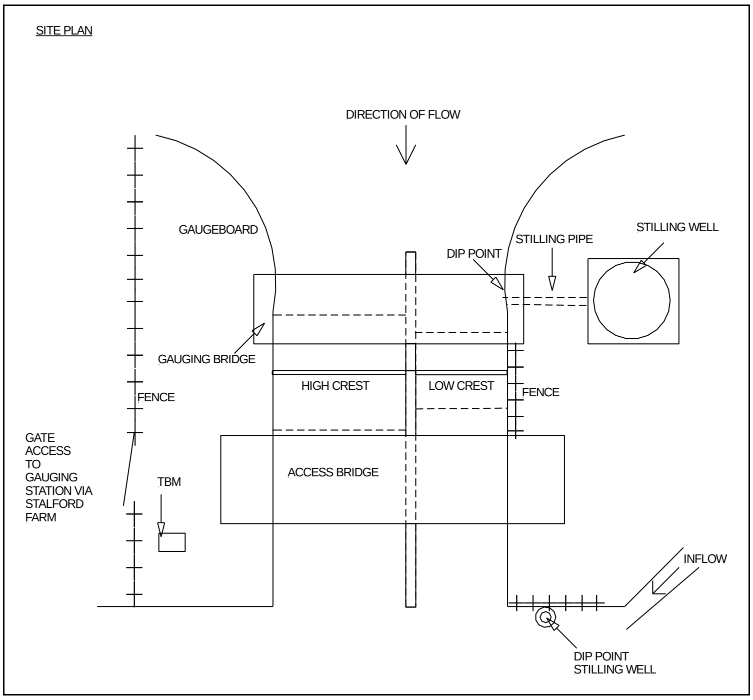


Figure 2.30 Brimpton G.S. site plan

2.5.2 Site survey: Brimpton

An initial project inception meeting and preliminary site visit was held on 19 September 2008, attended by Graeme Peirson, Nick Everard and Richard Iredale (Environment Agency) and Nik Whalley (Hydro-Logic Ltd). The primary objective of this meeting was as a scoping visit to review the site and determine the detail of the project requirements.

The initial site survey was undertaken on 23 October 2008 by Stewart Child, Karen Weekes and Alice Wiggins (Hydro-Logic Ltd). The site survey consisted of a topographical survey of the weir structure, including all datum points and the newly installed baffles. This survey included four cross-sectional profiles of the approach channel. Only the high crest, which was dry at the time of the site visit, could be surveyed in detail as the velocities over the low crest were too high to allow safe access. A subsequent check survey was undertaken under lower flow conditions on 5 August 2009, although access to the crest again proved difficult with the baffles very hard to access and survey accurately.

Assessment of the baffle elevations and layout revealed that the top baffle had been installed at the wrong elevation in relation to the low flow weir crest. Following internal discussion the Environment Agency decided to replace the top baffle to the original design specification and additional gauging was undertaken to assess its performance against the criteria for fish passage and flow measurement. Unfortunately, poor weather conditions were experienced throughout December 2009 and January 2010 and the replacement baffle was only installed in mid-February 2010. The baffles were re-surveyed on 16 February 2010, leaving a very limited period in which to undertake an intensive gauging schedule. As wide a range of flows were gauged as possible over a four-week period to enable a comprehensive assessment of the impact of the baffles on fisheries and flow measurement.

Under normal flow conditions, Environment Agency staff gauge downstream of the weir. The site is moved at high flows when access to the normal location is impossible due to high water levels. During the original site visit a boat-mounted Acoustic Doppler Current Profiler (ADCP) was used to obtain a flow value, velocity profiles and to assess the hydraulic conditions upstream of the weir. Additional gauging was performed downstream of the structure on the same day using a small rotating element current meter and an Ott ADC meter. Due to relatively high flow conditions during the calibration of the new baffles in February/March 2010, a boat-mounted ADCP meter was used for all but one of these gaugings.

2.5.3 Data collation

A relatively comprehensive data record is available for Brimpton. However, the review highlighted a number of areas where additional records and information would be useful for the purposes of this project.

Table 2.7 provides a summary of items requested prior to the completion of this report to enable a full assessment of the low cost baffle solution to be undertaken. An indication of whether these were available/received and comments on the level of detail and the relevance of each item are provided.

Relevant data requested	Received	Comment
Design drawings of the original structures and the aids to improve fish passage, and as-built dimensions, where they exist;	Yes	No as built drawing, Only dimensions of proposed gauging station. Two sets of levelling data.
Instrumentation details including set-up and historical records e.g. maintenance, replacement;	Part	Comprehensive details of set up, but no/ poor record of maintenance or set up dates.
Gauging station histories;	Yes	Comprehensive details of changes occurred on site, although may not be up to date.
Stage-discharge data and rating history;	Yes	Good historical records of previous rating through graphs. No details of what rating where used and when.
Current and historic ratings, how they have been derived and any supporting information;	Yes	Stage-discharge report detailing the current rating and developments of rating. Could do with more information of rating derived in the past. There are a wide range of gaugings at a range of flows.
Maintenance schedules/logbooks	Yes	There is no log of maintenance. There is a log of site visits.
Photographs of the structures, preferably over a wide range of conditions, particularly at extreme low and high flows which may not be experienced during the study period;	Yes	There are a selection of photos but could do with more at selection of flows. More digital photos of fish pass and debris catching. Could use photo upstream of gauging station to review upstream channel properties at a range of stages.
Any additional anecdotal evidence regarding the operation of the structure prior to and following the installation of aids to improved fish passage e.g. noticeable changes in velocity distribution, debris accumulation, geomorphological impacts.	Yes	Record of debris catching on weir could be valuable, as would records of accumulation of debris, build up of silt and any impact on geomorphology caused by the weir.

Table 2.7 Summary of data availability for Brimpton

Flow statistics for Brimpton Gauging Station, obtained from the National River Flow Archive (NRFA), are provided in Table 2.8 below:

Station details	Figures (m^3/s)
Mean Flow	1.32
Q95	0.159
Q10	2.94
POT	8.24
Modular limit	18

Table 2.8 NRFA flow statistics for Brimpton

POT = Peaks over threshold, flows above a selected threshold (such as five flood events per water year)
Q95 = The flow that is exceeded 95 per cent of the time
Q10 = The flow that is exceeded 10 per cent of the time

The modular limit for Brimpton Gauging Station is thought to be between 0.8 and 1.0mASD. The current Environment Agency rating is believed to be the one developed by Hydro-Logic in 2001 as part of a separate rating review study. Since the installation of the new baffles, surveyed on 16 February 2010, further gaugings have been undertaken by the Environment Agency. Both the Environment Agency's rating and a further rating developed by Hydro-Logic using the latest survey have been used in the assessment of the station following the baffle installation.

The limited time frame since the replacement baffles were installed means that an intense period of gaugings covering all available flows was undertaken. However this range is limited and further consideration of the limits of the analysis is provided in relevant sections below.

2.5.4 British Standards

The detailed survey information collected during the initial site survey was compared to British Standards, to assess whether the structure meets the guidelines. N.B.: Refer to glossary for explanation of terms.

Table 2.9 indicates that the Crump weir structure generally meets British and International Standards. Factors that do not technically meet the requirements are judged to be within tolerable limits for accurate flow measurement. These include the placement of the upstream head measurement location and width of the crest relative to H_{max} at the structure's capacity. Also identified is the potential for silt build up on the downstream apron of the high flow section, which may affect the gradient of the slope over time.

Criteria	High crest	Suitable	Low crest	Suitable
h at Q_{99} >0.03	Below crest- no flow	N/A	0.113	Yes
p >0.06	1.079	Yes	0.766	Yes
Width (b) >0.3	4.5	Yes	3	Yes
H_{max}	1.354		1.7	
h/p <3.5	1.255	Yes	2.219	Yes
b/ H_{max} >2	4.17	Yes	1.765	Pass Hmax should be 1.5m
Truncation US (H_{max}) DS(> 2 times H_{max})	N/A	N/A	N/A	N/A
Head water level sensor > 2 H_{max} upstream	2.705	Within error Should exceed 2.708	2.705	Should exceed 3.4
Head intake pipe level must be below crest – crest > 59.35	59.72	Yes	59.42	Yes
Tail water level sensor > 3 H_{max} (exceed 5.1)	8.04	Yes	8.04	Yes
Upstream slope 1:2	0.5	Yes	0.5	Yes
Downstream slope 1:5	0.19	Yes	0.2	Yes
Crest level	1mm	Yes	2mm	Yes

N.B.: Refer to glossary for explanation of terms.

Table 2.9 Conformance of the two weir crests to BS/ISO 4360:2008

The site survey undertaken by Hydro-Logic was compared to Halcrow's 1999 survey. Despite the Halcrow survey only being presented to two decimal places, the levelling appeared very similar and both surveys agreed to the nearest 10mm. The crest and upstream and downstream slopes are all level, suggesting that this structure is not experiencing subsidence or movement.

2.5.5 Work undertaken

Analysis at Brimpton included a desk-based study to form a working knowledge of the site.

The station history was assessed alongside the previous rating work at the site and the designs for the fish pass. This was followed by a detailed survey of the structure.

Following replacement of the baffles, further survey and spot flow gaugings were undertaken at the structure. These gauged flows were used to assess the theoretical rating and the impact of the baffles.

The final analytical work included assessment of the uncertainties relating to the surveyed baffles, further assessment of the ratings and analysis of the operational constraints on the site, including debris and head measurement.

2.5.6 Initial rating review

Historical rating analysis

Hydrometric data for this site is available from 1967. It should be noted that the theoretical rating applied from 1967 until 1977 was a basic Crump formula and did not include any correction for non-modular flow conditions. In 1977 the rating was changed to include a correction for periods when the weir was drowned. This appears to have been confirmed by only two gaugings and is therefore likely to be subject to considerable uncertainty. In 1991 a tail water level sensor was installed and corrections to the rating were made for non-modular periods using tail water levels. However, based on the initial inspection this rating continues to underestimate the flow when the river is out of bank (that is, above wingwall level). There are also concerns regarding the accuracy of the downstream water level record (refer to Section 2.5.8 Level Measurement).

In September 2001 Hydro-Logic reviewed the site as part of a separate project and derived a rating (Figure 2.31). This is believed to be that currently in use by the Environment Agency. Some of the historical gaugings provided are known outliers due to an error that occurred when transferring the gaugings from the Environment Agency's previous Spot Flows database to the present WISKI database. These have been removed from further analysis.

The historical gaugings undertaken at the site prior to the installation of any baffles are shown in Figure 2.31 below. When applied to the pre-baffle period the latest rating appears to slightly over-estimate the flow throughout the majority of the measured range.

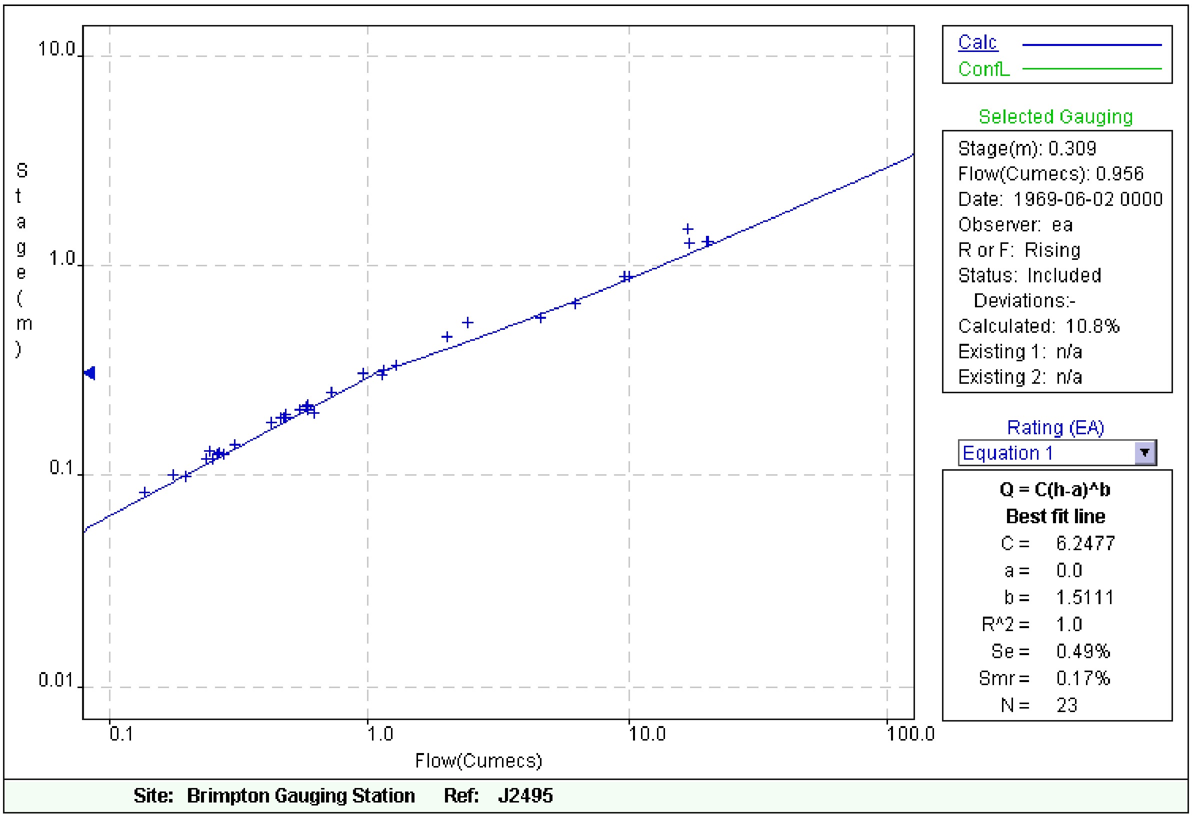


Figure 2.31 Environment Agency rating and gaugings to date

The stage deviation plot (Figure 2.2) appears to confirm that the rating is overestimating the flow relative to the gauged flows, as evident in the weighting of points to the positive area of the graph, particularly at very low and high flows. The high positive percentage deviation at higher flows is most likely due to the impact of non-modular conditions.

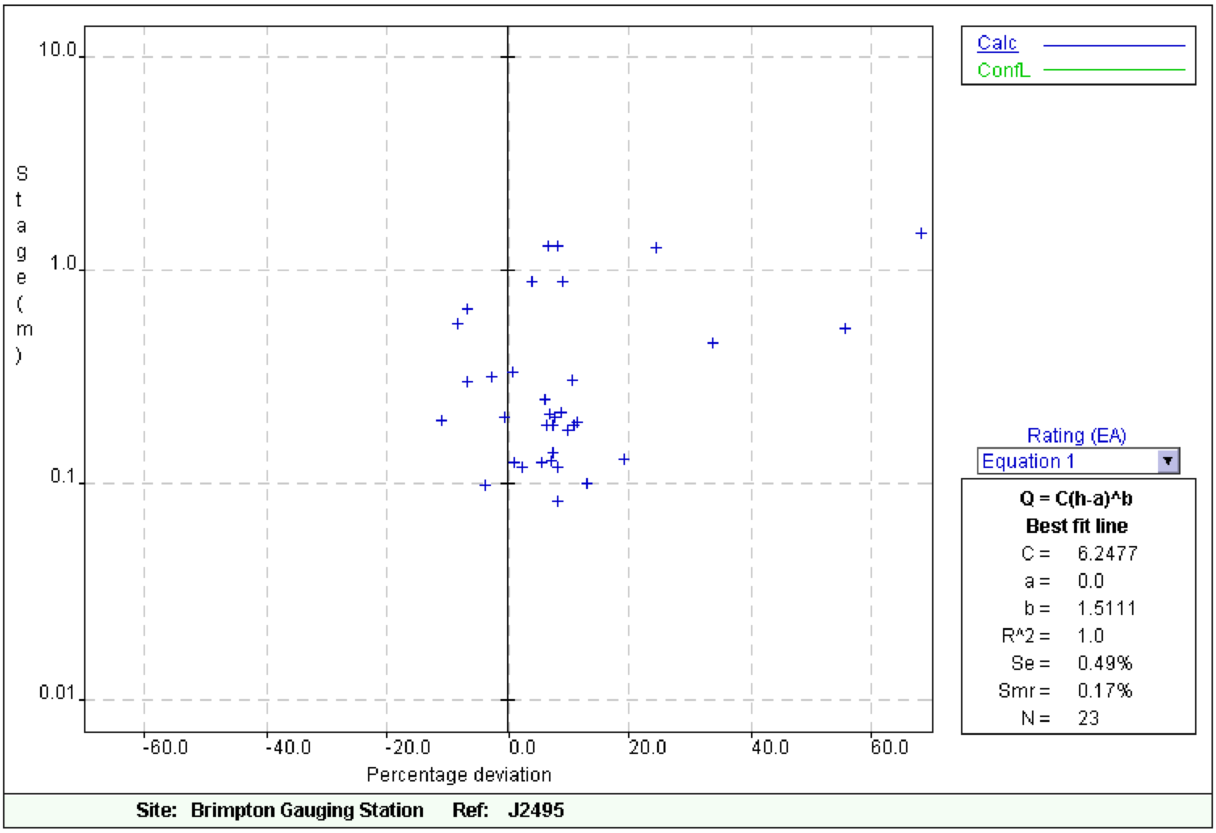


Figure 2.32 Stage deviation from current Environment Agency rating

Figure 2.3 indicates that the degree of scatter in the data has increased since 2000. This may in part be due to gaugings being undertaken over a wider range of stages and flows than was previously the case. There appears to be no significant seasonal variation.

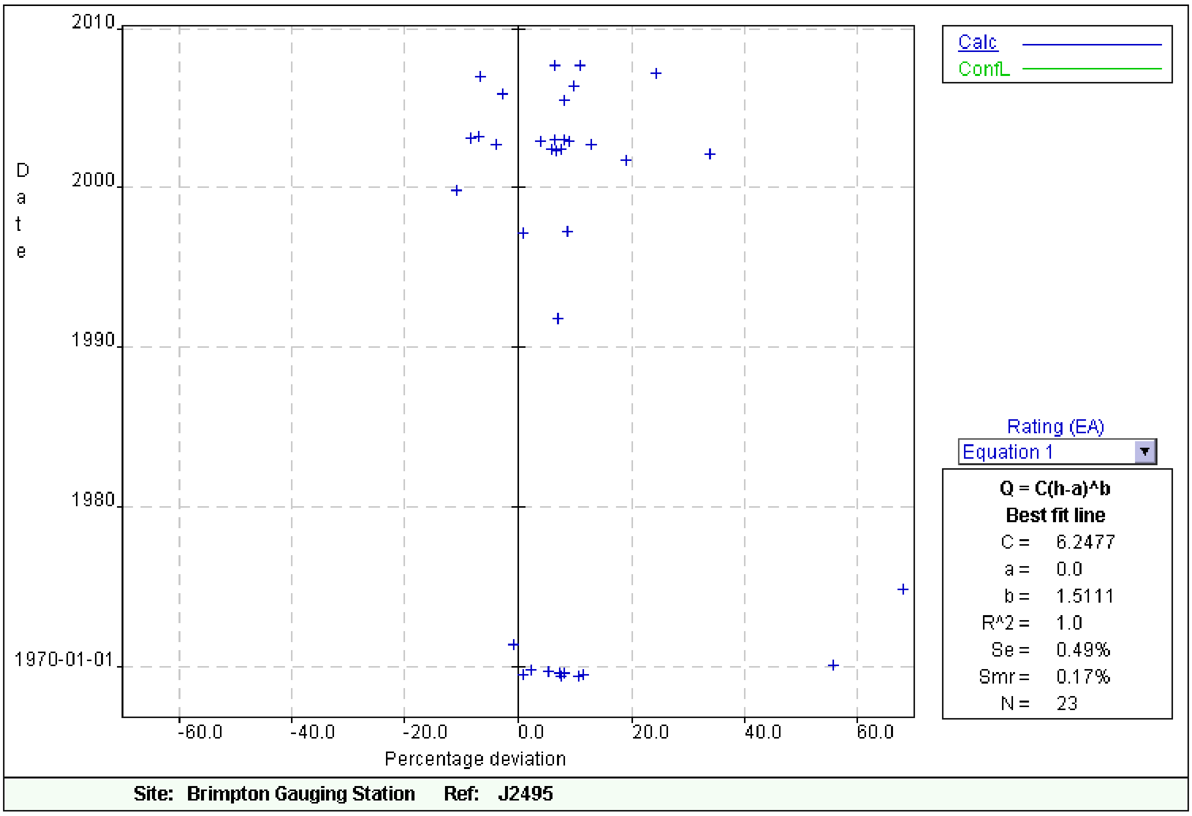


Figure 2.33 Date deviation from current Environment Agency rating

A comparison of flows recorded by spot flow gaugings and those derived using the current Environment Agency rating is provided in Table 2.0 below. This shows the percentage difference in gaugings before the baffles were installed. Most gaugings are within +/-10 per cent of the Environment Agency rating. The average percentage difference for gaugings undertaken before the installation of the baffles is 9.5 per cent, though this is adversely affected by high percentage differences, particularly at high flows when the structure goes non-modular. With the non-modular gaugings removed, the deviation is around 7.7 per cent.

Date	Stage US (m)	Flow m^3s-1	Environment Agency rating m^3s-1	Difference %
02/06/1969	0.3090	0.9560	1.0594	10.8
11/06/1969	0.1910	0.4760	0.5121	7.6
24/06/1969	0.1970	0.4810	0.5366	11.6
17/07/1969	0.1280	0.2770	0.2797	1.0
23/07/1969	0.1220	0.2400	0.2601	8.4
31/07/1969	0.1430	0.3080	0.3307	7.4
22/09/1969	0.1280	0.2650	0.2797	5.6
22/10/1969	0.1220	0.2540	0.2601	2.4
20/01/1970	0.5430	2.4200	3.7691	55.7
01/06/1971	0.2090	0.5900	0.5868	-0.5
15/11/1974	1.5200	17.1000	28.7682	68.2
16/10/1991	0.1300	0.2670	0.2863	7.2
08/03/1997	0.3390	1.2800	1.2915	0.9
26/03/1997	0.2210	0.5870	0.6384	8.8
21/10/1999	0.2020	0.6250	0.5573	-10.8
20/09/2001	0.1320	0.2460	0.2930	19.1

09/02/2002	0.4650	2.0100	2.6914	33.9
25/04/2002	0.2160	0.5770	0.6167	6.9
23/05/2002	0.2510	0.7290	0.7738	6.1
20/06/2002	0.2100	0.5490	0.5910	7.7
23/09/2002	0.1030	0.1780	0.2014	13.2
23/09/2002	0.1000	0.2000	0.1926	-3.7
16/11/2002	0.9000	9.6900	10.5587	9.0
16/11/2002	0.9020	10.2000	10.6048	4.0
02/01/2003	1.3100	20.4000	21.7488	6.6
02/01/2003	1.3100	20.1000	21.7488	8.2
11/02/2003	0.5750	4.6400	4.2555	-8.3
02/04/2003	0.3080	1.1300	1.0542	-6.7
23/06/2005	0.0850	0.1390	0.1507	8.4
09/11/2005	0.3200	1.1500	1.1191	-2.7
04/05/2006	0.1800	0.4260	0.4682	9.9
11/01/2007	0.6700	6.2600	5.8461	-6.6
06/03/2007	1.3000	17.2000	21.4357	24.6
28/08/2007	0.1910	0.4610	0.5121	11.1
28/08/2007	0.1910	0.4810	0.5121	6.5

Table 2.10 Percentage difference in the gaugings pre-baffle installation

A revised theoretical rating was produced using the survey dimensions obtained during the course of this project (Figure 2.4). The revised theoretical rating shows a reasonable fit with the pre-baffle gaugings over the full range of flows. The rating also appears to overestimate flow to a small degree, predominantly at lower stages.

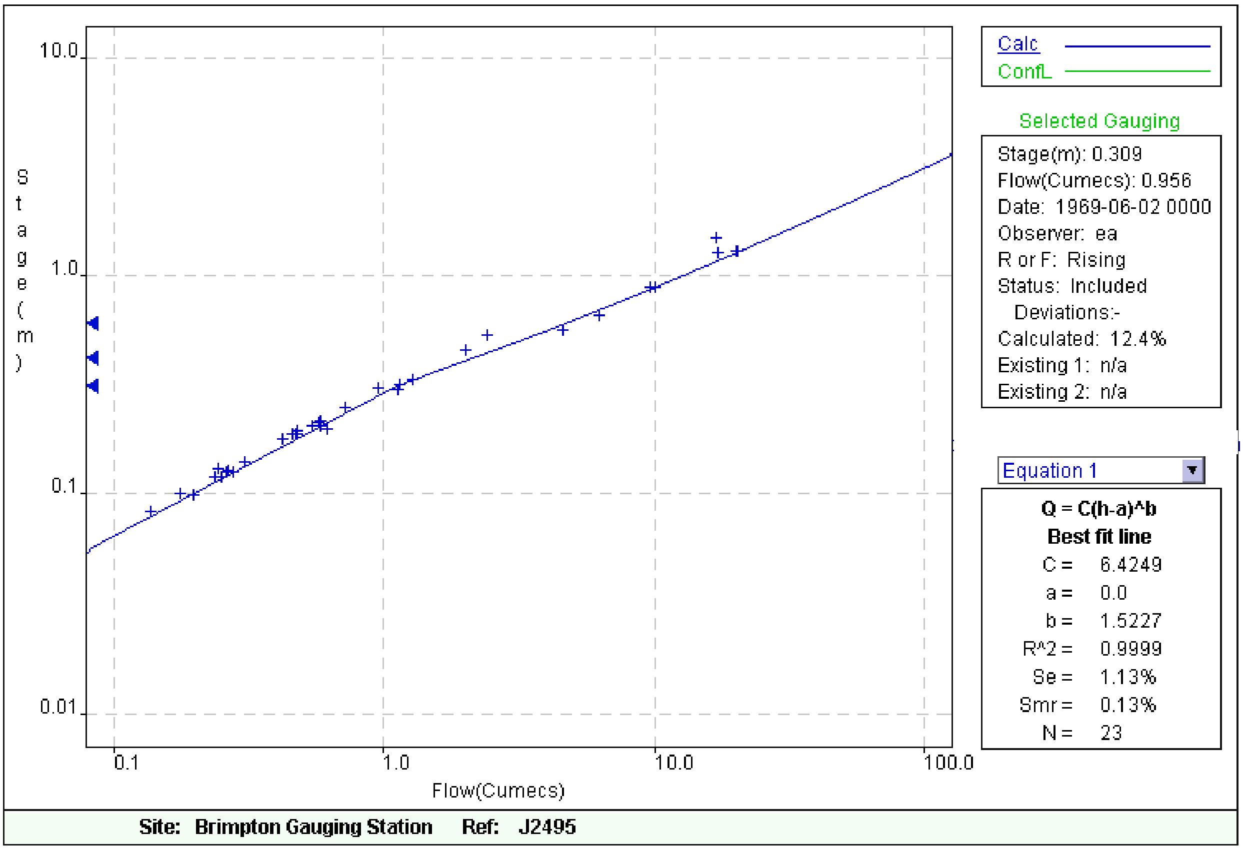


Figure 2.34 Revised theoretical rating from recent survey against gaugings to date

In Figure 2.5 and table 2.11, the revised theoretical rating line using the most recent weir dimensions (in blue) is displayed alongside the existing Environment Agency rating (in red). The maximum difference between the two ratings is found to be -5.2 per cent, with the revised rating fitting the recent data points slightly better than that derived in 2001. The kick in the existing Environment Agency rating at the change between high and low crests is a technical concern. If the existing Environment Agency rating is to remain in use, this should be reviewed and amended.

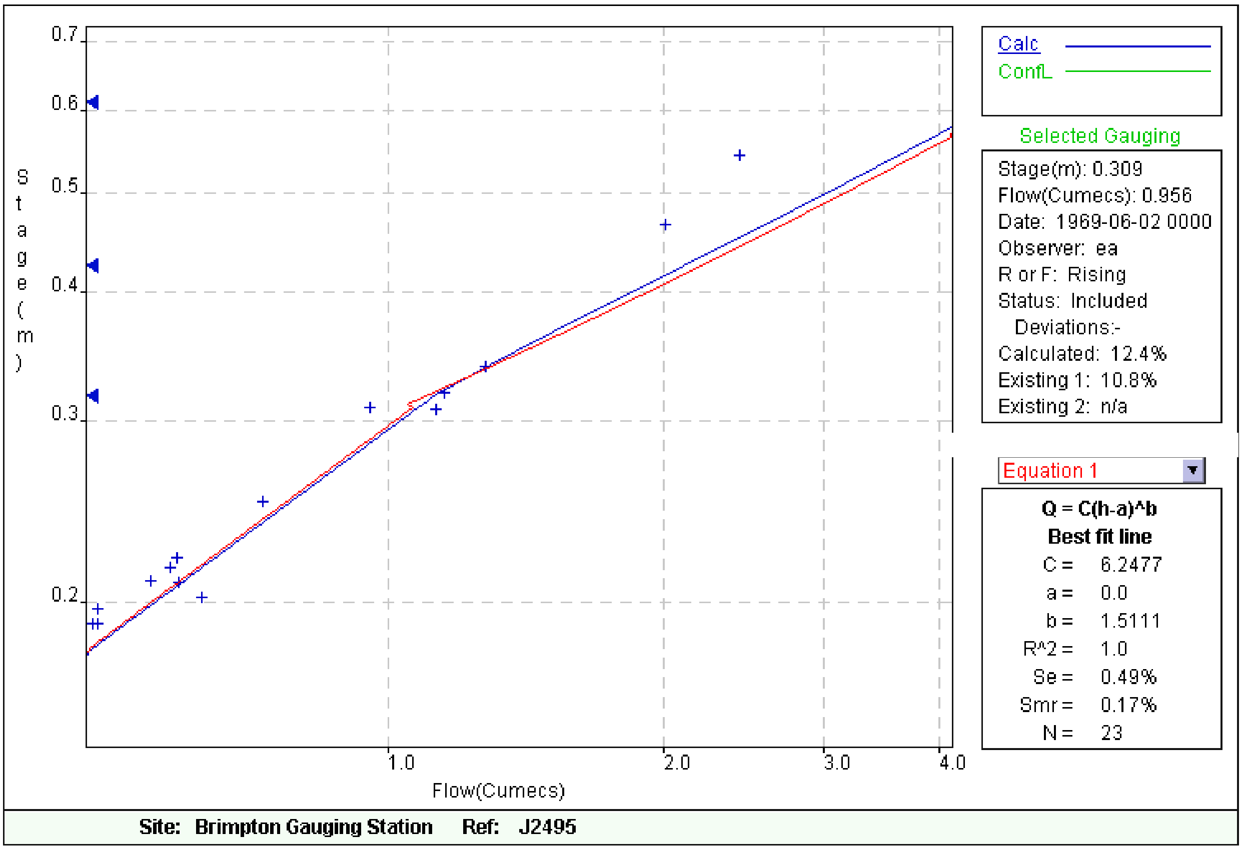


Figure 2.35 Environment Agency and Hydro-Logic ratings at change point

The conclusion of the previous rating review, undertaken by Hydro-Logic in 2001, was to use the theoretical Crump weir relationship based on the latest available structural dimensions at the time, as no justification could be found for applying an alternative rating. The current Environment Agency rating is considered to provide a suitably accurate baseline against which to undertake further analysis of the performance of the retrofitted baffles. Whilst the slight jump observed at the change point at approximately 0.3mASD is a concern and should be reviewed by the Area Hydrometry and telemetry team, all the recent gaugings with 200mm baffles are assessed relative to the upper limb of the stage-discharge relationship.

Ref.	H_{min}	H_{max}	C	a	β
Existing Environment Agency theoretical rating:					
Segment 1	0	0.319	6.2477	0	1.511
Segment 2	0.320	0.999	15.507	-0.097	1.7518
Revised theoretical rating:					
Segment 1	0	0.317	6.4249	0	1.5227
Segment 2	0.318	0.425	7.7153	-0.293	3.9120
Segment 3	0.425	0.610	14.7328	0.085	1.8034
Segment 4	0.610	0.999	15.1560	0.115	1.6934

Table 2.11 Summary of existing and revised theoretical rating equations

It is recommended that the revised theoretical rating be adopted by the Environment Agency as this is based on the most recent available survey dimensions and is considered to provide improved flow prediction based on theoretical Crump weir formulae.

Post-baffle rating analysis: 120mm baffles

Initially baffles were installed at Brimpton with a height of the top baffle of 120mm. Detailed analysis on the potential impact of these baffles on the hydrometric performance of the structure is provided below.

The 120mm baffles were surveyed on 23 October 2008. This revealed that the first two baffles were at a similar height. The baffles were measured as accurately as possible and the top baffle found to be 0.108m in height, and 0.119m below the weir crest elevation. The survey indicates that the second baffle is only 2mm lower than the first baffle at 0.121 m below the weir crest elevation. Given the flow conditions at the time of the survey, and the difficulties of gaining accurate levels on a sloping weir crest and wooden baffles, it is likely that the levels provided are only accurate to +/- 3mm at best.

A limited range of gaugings were undertaken during the period when these baffles were in place, the results of which are below in Table 2.2. The gaugings undertaken at the site while the 120mm baffles were in place show a slightly reduced bias with respect to the existing Environment Agency rating (Figure 2.6).

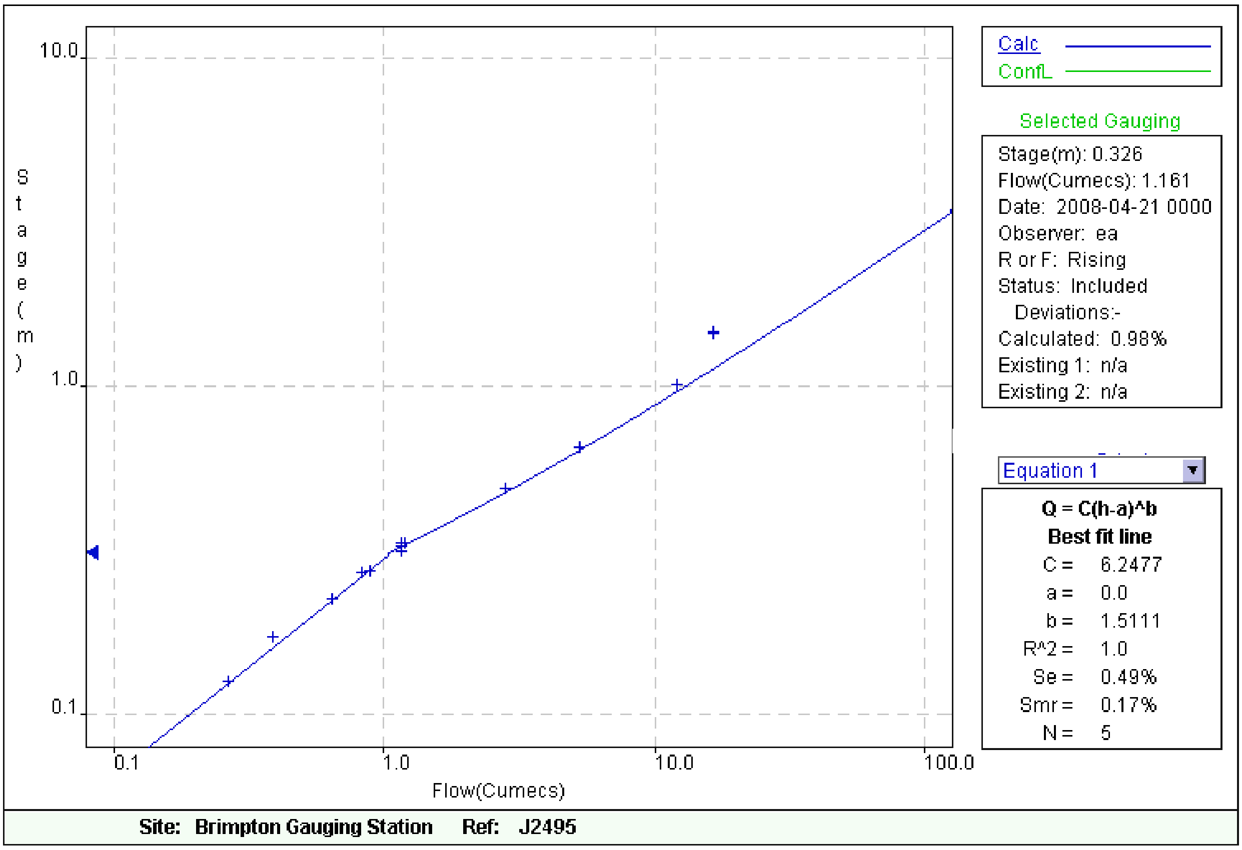


Figure 2.36 Gaugings undertaken with 120mm baffles compared to current rating

The deviation with stage and date shown below (Figure 2.7 and Figure 2.8) also suggests slightly reduced bias with respect to the Environment Agency Rating.

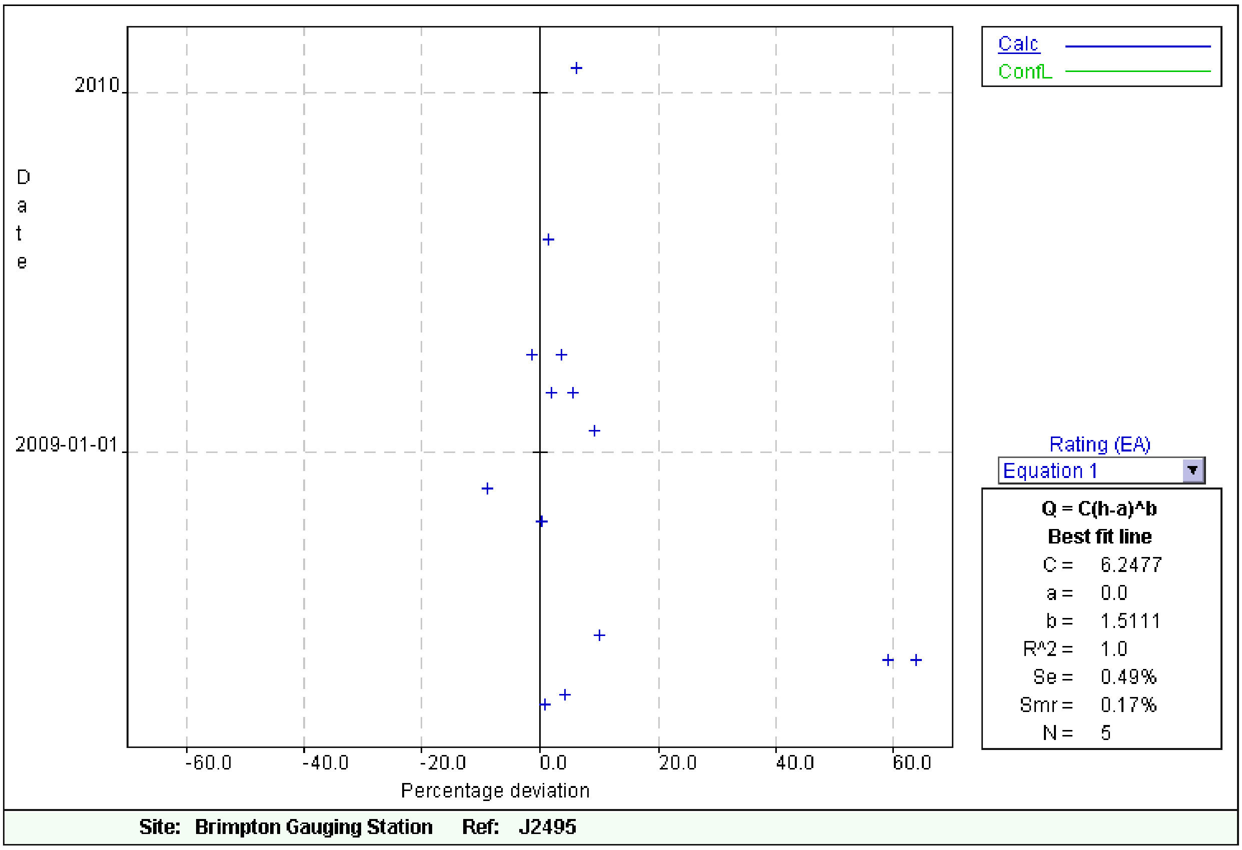


Figure 2.37 Gauging deviation with date: 120mm baffles

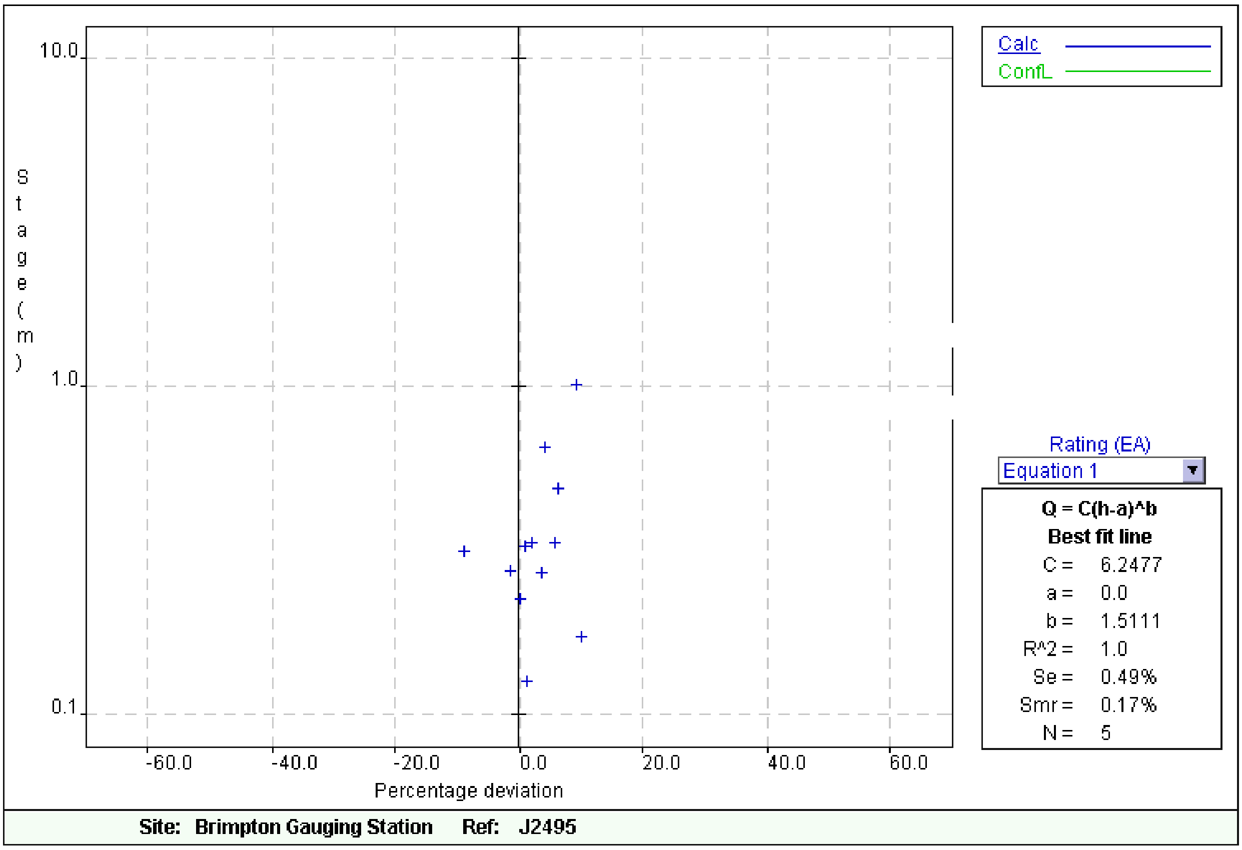


Figure 2.38 Gauging deviation with stage: 120mm baffles

A summary of the gauged flows during the period when the 120mm baffles were in place is shown below. The percentage difference from the existing Environment Agency rating is 11.3 per cent. The average is skewed by the non-modularity of the gaugings undertaken on 4 June 2008. When these gaugings are omitted, the average is 2.9 per cent. Over the same stage range, deviation prior to the baffle installation was 8.1 per cent, with no non-modular gaugings undertaken within this range.

Date	Stage US(m)	Flow m^3s-1	Environment Agency rating m^3s-1	Difference (%)
21/04/2008	0.326	1.1610	1.1724	1.0
01/05/2008	0.654	5.3300	5.5631	4.4
04/06/2008	1.450	16.5340	26.3351	59.3
04/06/2008	1.470	16.4840	27.0209	63.9
30/06/2008	0.171	0.3930	0.4333	10.3
23/10/2008	0.223	0.6450	0.6472	0.3
26/11/2008	0.313	1.1600	1.0583	-8.8
23/01/2009	1.010	12.1000	13.2215	9.3
02/03/2009	0.332	1.1600	1.2268	5.8
02/03/2009	0.332	1.2000	1.2268	2.2
09/04/2009	0.270	0.8320	0.8640	3.8
09/04/2009	0.273	0.8900	0.8785	-1.3
05/08/2009	0.125	0.2660	0.2699	1.5
25/01/2010	0.490	2.8400	3.0198	6.3
			Average difference	11.28

Table 2.12 Gauging record for the 120mm baffle period

The observed reduction in the deviation of the rating from the gaugings would occur as a result of a reduced head for the same flow. This apparent overall reduction of the scatter in the data may result from more accurate gauging over the observed range, a datum shift in the stage data, improvements in the maintenance regime or the weir crest being kept clean during this period, or simply the product of a relatively limited statistical sample. There is little physical justification for the reduction being a result of the installation of the baffles.

Post-baffle installation rating analysis: 200mm baffles

Following installation of the 200mm replacement baffles in February 2010, an intense phase of gauging was undertaken by Hydro-Logic to produce a data set for analysis of the final baffle configuration. Gaugings were undertaken in the range 0.4m to 0.5m, where in theory the baffles are likely to have the most impact in terms of percentage uncertainty in flow measurement.

At the time of the gauging undertaken by Hydro-Logic on 22 February 2010, a large tree was lodged on the high crest weir. While this may have increased the deviation of this gauging slightly, it is not thought that it would have resulted in the full 19 per cent deviation seen. A gauging was also undertaken by the Environment Agency approximately 40m downstream of the weir structure. The side stream is reported to have been having minimal impact at this time.

These gaugings are shown plotted against the current Environment Agency rating in Figure 2.9. The apparent bias is similar to that observed for the pre-baffle gaugings, suggesting that the 200mm baffles do not significantly impact on the hydrometric performance of the structure.

The Environment Agency rating is shown below, in Figure 2.9. Deviation with stage is shown in Figure 2.40 and Table 2.13.

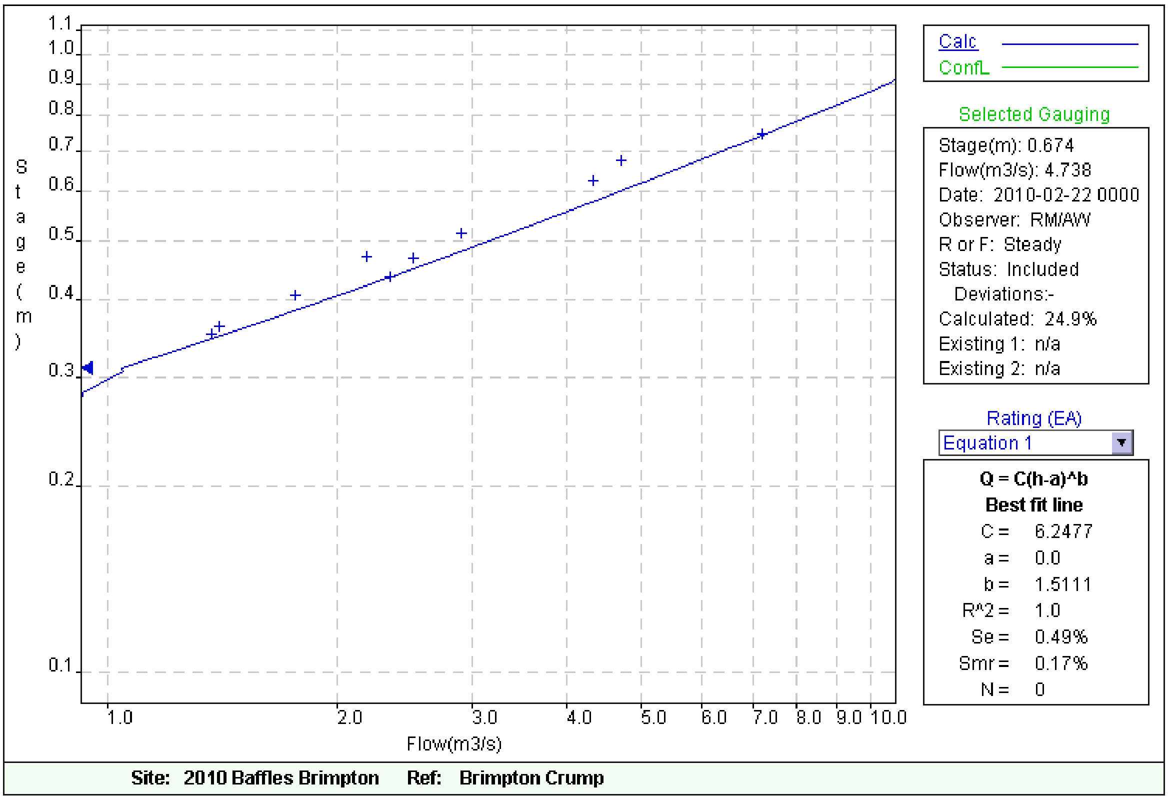


Figure 2.39 Post-baffle installation gaugings compared to current rating

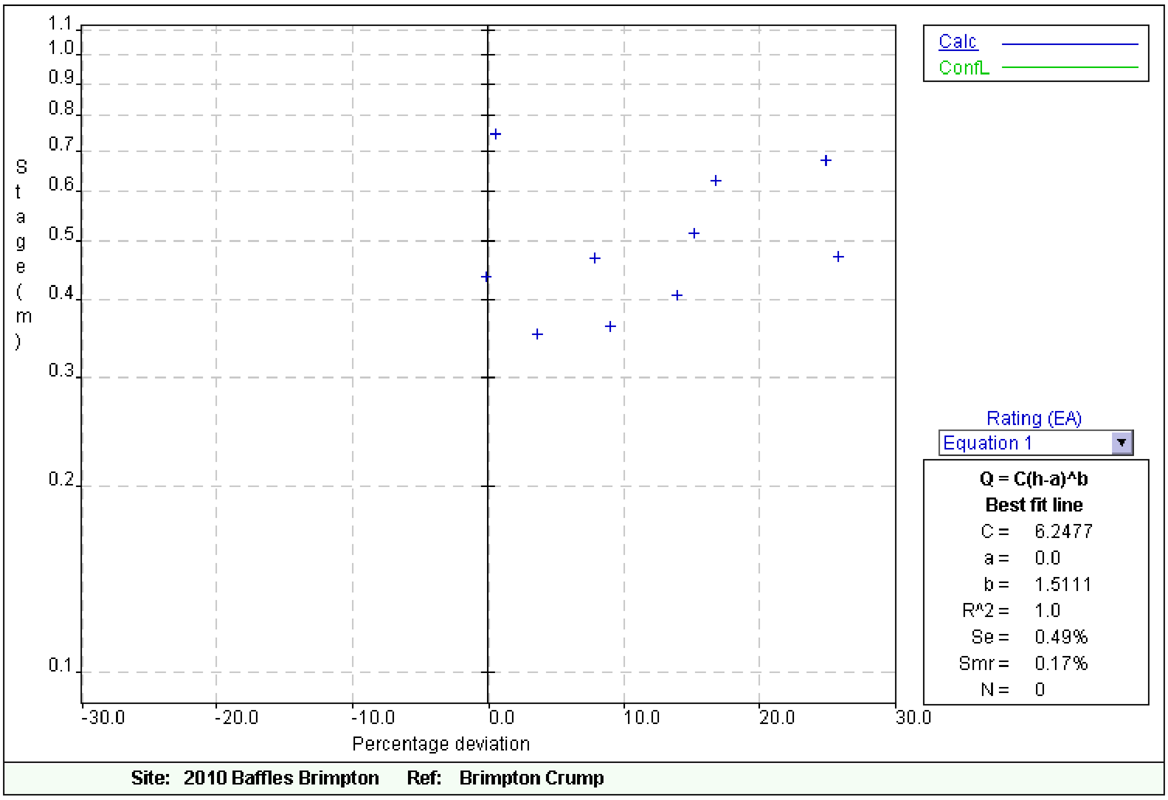


Figure 2.40 Stage deviation in post-baffle installation gaugings compared to current rating

The structure was observed to be modular, based on the dipped downstream stage values, under all flow conditions gauged since the installation of new baffles in mid-February 2010.

The average deviation of the current Environment Agency rating from the gaugings is 18.7 per cent for the pre-baffle gaugings and 11.75 per cent for the post-baffle gaugings, over the same stage range. This suggests that the baffles have no significant or observable effect leading to an increase in the stage measurement at Brimpton. The deviation does however suggest a fall in stage leading to a 7 per cent improvement. It is important to note that these conclusions are only valid for the range of stages monitored (0.353m – 0.746m), and within this range there are only four pre-baffle gaugings.

Date & time	Stage US(m)	Flow m^3s^{-1}	Environment Agency rating m^3s^{-1}	Difference%
19/02/2010 10:18	0.471	2.200	2.769	25.9
22/02/2010 12:21	0.674	4.735	5.911	24.8
26/02/2010 11:19	0.746	7.232	7.271	0.5
01/03/2010 14:55	0.626	4.341	5.083	17.1
02/03/2010 15:26	0.515	2.9200	3.364	15.2
03/03/2010 14:19	0.468	2.5390	2.730	7.5
04/03/2010 00:00	0.438	2.3570	2.355	-0.1
05/03/2010 11:43	0.409	1.7690	2.016	13.9
08/03/2010 12:22	0.364	1.4080	1.534	9.0
10/03/2010 15:30	0.353	1.3750	1.425	3.7
			Average difference	11.75

Table 2.13 Percentage comparison of post-baffle installation gaugings with current rating

As with the 120mm baffles, it is apparent that the rating now seems to fit the gaugings more closely than it did historically. This would be caused by greater flow for the same stage. Both sets of baffles appear to have seen an improvement of around five to seven per cent in the derived flows. While the mounting of baffles on the downstream face of the weir would not have caused this through any hydraulic impact, other factors that may have contributed to this improvement include:

- The maintenance regime may have improved with the installation of the fish pass baffles; for example, algal growth cleaned more regularly than in the past.
- The choice of gauging location or the technology used may have provided more accurate spot flows than those taken historically.
- A change in the datum offset or the method of stage measurement may have historically affected the gaugings.

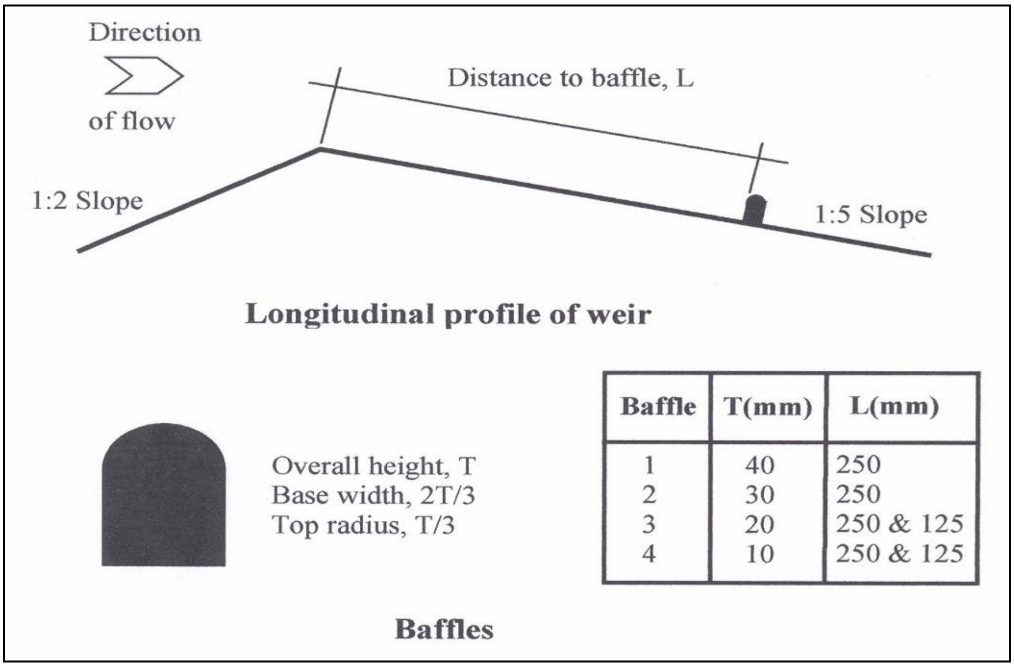
Alternatively it is possible that the apparent reduction in bias is a function of the relatively limited statistical sample available in terms of total gaugings undertaken.

Future measurements should be taken to ensure that the side channel on the left bank immediately downstream of the structure is accounted for, when relevant. Ideally this should be through selection of a gauging section upstream of the structure when there is a significant contribution in flow from the side stream or through independent measurement and subtraction of the flow from the side stream from the total for the main channel. Gaugings undertaken upstream of the structure require the use of a boat-mounted ADCP instrument and are typically most appropriate under higher flow conditions. All Hydro-Logic ADCP gaugings undertaken in February and March 2010 have been undertaken upstream of the bend in the approach to the structure, ensuring that skewed flow was avoided. The Environment Agency gauging undertaken on 4 March 2010 was undertaken 40m downstream of the structure. The side channel is reported not to have been significantly contributing to the total flow in the main channel at this time.

2.5.7 Uncertainties associated with baffle arrangement at Brimpton

The latest guidelines for installation of baffles to improve fish passage (White *et al*., 2006) provide guidance on the maximum height and location of baffles relative to the invert of the crest. Baffles that are either too high or installed too close to the crest will affect the modular flow conditions and in turn the accuracy of the structure. However, the baffles must be placed as close as possible to the crest to minimise the barrier for fish travelling upstream.

As reported by White, Iredale and Armstrong (2006), laboratory-based research has been undertaken to investigate the effect of installing fish baffles on flow measurement structures. Coefficients for the optimum location of baffles and the impact of these in relation to stage are a product of the height of the baffles and the distance from the crest to the first baffle down the face of the weir (refer to Figure 2.41).



Baffle	T(mm)	L(mm)
1	40	250
2	30	250
3	20	250 & 125
4	10	250 & 125

Figure 2.41 Optimum location of baffles on V-profile weirs (White *et al*., 2006)

The impact analysis uses the relationship between H/L and H/T, where H is the head over the weir, L is the length between the crest and the first baffle (measured down the face of the weir) and T is the height of the baffle.

At Brimpton Gauging Station, the original top baffle was found to not meet the correct specifications and a new top baffle was installed in February 2010. Initial calculations provided by Richard Iredale recommended that the 0.2m height baffles used at Brimpton should be a minimum of 1.2m downstream of the crest

(L) assuming a modular limit of 0.5m. Despite the difficulties in surveying the weir structure and baffles, it was confirmed that the crest of the reinstalled Brimpton baffles are located approximately 1.26m downstream of the low flow Crump weir crest.

A comparison of the performance of the baffle arrangement at Brimpton with the results of the theoretical investigation is provided in Figure 2.2 below. The solid line has been derived using the coefficient of discharge from the laboratory research. At or below this line the baffles will have no effect on the measurement accuracy of the structure. This line has been plotted for a range of values using two separate equations with the change point a product of head over the weir in relation to H/T.

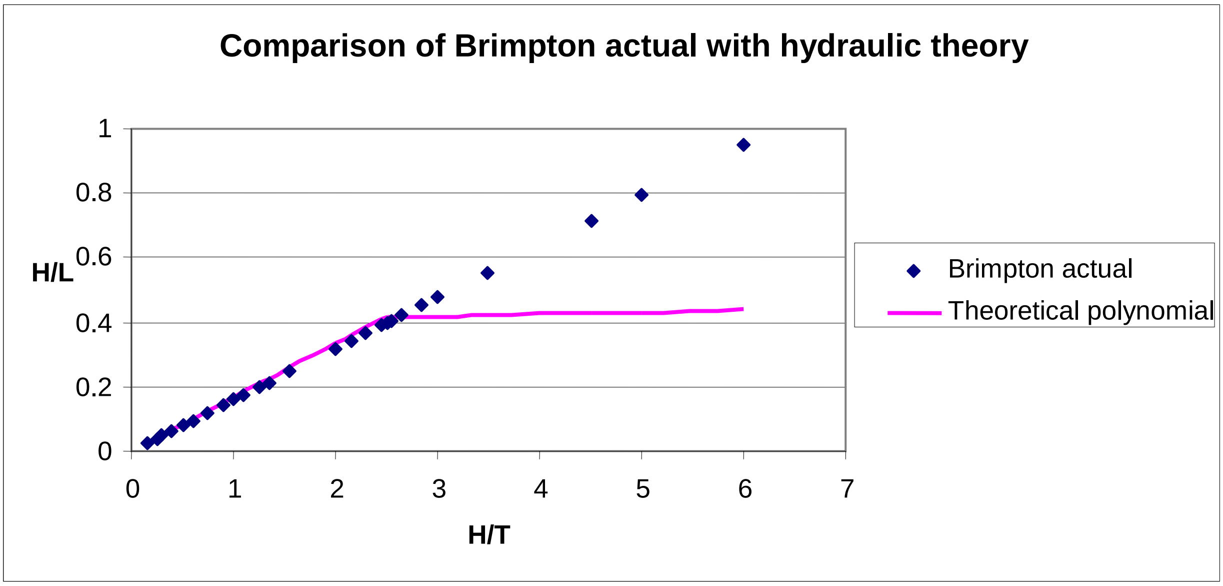


Figure 2.42 Performance analysis of Brimpton baffles

The graph indicates that for stages up to approximately 0.5m (H/L = 0.4) the impact is below the coefficient and the baffles should be having no measurable impact on the accuracy of flow measurement associated with the Crump weir. Above this point, up to a stage of 0.8m (H/L = 0.63), error should be less than 2 per cent. This is related to deviation from the coefficient of discharge. Above a stage of 0.8m, non-modular flow conditions begin to occur. Providing baffles of the correct size and shape are accurately installed, the theoretical impact of the retrofit baffles should be minimal and within acceptable limits.

The latest baffles installed in February 2010 are shown in Figure 2.3 below. These show a hydraulic disturbance much closer to the crest than would be expected. It is likely that this disturbance is caused by the stop-log slots at each side, despite an attempt being made to block these off with wooden inserts.

Figure 2.43 Hydraulic performance of the reinstalled baffles at Brimpton

2.5.8 Level measurement

Although the tail water level sensor meets British/International Standards, being located a minimum of three times H_{max} downstream of the crest, the water level sensor is reported to be affected by the hydraulics of the weir exit, and eddying and turbulence have been noted around the stilling tube. The turbulence at the tail sensor was observed during the site survey visit and was also noted by Nick Everard and Adam Whalley (Environment Agency) on separate occasions. The Environment Agency records state that at high flows the water level sensor readings could be up to 30mm out from the dip value, due to the turbulence.

Figure 2.4 below shows the head and tail water level records for the period January 2005 to December 2008.

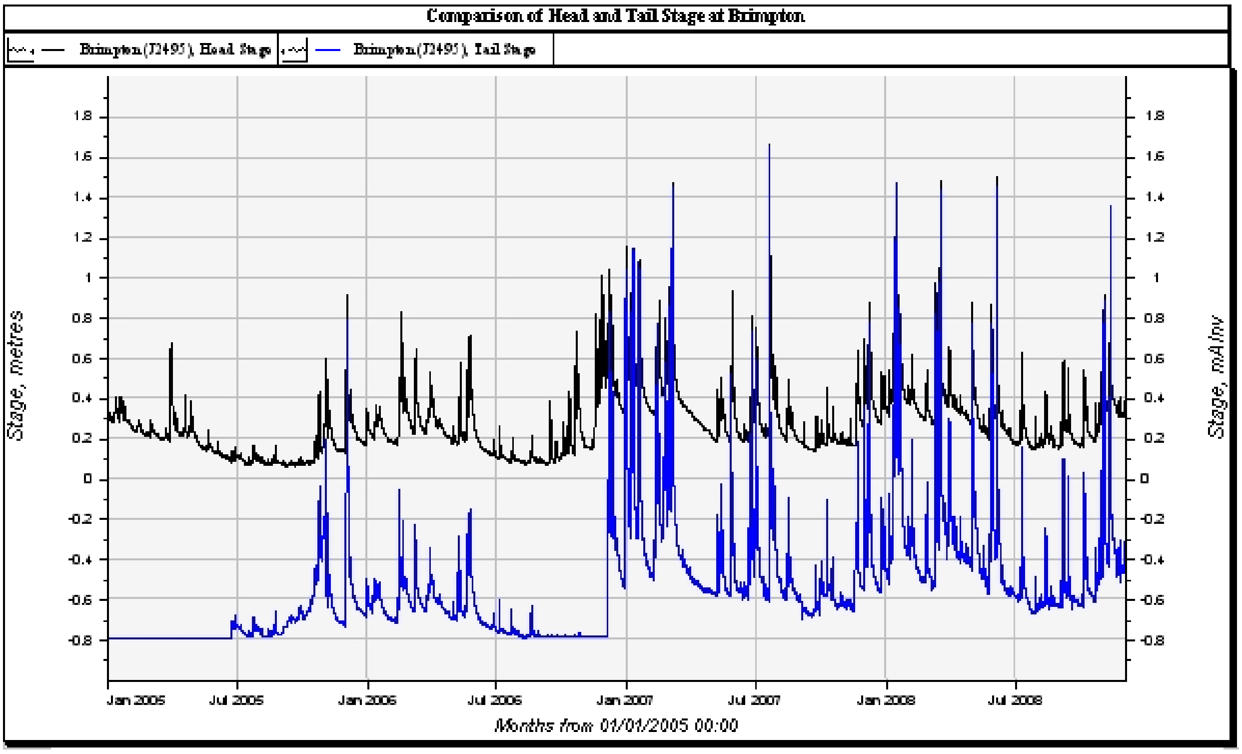


Figure 2.44 Comparison of head and tail water level data

An attempt was made to undertake a modularity assessment using the data in this period. It was found that the data from the tailwater recorder was out from the datum reading on most visits by a varying but always significant degree (by 29mm on 19 September 2008, for example). Record sheets indicated that there was considerable drift, particularly in months where there was a large range in stages. It is possible that some of these discrepancies may be the result of turbulent conditions in the vicinity of the downstream stilling pipe, leading to significant differences between the dip readings and associated logged stage values. However, in some cases the magnitude of the difference suggested a more significant issue, possibly related to the ranging of the instrument. In an attempt to resolve this issue a member of the Environment Agency Hydrometry and Telemetry team recalibrated the water level sensor on 26 November 2008.

Since recalibration, the major impact on the downstream tail record has been turbulence. This has been noted on the station log sheets on a number of occasions, and in some cases the tail level has not been reset due to the difficulties associated with gaining a representative measurement in turbulent conditions.

Figure 2.5 below provides an overview of the stage records at Brimpton throughout the project. Although the stage records appear reasonable for the majority of the period, the tailwater record exceeds the upstream stage record during the high flow event on 14 December 2008.

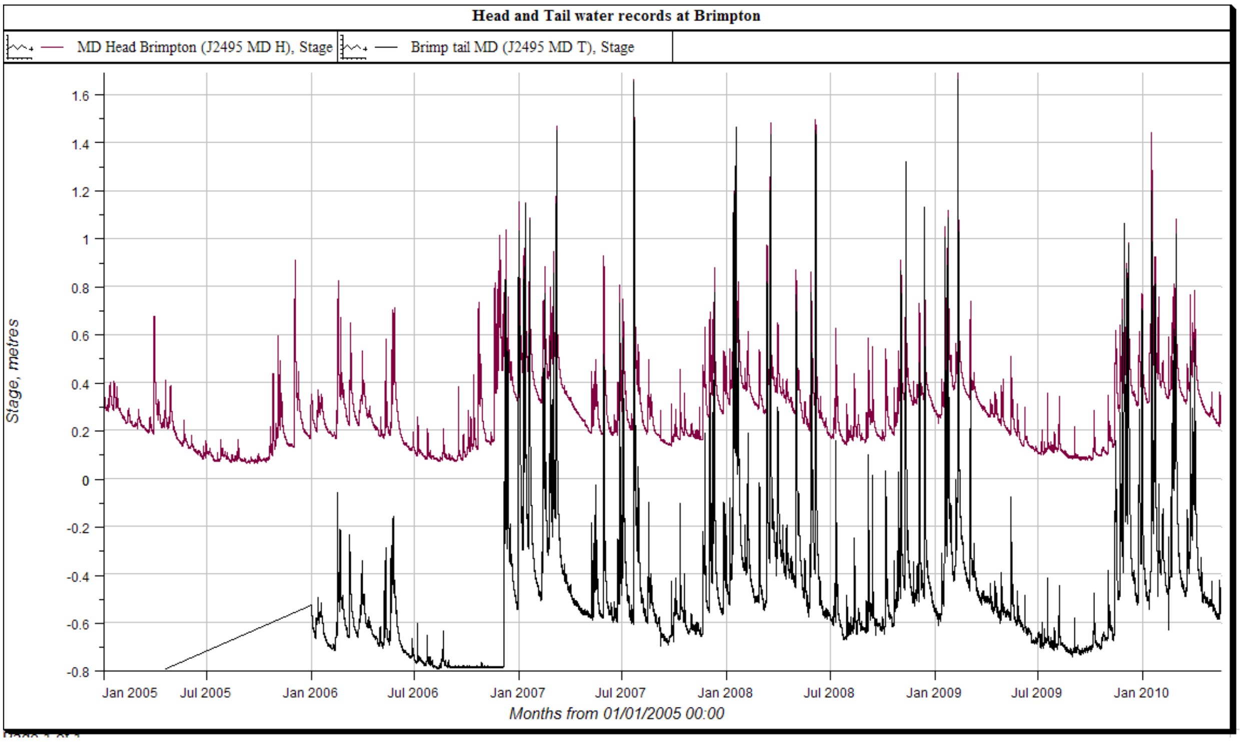


Figure 2.45 Brimpton head and tailwater full stage records

Figure 2. below clearly shows the tailwater exceeding the headwater value by approximately 22mm at its peak (~02:30hrs). A communication from the Environment Agency indicates that the 'live' (telemetered) site record was fluctuating by up to 20mm based on a one second time step. However, this does not fully explain the consistent plot of the tailwater trace above the upstream stage for this event. It may be that the observed anomaly is the result of an initial error associated with gaining a suitable dip value in turbulent conditions then being applied throughout the subsequent record period. This issue occurred again on 29 November 2009. This showed a much more turbulent trace, with tail level generally greater than head level for a period of approximately six hours.

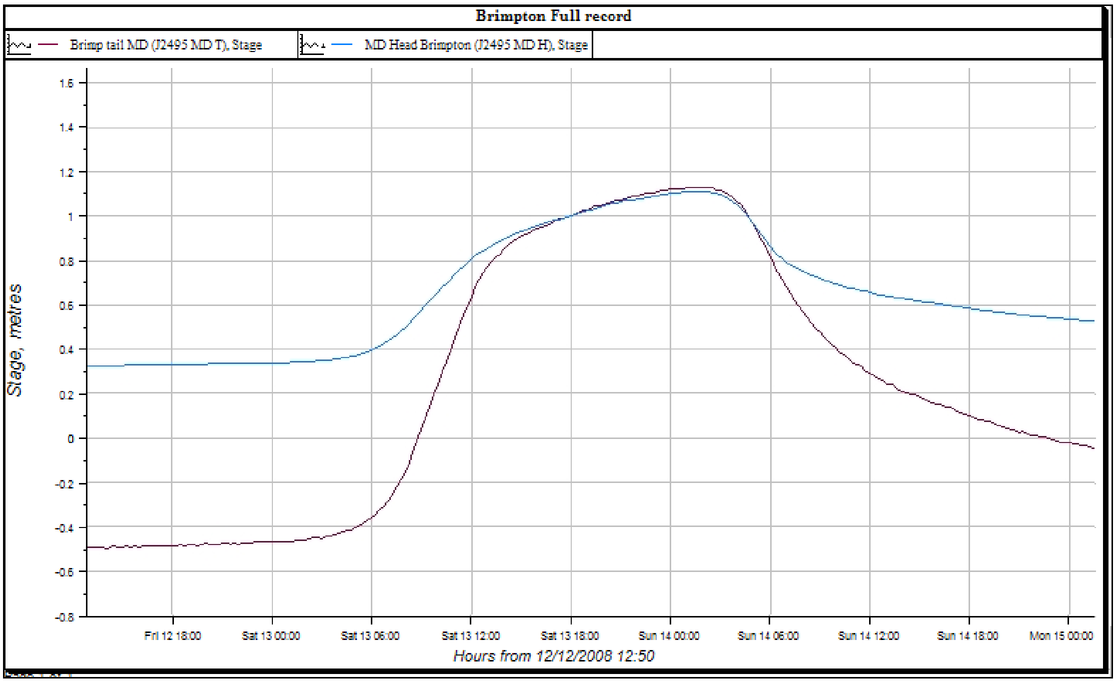


Figure 2.46 Brimpton head and tailwater stage records (Sunday 14 December 2008)

It was recommended at the inception phase that a temporary water level recorder be installed in the downstream channel, where water levels are less turbulent. This was not undertaken and the record for the existing tailwater monitoring installation is the only one available. Log sheets indicate that significant turbulence remains an issue and the level has been reset on a number of occasions for differences of up to 52mm. It is recommended that this source of error is corrected in future to allow accurate adjustment of non-modular flows. This may be best achieved by the installation of a separate tailwater recorder at a different location (for example slightly further downstream, below the inflow from the drainage channel on the left bank).

2.5.9 Operational considerations

Debris and weed growth

At any hydrometric monitoring site, it is essential to keep the structure clear of debris and weed growth to ensure successful operational performance. In the case of Brimpton Gauging Station, as well as making the weir unattractive for fish passage, it will potentially have a significant effect on the hydrometric performance of the structure (White *et al*., 2006). Figure 2.7 below clearly illustrates the potential for debris to get caught at this site. The station log sheets reveal an accumulation of weed and algal growth on the baffles and crest. There is insufficient information in the historical records to ascertain whether this represents an increased impact. A telemetry-linked camera is located on the upstream bridge to monitor the lower weir crest and baffle arrangement. The camera was installed on 22 June 2009 and at least one image per day is available. A visual assessment of the available images revealed a number of incidents in which debris was noted to catch on the baffles (Table 2.14). While it is not possible to determine what impact the debris may have had on the upstream stage measurement, the photographic record strongly suggests that the presence of the baffles has lead to an increased risk of snagging and debris build-up on the downstream face of the weir.

It is therefore critical that this is carefully managed, with the implementation of a regular maintenance regime. The routine operational use of telemetered cameras to provide a daily check on the weir structure to identify anything that may be significantly affecting its performance is also recommended.

Date	Comment
22/06/2009	Significant algal growth on weir crest.
24/08/2009	Log/branch caught on baffles no impact on upstream head.
22/09/2009	Wildfowl on weir attracted by algal growth. No impact.
01/10/2009	Branch caught by baffles, no impact on head.
04/10/2009	Branch caught by baffles, possible impact on head.
07/10/2009	Branch caught, potential impact.
27/10/2009	Branch caught on baffles, no impact on head measurement.
15/11/2010	Large tree visible upstream, caught above weir.
28/11/2009	Potential hydraulic impact of baffles at high flows.
06/12/2009	Unusual hydraulic conditions in high flow, unknown cause.
15/06/2010	Large debris on weir crest; not sure if caused by baffle.

Table 2.14 Brimpton assessment of camera record

The periodic build-up of algae and weed growth on the crest and baffles may have some impact on the accuracy of flow measurement due to the associated increase in water level. Although some records are available on monthly station log sheets, these are of limited detail and do not allow the potential impact of algae/weed growth to be fully quantified. A record of debris clearance, and any resultant change in stage, was not available. It is recommended that in future, a comprehensive record should be maintained as part of standard site operation, maintenance and quality assurance activities.

Figure 2.47 Log caught on baffles on low flow Crump weir.

At very low flows the potential for debris entrainment over the low crest may increase and cause further risk from debris snagging. It was noted that a large tree snagged on the weir on 31 May 2008, weed growth occurred on the weir on 12 May 2009 and that a log was lodged on the weir face on 20 May 2009. Available video footage for the periods 16-30 April 2008 and 1-15 May 2008 did not reveal any major occurrences of snagged debris. It should be noted that smaller twigs, debris or weed would prove difficult to identify in video footage.

The presence of the baffles appears to encourage weed/algae growth on the downstream face of the weir, which has the potential to impact on the hydrometric performance of the structure. It is therefore critical that a regular maintenance programme be put in place to ensure that any weed or algae build-up is kept in check.

A more comprehensive record of debris would be required to fully understand the potential impact of baffle fish passes on flow measurement performance at Crump weir structures.

2.6 Conclusions and recommendations: Brimpton Gauging Station

The fieldwork and subsequent analysis has led to the following conclusions and recommendations relating to the on-going operation of Brimpton Gauging Station. Broader observations relating to the future use of retrofit baffle fish passes at Crump weir flow measurement structures are also provided.

- The existing Environment Agency rating, derived using the available structural dimensions in 2001, was reviewed, and a revised theoretical rating also created using the structural dimensions obtained during this project. The maximum difference between the two ratings was found to be -5.2 per cent, with the recent data points fitting the revised theoretical rating slightly better than the existing rating. It is therefore recommended that the revised theoretical rating be adopted by the Environment Agency. This is based on the most recent available survey dimensions and considered to provide improved flow prediction whilst still using theoretical Crump weir formulae.

- Based on the available gauging data and historical observation, the modular limit of the Brimpton Gauging Station is thought to occur between 0.8 and 1.0mASD. A tailwater recorder was installed in 1992 to allow corrections for non-modular flow to be applied. Although installed in accordance with British and International Standards (3x H_{max} downstream of the crest), the site record sheets indicate that significant errors of up to 30mm continue to exist due to turbulence in the tailwater measurement location. It is therefore recommended that a separate tailwater record be established at an alternative location, possibly a short distance downstream of the drainage inflow on the left bank, to ensure improved accuracy and reliability of high flow records at the station.

- The available data suggests that the operational performance of the low flow Crump weir at Brimpton is not adversely affected by the presence of the baffles, within the observed stage range (0.353m-0.746m). The average deviation of gaugings from the current Environment Agency rating is -13.92 per cent for the pre-baffle gaugings and -11.75 per cent for the post-baffle gaugings. While this conclusion may be considered valid for the range of stages monitored, it is based on a very limited number of gaugings. It is therefore recommended that further field-based research is undertaken to confirm the impact of the baffles on flow measurement accuracy over the full stage/flow range.

- The presence of the baffles has been observed to lead to a greater risk of debris snagging and also appears to encourage weed/algae growth on the downstream face of the weir, which has the potential to impact on the hydrometric performance of the structure. It is therefore critical that a regular maintenance programme be put in place to ensure that any weed or algae build-up is kept in check.

- A record of debris problems, subsequent clearance and any resultant change in stage, was not available at this site. A more comprehensive record of debris is required to fully understand the potential impact of baffle fish passes on flow measurement performance at Crump weir structures. It is recommended that in future this should be undertaken as part of standard site operation, maintenance and quality assurance activities to ensure a comprehensive site record exists in future.

- Cameras were installed at Brimpton for a short period prior to the start of the project and provided a record of the operational performance of the low flow Crump weir with the original fish baffle arrangement in place. A permanent telemetered camera is in place on the footbridge operated by the Area Hydrometry and Telemetry team. Providing the camera images are readily accessible and monitored on a regular basis, this is considered to provide a significant benefit to the successful operation and maintenance of the site. Remote observations allow the proactive and timely clearance of debris and weed accumulations on the baffles, targeted spot flow measurements and a general check of conditions and the integrity of the gauging station as an Environment Agency asset.

2.7 Summary conclusions and recommendations

Both structures appear to be performing reasonably well from a fish passage perspective. Tagged fish are known to have passed the structure at Brimpton with the original baffles in place and it is not thought that the replacement baffles will have degraded conditions for fish passage. From a hydrometric perspective, Louds Mill Gauging Station appears to be performing largely as expected with the potential for some non-modularity above stage of 0.45m. Further gaugings are needed to confirm the requirement for an alternative rating above this stage. In the interim, it is suggested the original rating should not be extended beyond the gauged range without adequate caution in the application of the derived flows.

The recent gaugings at Brimpton suggest that the replacement baffles, installed in February 2010, are having no observable impact on the hydrometric accuracy of the weir structure. However, due to the limited range of gaugings available since the replacement of the top baffle, continued gauging and further assessment are recommended to confirm this conclusion.

A summary of key conclusions and recommendations is provided in Table 2.15 below:

Louds Mill Gauging Station:
1. The Larinier fish pass is considered to be performing in accordance with hydraulic theory up to a stage of approximately 0.45mASD. Above this level the available gaugings deviate from the theoretical rating, suggesting the structure is no longer performing according to hydraulic theory and may be going non-modular. Further gauging should be targeted at stages greater than 0.45mASD to confirm (or otherwise) this observation.
2. The existing Environment Agency theoretical rating at Louds Mill could be improved slightly to address rounding errors relating to the structural dimensions used for the derivation of the rating. The potential improvement is of the order of 1 per cent throughout the stage range.
3. Due to the complex nature of flow measurement structures (two Crump weirs and a one Larinier fish pass), the installation of the Larinier fish pass at Louds Mill is likely to improve the sensitivity and reduce overall uncertainty in low flow measurement.
4. The Larinier fish pass was found to be subject to a significant degree of weed and debris snagging. However, the measurable effect on the performance of the structure for flow measurement was very limited within the observed stage range. Further gauging and observation should be undertaken to confirm whether this remains the case under low flow conditions.
5. The routine operation and maintenance regime at Louds Mill is relatively comprehensive and to be commended. Accurate site records are maintained which detail any issues and corrective action relating to instrumentation, weed growth and debris clearance, and so on. The installation of cameras to monitor the main weir complex and the approach to the fish pass is considered to provide a significant benefit and contribute to the successful operation and maintenance of the site. Remote observations allowed the timely clearance of weed accumulations in the fish pass, targeted spot flow measurements and a general check of conditions and the integrity of the gauging station as an Environment Agency asset. These practices are considered an example of good practice that should be replicated throughout the Environment Agency hydrometric network.

6. It is recommended that, where possible, the approach to the fish pass structure should be installed in line with the guidance provided by ISO26906:2009; that is, in an artificial channel the channel shall be straight for a length equal to at least five times its breath, this may be greater for discharge through bends or angles.
7. Additional lifetime costs relating to the installation of a new gauging station and its subsequent operation, maintenance and data processing costs should be considered at the feasibility stage of future projects.
Brimpton Gauging Station:
1. The proposed revised theoretical rating, based on the most recent survey dimensions, appears to provide an improvement over the existing theoretical rating of up to 5 per cent throughout the flow range. It is therefore recommended that the revised theoretical rating be adopted by the Environment Agency.
2. Although installed in accordance with British and International Standards (3x H_{max} downstream of the crest), the site record sheets indicate that significant errors of up to 30mm continue to exist due to turbulence in the tailwater measurement location. It is therefore recommended that a separate tailwater record be established at an alternative location, possibly a short distance downstream of the drainage inflow on the left bank, to ensure the improved accuracy and reliability of high flow records at the station.
3. The operational performance of the low flow Crump weir at Brimpton does not appear adversely affected by the presence of the baffles, within the observed stage range (0.353m – 0.746m). However, this conclusion is based on a very limited number of gaugings taken over a short period of time. It is therefore recommended that further field-based research is undertaken to confirm the impact of the baffles on flow measurement accuracy over the full stage/flow range.
4. The presence of the baffles results in a greater risk of debris snagging and weed/algae growth on the downstream face of the weir. It is therefore critical that a regular maintenance programme be put in place to ensure that any weed or algae build-up is kept in check. This should include the maintenance of an accurate and detailed site maintenance record. The use of cameras to undertake a visual inspection of the site on a regular (daily) basis would allow a proactive approach and timely clearance of debris and weed accumulations.

Table 2.15 Summary of key recommendations

To conclude, it is clear that work to incorporate improvements for fish passage is vital to help mitigate for the barrier formed by hydrometric structures on many of the UK's rivers. While new technologies mean that weirs and flumes are often no longer economically viable for new gauging stations, remedial work on the range of existing structures is seen as vital to protect and enhance fish stocks.

Providing careful survey and theoretical calibration are undertaken, the Larinier super active baffle fish pass is capable of providing an accurate means of flow determination within specified operational ranges. It is critical that such structures are well-installed and maintained and that the design includes adequate approach conditions, where practical. Care should be taken in deriving flows at higher stages above approximately 0.4m, as above this stage the gaugings appear to deviate from hydraulic theory, possibly due to non-modularity. Further field testing should be undertaken to explore whether this is a site-specific phenomenon.

Whilst the conclusions of this project suggest that informal baffle arrangements have a limited impact on hydrometric performance, it is critical that sites are well-installed, maintained and operated in line with good practice guidelines and the appropriate

British and International standards for hydrometric structures, where relevant. Further field testing should be undertaken to confirm this conclusion over a full range of flows and at sites with different configurations (crest width, height and modular range).

3. Fish passage: Brimpton Weir – The low cost baffle solution

3.1 Site, materials and methods

3.1.1 The River Enbourne

The River Enbourne is one of seven tributaries of the River Kennet. The Enbourne is 26 kilometres long and has a number of sources from springs under the escarpment of the North Hampshire downs, joining the River Kennet to the South East of Newbury (Figure 3.1). It has a pronounced riffle/pool regime and a predominantly clay catchment It therefore responds quickly to rainfall events and is known as a 'flashy' river, making it a very different river to others in the Kennet catchment.

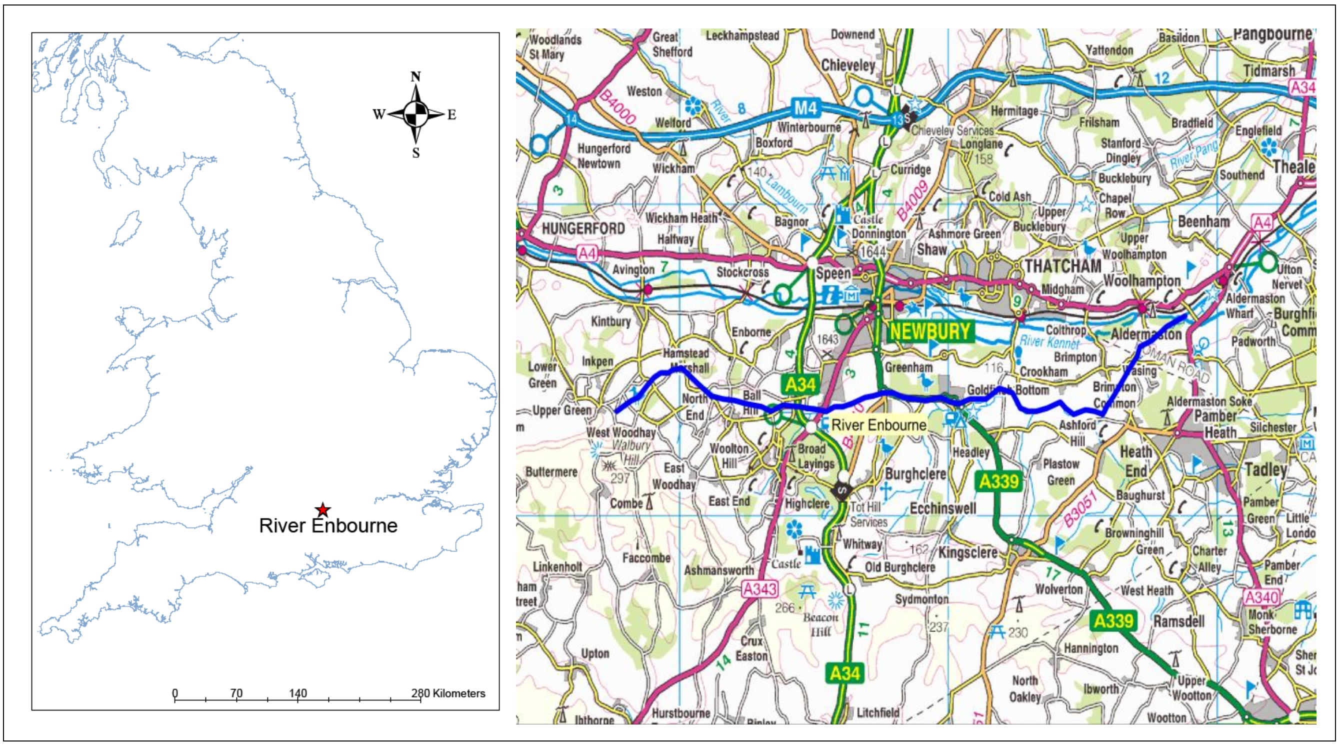


Figure 3.1 Location of River Enborne.

3.1.2 Fish populations in the Enborne

The fish population on the Enborne has been surveyed on a number of occasions (Butterworth *et al*., 1990; Preston *et al*., 1996). Results showed the Enborne is a mixed fishery, with stocked brown trout (*Salmo trutta*) co-existing with coarse fish such as chub (*Leuciscus cephalus*) and barbel (*Barbus barbus*). Small numbers of grayling (*Thymallus thymallus*) are present, probably originating from past stockings of these fish into the Enbourne/Kennet confluence downstream of Woolhampton. The habitat within the Enbourne is impoverished in places, as the river flows through a deep cut channel with heavy overhead tree cover and limited in-stream macrophytes and emergents. This, combined with the rapid response to rainfall and likely high level of fry wash-out, was identified as the main limiting factor in recruitment on the Enborne, exacerbated by the gauging weir which would hinder recolonisation of the upper reaches from downstream. Notwithstanding this, it was found that both biomass and densities were satisfactory for a small river of this nature.

The river around Brimpton gauging weir was surveyed again in Autumn 1997 and Spring 1998, as part of a study by Pinniger (1998). The results revealed that the downstream section below the weir had good numbers of rheophilic fish and there was evidence of recruitment. Chub made up half the biomass with a good range of sizes indicating numerous year classes. Dace (*Leuciscus leuciscus*) were also present in high numbers. In the impounded section above the weir, very few rheophilic fish were found, with more generalist species such as perch (*Perca fluviatilis*) and roach (*Rutilus rutilus*) dominating. There was little sign of recruitment in any species. The sections further upstream had a strong brown trout population and a good grayling population. Overall, Pinniger's (1998) results showed that that the fish community immediately above the weir was poor, suggesting that the weir was a barrier restricting fish access to the upstream habitat.

A full description of the weir and its dimensions are given in Chapter 2 - section 2.51

Being known as a site that restricted fish movement, it was an ideal site in which to model Servais' (2006) laboratory-based study that identified a potential low-cost baffle solution for fish passage at Crump weirs, that would lower velocities on the weir-face while maintaining sufficient depth for the fish to pass.

Pinniger (1998) undertook a radio tracking study at Sheepbridge Weir on the River Loddon, a Kennet tributary, in order to determine whether coarse fish could successfully ascend the weir. The Sheepbridge weir is very similar to Brimpton Weir, having an upstream slope of 1:2, and a downstream slope of 1:5 as does Brimpton, though it is narrower (2.15 m wide compared to 3m at Brimpton) and is slightly higher (0.84m. compared to 0.766m). In both cases the velocities at the tail of the weir would be well beyond the burst speeds for coarse fish (4.06m s^{-1} for Sheepbridge and 3.86m s^{-1} for Brimpton). Mean daily flows are similar (1.51 m^3s^{-1} for Sheepbridge, 1.32 m^3s^{-1} for Brimpton).

The results of the tracking study showed that out of the 16 fish tagged, six approached the weir, none of which passed over it during the period of the study. Care must be taken in extrapolating the findings from this study not least because of the very small numbers of fish used in the study but also because although the weirs are similar, flow characteristics of the two rivers will differ. Nevertheless, on the basis of the Sheepbridge work, Brimpton Weir was considered to be impassable to coarse fish under all except possibly extreme high flows when the weir drowns out.

3.1.3 The Low Cost Baffle arrangement

The wooden baffles were fitted to the low flow section of the compound Crump weir on 10 April 2008, based on a modified 'rotated-V' design as set out in Servais (2006) and Rhodes and Servais (2008) (Figure 3.2a). The ideal arrangement of the baffles was developed in laboratory tests on a scaled down version of Brimpton Weir. This showed that the flow velocities at several points within the structure were below the critical limits for fish passage, at less than 0.5m s^{-1} in the lab model (1.1m s^{-1} at field scale). The criteria for fish passage were deduced from the fish swimming speed database (Clough and Turnpenny, 2001; Turnpenny *et al.,* 2004), in which it was found that most freshwater fish greater than 100mm in body length had a burst speed capability in excess of 1.1m s^{-1}.

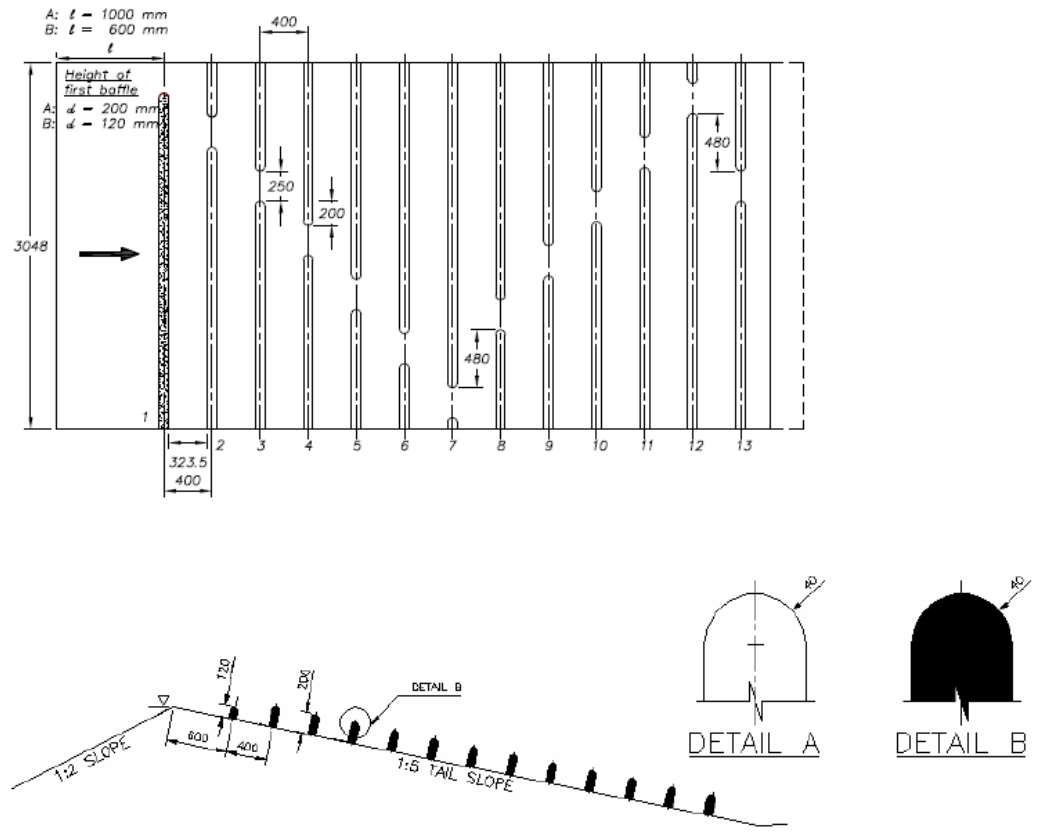


Figure 3.2a Proposed field scale layout, in plan and elevation, of the rotated-V baffle fish pass at Brimpton (taken from Servais, 2006).

Figure 3.2a is the ideal arrangement, with the first baffle smaller than the rest, as close as possible to the crest to minimise velocities during the final stages of fish ascent. White *et al*. (2005) considered the effect of the first baffle on the coefficient of discharge from the perspective that the coefficient of discharge should not be allowed more than a 1 per cent reduction from the existing standard. The position was calculated using the formula stated in White *et al*. (2005), which looks at the relationship between the baffle height and its distance downstream of the crest, in order to provide a reliable modular flow performance up to a head of 0.3m. For Brimpton Weir, it was agreed that the first baffle should be positioned 1.2m down from the weir crest, but would be the same height (200mm) as the others, and the whole baffle array moved further down the slope (Figure 3.2b). However, when the baffles were installed the first baffle was only 120mm high and was positioned 1260mm down from the crest (Figure 3.2c). The as-built fish pass also differed from the design in that the tops of the baffles were only chamfered and not properly rounded as in Figure 3.2a, and in addition the vertical edges of the slots were not radiused as in the original design. Figures 3.3 and 3.4 show pictures of the baffles at Brimpton as initially installed. After some damage to the fish pass that occurred after the fish passage experiments were complete, some replacement baffles were installed with the correct dimensions and shaping (Figure 3.5).

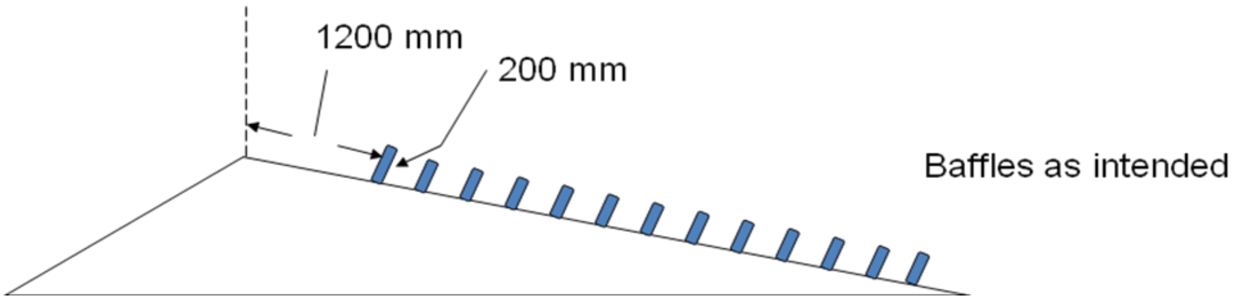


Figure 3.2 b. Modified layout for Brimpton rotated " V" baffle fish pass

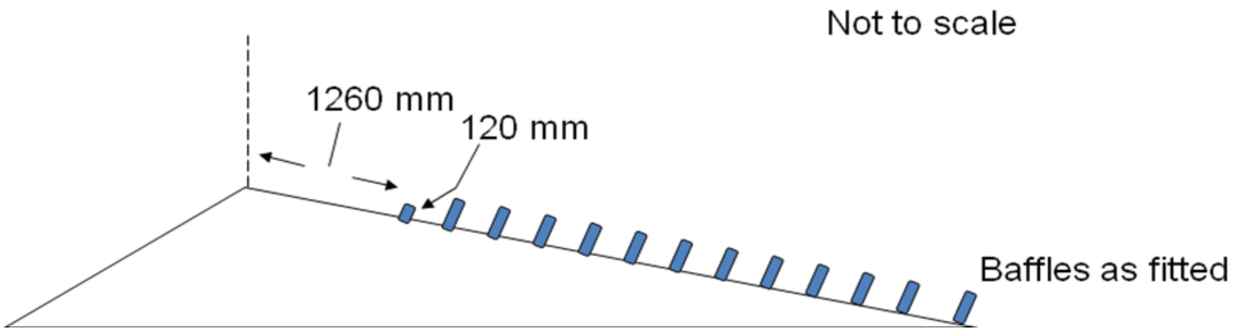


Figure 3.2 c "As-built" layout of Brimpton rotated "V" baffle fish pass

Figure 3.3 Image of baffles at Brimpton when the weir was de-watered. Upwards looking aspect.

Figure 3.4 Image of baffles at Brimpton Weir. Downwards looking aspect.

Figure 3.5 Replacement baffles being fitted after damage. Note the radiused tops and edges of slots.

Although the fish pass arrangement has been designed with the maximum burst speeds in mind, fish are considered to be able to attain instantaneous speeds that are higher than burst speed velocities for very short periods of time (Armstrong, pers. comm.) It is expected that fish would be able to exploit those abilities enabling them to surmount the final stretch between the first baffle and the crest, where water velocities are still higher than the burst speeds of most cyprinid fish.

3.1.4 Monitoring

The strategy for monitoring the effectiveness of the fish pass was to capture numbers of fish from upstream of the weir, tag them and then translocate them to the area downstream of the weir during the pre-spawning period in Spring 2008, in order to study the fish it was believed would have maximum motivation to ascend the weir. It was expected that a combination of the urge to move upstream to spawn and the natural homing instinct (Lucas *et al.,* 1998) would motivate the fish to try and ascend the weir.

Fish capture and tagging

Roach, chub, dace and perch were electric fished from various locations in the Enborne catchment on 24 and 25 April, and 8 and 13 May 2008. Once they had recovered from the electric fishing, they were then anaesthetised with 2-phenoxy ethanol (approximately 40mg per litre of water) and underwent a minor surgical procedure. A passive integrated transponder tag was inserted into the peritoneal cavity (See Table 3.1). A Home Office Licence was required for this procedure. Fork length was recorded, and a scale was removed for age determination. Once the fish had recovered in an oxygenated tank, they were released into the gauging station weir pool.

Table 3.1 Fish capture and tagging procedure.

1) Electric Fishing team moving upstream by boat	2) Anaesthetised chub on measuring board	3) Removal of 3-4 scales to expose skin	4) Small 2mm wide incision just through the skin layer
			
5) Insertion of PIT tag	6) Moving tag up into the peritoneal cavity	7) Very small hole remaining after tag insertion	8) Chub released into weir pool when fully recovered
			

Sample size to estimate efficiency of fish pass

It was important that sufficient fish were tagged and released in order to allow adequate statistical treatment of the results. It was estimated that a sample size of 70 was required to be able to detect fish pass efficiency to a precision of +/- 10 per cent at a confidence level of 95 per cent (Zar, 1984). Previous experience (Lucas Baras, 2000; Armstrong,pers. comm.) suggested that at least 100 fish would need to be tagged in order to know the fate of 70 individuals, to allow for fish that subsequently do not try and ascend the weir and/or leave the study area.

Unfortunately, despite four fish capture expeditions it was not possible to capture enough fish from the Enborne upstream of Brimpton Weir to fulfil these recommendations. Although not strictly comparable with the upstream fish, additional fish were translocated from other reaches of the river (including a fish-trap on Blakes Weir, downstream on the main river Kennet) and from a small on-line lake. The motivation of fish sourced from downstream of the weir to move upstream was questionable, and the swimming ability of fish from the lake is likely to have been significantly less than riverine fish.

Passive integrated transponder tag detection system

The approach used to measure attraction to the weir and passage efficiency was to remotely detect coarse fish tagged with passive integrated transponder (PIT) tags at strategic locations throughout the site.

The experimental fish were tagged intraperitoneally with small bio-stable tags (Figure 3.6), which are energised when exposed to a 400 kHz field from an induction coil. Once energised, they transmit their identity code which is picked up by the antenna and transmitted to the reader (Lucas & Baras, 2000). PIT technology is almost independent of environmental conditions such as salinity and depth (which restricts other remote sensing methods), as long as the tagged fish swims within the range of the detector (Lucas & Baras, 2000). The infinite lifespan of the tags allows complex behavioural information to be gathered throughout the lifetime of the fish.

PIT tag detection systems have been increasingly used in fish detection studies (Ibbotson *et al*., 2004; Aarestrup *et al*., 2003; Riley *et al*., 2003 & 2006; Roussel *et al*., 2000 & 2004; Lucas, 2000; Zydlewski *et al.*, 2001).

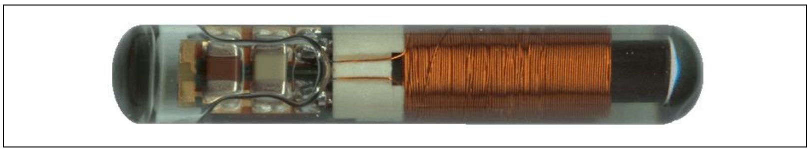


Figure 3.6 Passive integrated transponder tag.

Prentice *et al*. (1990) were one of the first to study the feasibility of using PIT tags in salmonids. They found that survival of tagged juvenile and adult salmonids after 400 days was almost 90 per cent. Growth rate was depressed for up to 20 days after implantation but then returned to normal. For juvenile fish (fingerlings and smolts), PIT tags had no apparent effect on growth or survival, tag retention was 100 per cent and tagging did not compromise swimming stamina, stride efficiency or respiratory rate. Baras *et al.* (2000) found no evidence of internal damage or tag expulsion in juvenile perch (*Perca fluviatilis*) during four months post-tagging, though there was depressed fish growth during the first post-tagging days, and slower healing rates. Skov *et al.* (2005) found that surgically implanting the tags without using sutures to close the incision was the most successful procedure for small cyprinids. It was therefore decided that this would be the best technique to use in this study.

The largest commercially available tags (Wyre Micro Design) were chosen for this study (23.1 by 3.9mm) because they give they have a greater detection range compatible with the loop aerial antenna system described below. The fish available for this study were large enough to accommodate this size of tag, which is suitable only for fish of at least 12cm fork length.

Previous studies suggest that these half-duplex tags have a detection efficiency of 93 +/- 2 per cent (Zydlewski *et al*., 2001). The reading range varies slightly with the position and orientation of the tag with respect to the antenna coil. If a tag is passed through with its long axis parallel to the antenna plane, or at an oblique angle, it cannot be read. Also, it is unable to distinguish two fish in the antenna field at the same time.

The antenna system was designed and installed with the assistance of Wyre Micro Designs. The PIT tag antenna is a wire loop that generates a close-range electromagnetic field that extends approximately 50cm from the plane of the antenna coil. Three antennae were positioned on the downstream face of the low crest of the weir at 1.6m, 5.3m and 6.6m down from the crest. The high crest was considered totally impassable and was therefore not monitored. Also, another antenna was installed approximately 80m downstream of the weir in order to monitor downstream movement of fish. These were all installed on 12 April 2008. Figure 3.7 below details the design of each antenna in the weir channel.

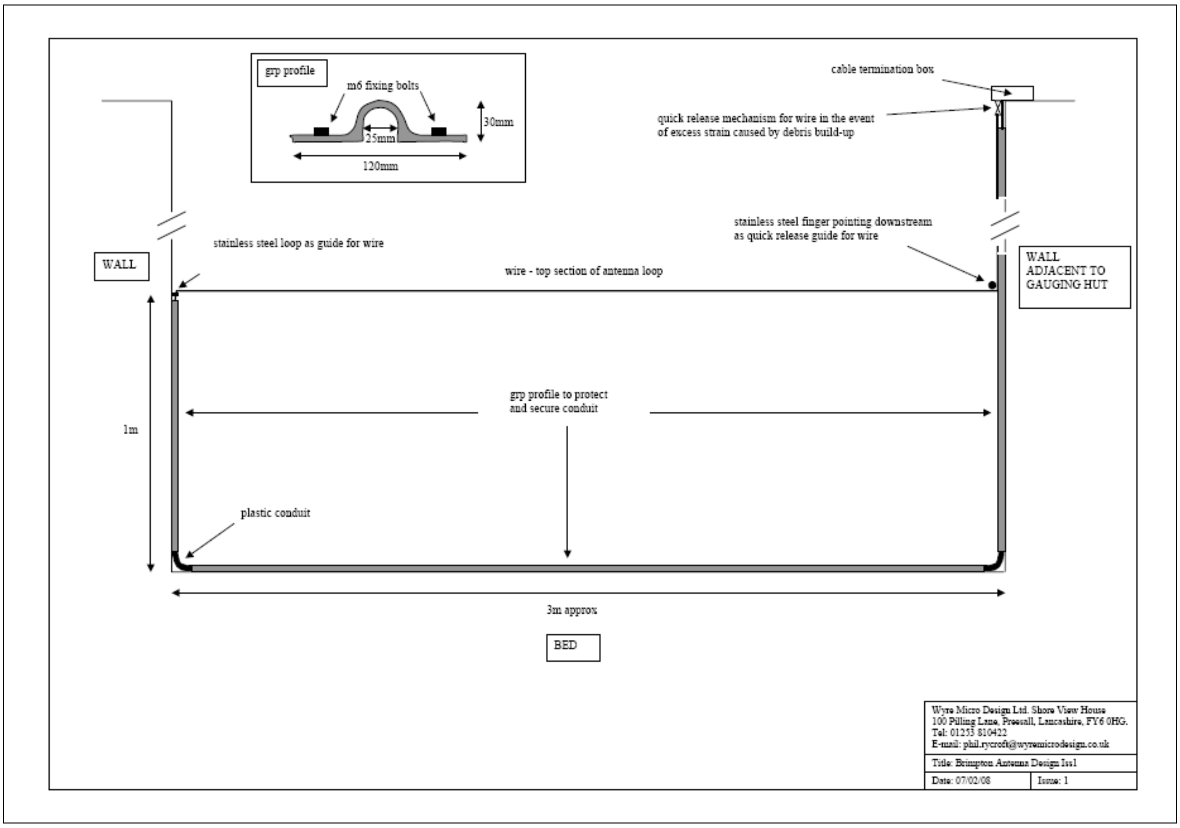


Figure 3.7 Design of each antenna in the weir channel.

A quick release mechanism was incorporated into all four antennae. This feature was designed specially for this study in anticipation of high flow events. Essentially, it consists of 15lb fishing line tensioned with a spring (Figure 3.8). In the event of high flows or large downstream moving debris, the fishing line would break, and the overhead wire would be released downstream. This meant that the wire would not break, and could be simply re-attached without having to enter the weir. The maximum distance between the top and the bottom of the loop is one metre, meaning that a fish passing through the loop will be no further than 0.5m from the wire, within the detection range for the size of tag used. The diagram below (Figure 3.9) details the position of each PIT antenna at the site.

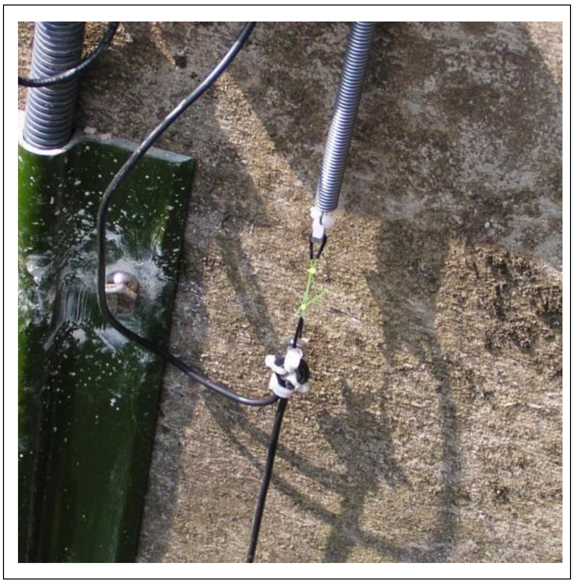


Figure 3.8 Quick release mechanism.

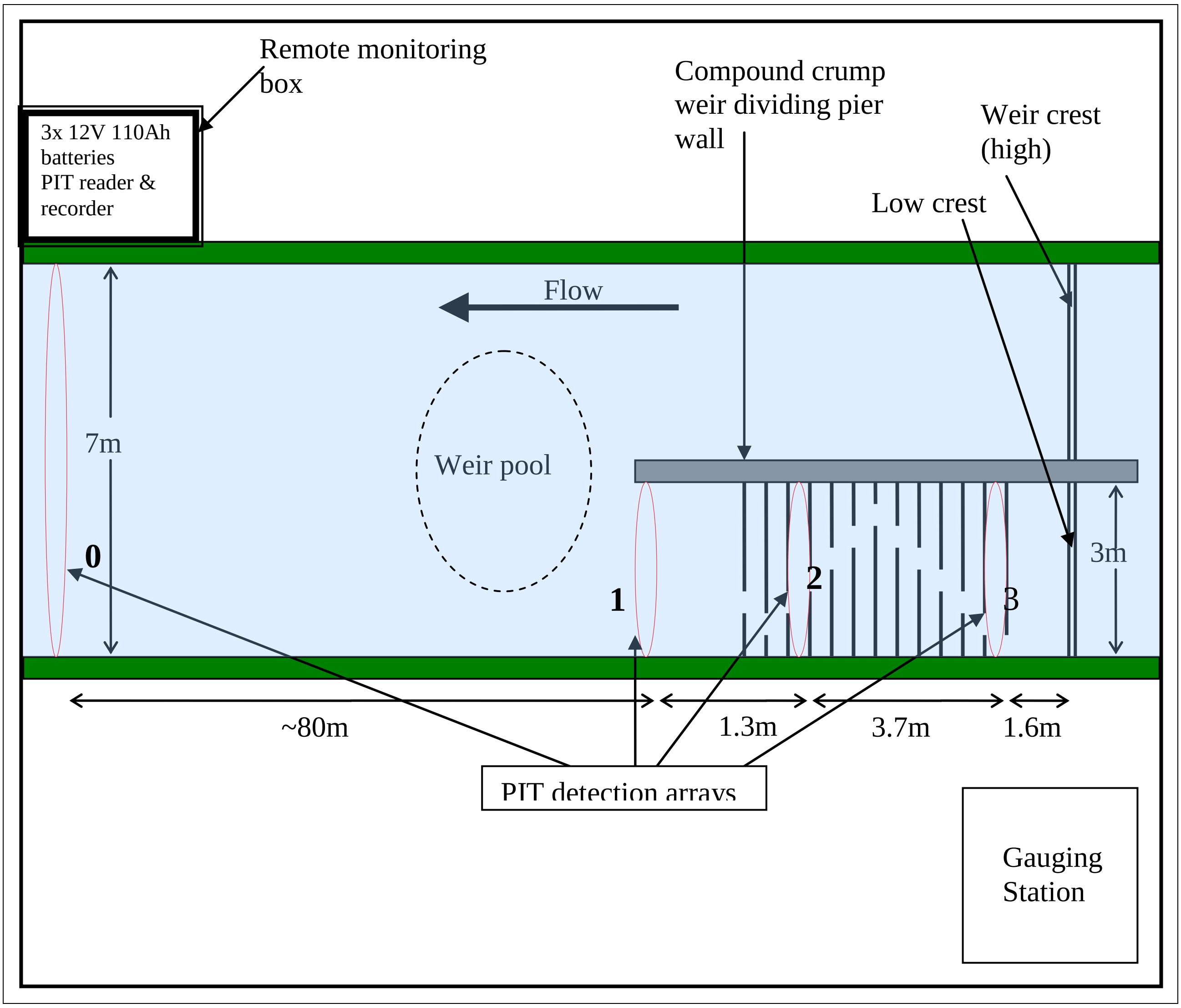


Figure 3.9 Basic site layout (not to scale).

A remote site (antenna 0) was situated approximately 80m downstream of the weir. It was powered by three 12V 110Ah batteries connected in series. Battery run time was 10 to 12 days. The antenna wire was secured to the bottom of the riverbed with chain. To prevent any electromagnetic interference from the metal chain, the wire was attached to it, but was approximately 30cm away from it, through the use of long cable ties. The wire was secured to fence posts on each bank to create the loop. The maximum distance between the top and the bottom of the loop was 90cm. The readers, batteries and data logger were contained within a weather-proof box located immediately above the antenna, approximately one metre away on the river bank. This remote system was completely separate from the other three antennae.

The remaining antennae worked as a combined system, which was powered from the mains supply in the gauging station. The system was running with a two second polling interval, whereby each antenna was scanned, then the reader waited two seconds before scanning again. Antenna 1 was situated at the bottom of the weir at the downstream end of the dividing pier wall. It detected the fish that had moved up into the weir pool from downstream of the gauging station and to the base of the weir, that is, potentially looking to ascend the weir. Antenna 2 was positioned on baffle number ten (of thirteen), 5.3m down from the crest. Detections here would indicate fish that were committed to moving up the fish pass. Antenna 3 was positioned on baffle number two

(1.6m down from the crest), to detect the number of fish that successfully made it to the top of the baffle system. It could not be placed any nearer the weir crest, as it would have caused too much turbulence if it was positioned at baffle number one, and would have interfered with flow gauging if it was placed on the crest.

Video monitoring

Cameras and infrared lamps (Clabburn *et al*., 2008) were positioned to monitor the top section, from the first baffle to the crest. This was to confirm whether the fish that had reached antenna 3 had gone on to reach the crest and continued upstream. Unfortunately, due to the logistics of the site, additional antennae could not be placed in the upstream section as it was too deep, and the antenna loop would be permanently under water. Figure 3.10 below shows the weir (looking downstream) at low flows. The baffles, PIT antennae and camera systems are clearly visible.

Figure 3.10 Image of weir with baffles and PIT antennae. Downstream looking aspect.

Note in figure 3.10 that the streams of turbulence against the left and right walls, generated by the stop-log slots, had the potential to compromise fish passage; the intention was to fill these in, however this proved difficult in practice. Frequent checks were made using a tag attached to the end of a pole to check that all antennae were functioning throughout the study. The tag was repeatedly passed through the four antennae, and the detection rate recorded.

The camera equipment was adjusted several times throughout the study. Initially the cameras were mounted above the weir under a concrete walkway, looking downwards. With this arrangement, however, the cameras were too far away for accurate observations of fish passing from the top baffle to the crest. Also, the infrared lamps that enabled observations at night were too far away for the camera to pick up. Another camera and infrared lamp were therefore mounted closer to the weir, which resulted in much better images by day and by night. The other cameras remained operational in order to assess trash build up.

3.1.5 Flow measurement

Total flow over the weirs was monitored routinely using continuous measurement, and the data archived by Thames Region West Area Hydrometry staff, and the data used to assess whether there were relationships between flow volume and characteristics and fish activity and their ability to ascend the weir.

3.1.6 Temperature data

Temperature data were taken from two Tempcon Water Temp Pro V2 Loggers. They were installed on 24 April 2008 at antenna 0 at each side of the riverbank. Temperature readings were recorded every fifteen minutes.

3.1.7 In-slot velocities model – field evaluation

The configuration of dimensions and spacing of the baffles in the fish pass design was developed from theoretical hydraulic modelling to ensure a pathway through the baffle array in which water velocities would be below the burst swimming capability of the fish species present in the Enborne (Servais, 2006; Turnpenny *et al.*, 2001).

In April 2009 the flow velocities around the upstream baffles in the fish pass were measured using an Ott C2 rotating element current meter (technical details at http://www.ott.com/web/ott_de.nsf/id/pa_c2_e.html) deployed from the concrete bridge directly overlooking the fish pass. The velocities were measured at different depths, between and over the top of the baffles, and in the section between the weir crest and the top-most baffle. Flow during the test exercise was 0.89 cumecs (approximately Q_{45}).

3.2 Results

3.2.1 Fish re-located and tagged

Table 3.2 Date of fish release by species (total numbers, with fish from upstream of Brimpton Weir in brackets)

Date	Chub	Dace	Perch	Roach	Total
24/04/2008	33 (33)	7 (7)	1 (1)	0	41 (41)
25/04/2008	27 (9)	2 (2)	0	0	29 (11)
08/05/2008	3 (3)	0	5 (4)	67 (2)	77 (9)
13/05/2008	0	0	10	0	10
Totals	63 (45)	9 (9)	16 (5)	69 (2)	157 (61)

A total of 157 fish were tagged and released into the River Enborne in the weir pool below Brimpton Weir between 24 April and 13 May 2008 (Table 3.2). These included chub (*Leuciscus cephalus*), dace (*Leuciscus leuciscus*), perch (*Perca fluviatilis*) and roach *(Rutilus rutilus)*. Unfortunately, it was not possible to obtain the desired numbers of fish of any species from river reaches upstream of Brimpton Weir, and fish from other parts of the system were used. Table 3.3 shows a complete breakdown of tagged fish. All of the fish tagged were in good condition: 157 (97 per cent) of the 162 fish originally tagged recovered well from the anaesthetic. The five fish that did not recover from the anaesthetic were roach from The Chase that had also encountered netting stress and were not therefore released or included in the analysis.

Table 3.3 Breakdown of catch location, species, number and size range (fork length in mm) of fish tagged

Species	Upstream Brimpton Weir			Downstream Brimpton Weir			The Chase			Blakes Trap			Total
	n	Fork length (mm)		n	Fork length (mm)		n	Fork length (mm)		n	Fork length (mm)		
		Mean	Range		Mean	Range		Mean	Range		Mean	Range	
Chub	45	433.6	237-510	18	401.7	153-485	0			0			63
Dace	9	209.3	185-240	0			0			0			9
Perch	5	220.6	147-283	0			1	224		10	144.4	120-219	16
Roach	2	242.0	240-244	0			67	168.3	142-222	0			69
TOTAL	61			18			68			10			157

3.2.2 Fish detection on the PIT antennae

The detection rate of tags by the antenna was tested as described in section 3.1.4 and was shown to be 100 per cent. However, it is possible that not all movements of tagged fish may have been detected. It was apparent that fish were holding near antenna 0, antenna 1 and sometimes antenna 2, often for up to an hour and sometimes more. These fish may very well have inhibited the detection of other fish passing through. There is no evidence that the loops themselves deterred fish from passing through the array.

Of the 157 tagged fish released into the river, 154 (98 per cent) were detected on at least one of the PIT antennae at least once. Figure 3.11 shows the patterns of fish activity as measured by the total number of detections on all antennae, during the study period.

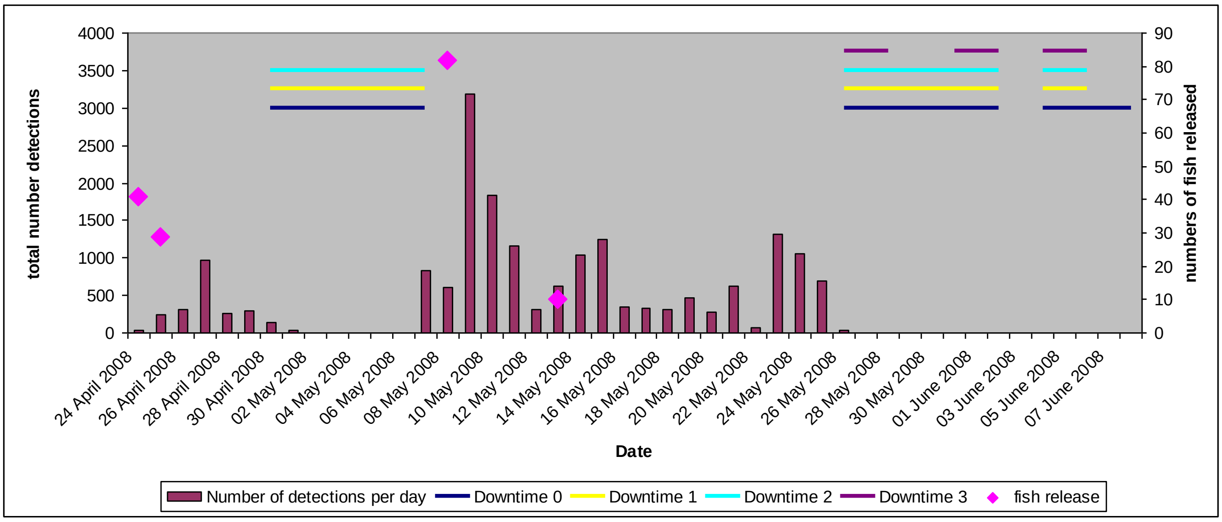


Figure 3.11 Total numbers of fish detections per day, Brimpton Weir, spring 2008, showing periods of downtime for antennae 0, 1, 2, 3 respectively, and dates of release of tagged fish

Unfortunately the patterns of activity around the various antennae were obscured by considerable periods during which they were out of action. However, it can be seen that each of the four introductions of tagged fish was followed by an marked increase in detections over the next two to three days.

3.2.3 The effects of flow and temperature on fish movement

Figure 3.12 shows daily mean flows (plus the Q_{10} flow values) daily average water temperatures and photoperiod during the study.

Temperatures generally increased throughout the study period, although there was a sharp drop from 14.76°C to 12.14°C on 15 May, with another cooler period from 16- 24 May. Flows are very changeable on the River Enborne – the flashy nature of the river is apparent when analysing the 15-minute flow data. An extreme example sees the flows range from 0.997m^3s^{-1} to 17.4m^3s^{-1} then back down to 2.41m^3s^{-1} within 72 hours throughout 3 June to 5 June. Daily mean flows ranged from 0.579 m^3s^{-1} to 13.1m^3s^{-1} during the seven-week study period.

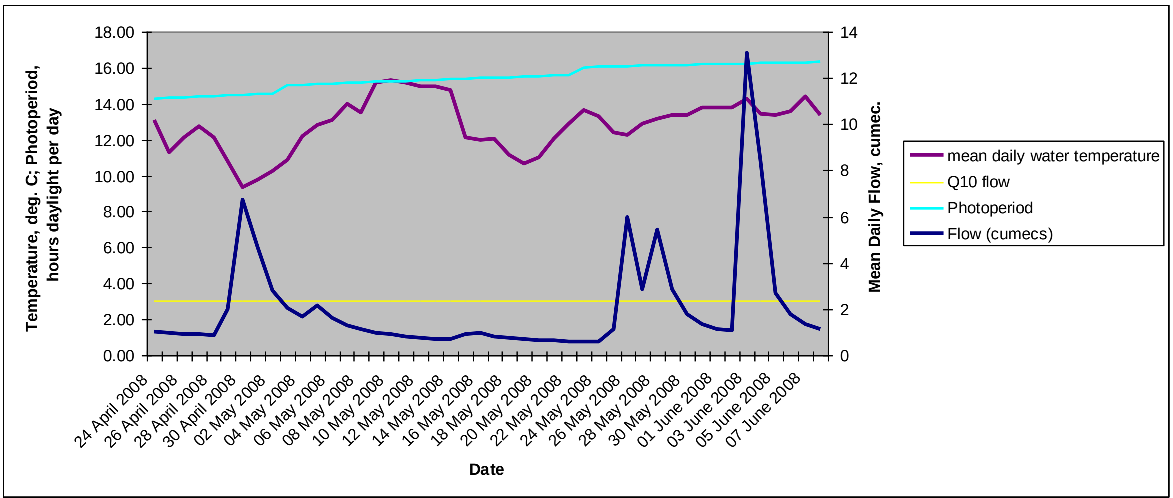


Figure 3.12 Water temperature, daily mean flow and photoperiod, River Enborne, spring 2008.

Figure 3.13 shows the percentage of the total number of individuals that were detected at each antennae per day. Both graphs show periods of high fish activity during the low flow periods post-translocation into the weir pool, between 24 and 30 April, and 7 and 14 May. During these periods of high activity, the daily mean flows (DMFs) were between 0.57m^3s^{-1} and 1.29m^3s^{-1}. Whilst overall fish activity seemed to decline as flows rose and temperature water temperature fell, there is evidence of greater utilisation of higher flows for successful fish passage, as there are a greater number of individuals at antenna 3 just after the first peak in flow on the 30th April.

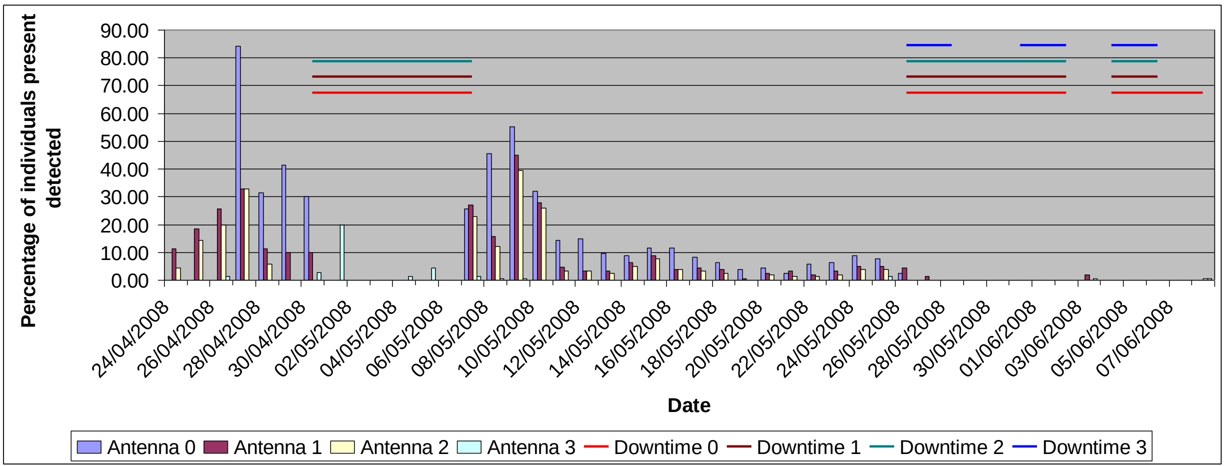


Figure 3.13 Percentage of fish detected on each antenna each day, April – June 2008

It was not possible to gain a complete picture of fish movement at high flows because of considerable antenna downtime during such conditions. Antenna 0,1 and 2 were off for approximately 15.5 days in total, whilst antenna 3 was off for only seven days, (perhaps because it was higher up the weir and thus subject to slower water velocities). The antennae could only operate with a maximum of a 1m high loop. When Daily Mean Flows reached 2.6m^3s^{-1} and above, the water level was above the top of the antennae and they began to fail; those at the bottom of the weir were the first to break.

When flows exceeded1.07 m^3s^{-1}, water flowed over the high flow weir. This flow was exceeded 35 per cent of the time. Under these conditions it was possible that fish may have ascended the low flow weir, and returned to the weir pool via the high flow weir, without being detected. However, it is likely that these would have been detected again either on antenna 0 downstream of the weir or on antenna 1 or 2 upon attempting to re-ascend the low flow weir. It is logical to assume therefore that if the last detection of a fish was at antenna 3, and they had not subsequently been detected on any other antennae, then that fish had successfully ascended the pass.

Antenna 3 survived until it was hit by debris on 31 May. Unfortunately, the cameras were not effective in high flow conditions as the water was too turbid to observe fish ascending the weir. Indeed their effectiveness even under clear water conditions was limited due to turbulence and light factors and they produced no useful data.

Throughout the study period, temperatures ranged from 9.36°C to 14.94°C. Travade *et al.* (1998) state that for all cyprinids, the likely minimum temperature for use of the passes is between 9-10°C. Water temperature was therefore never low enough to potentially deter fish from migrating up the weir.

The study ran during the period leading up to the longest day of the year; consequently the photoperiod increased throughout the study period. There was no evidence of any effect of increasing photoperiod on fish movement, any such influence would be masked by other factors such as releases of fish, temperature and flow.

3.2.4 Fish movement and time of day

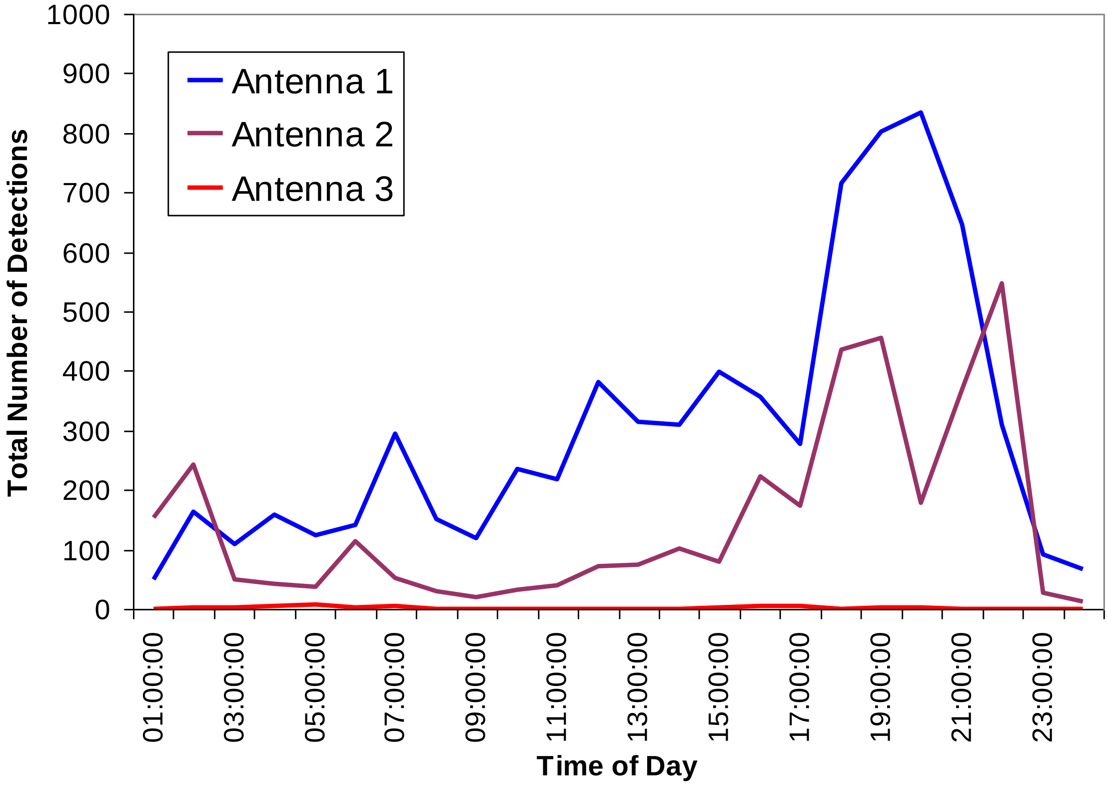


Figure 3.14 Number of detections on each antenna throughout the day.

Figure 3.14 shows fish activity at each antenna in relation to time of day. There were numerous detections on antenna 1 throughout the day, rising in the evening, peaking at 20:00, then falling sharply towards midnight. Antenna 2 showed lower numbers of detections during the day with a peak in late afternoon to late evening. For both antennae there were small peaks in the early hours of the morning and again just after dawn.

Antenna 3 detections occur between 02:00 and 08:00, and 15:00 and 21:00, with no activity apparent during the middle hours of daylight. This suggests that successful ascents were likely to occur in darkness or at dawn and dusk.

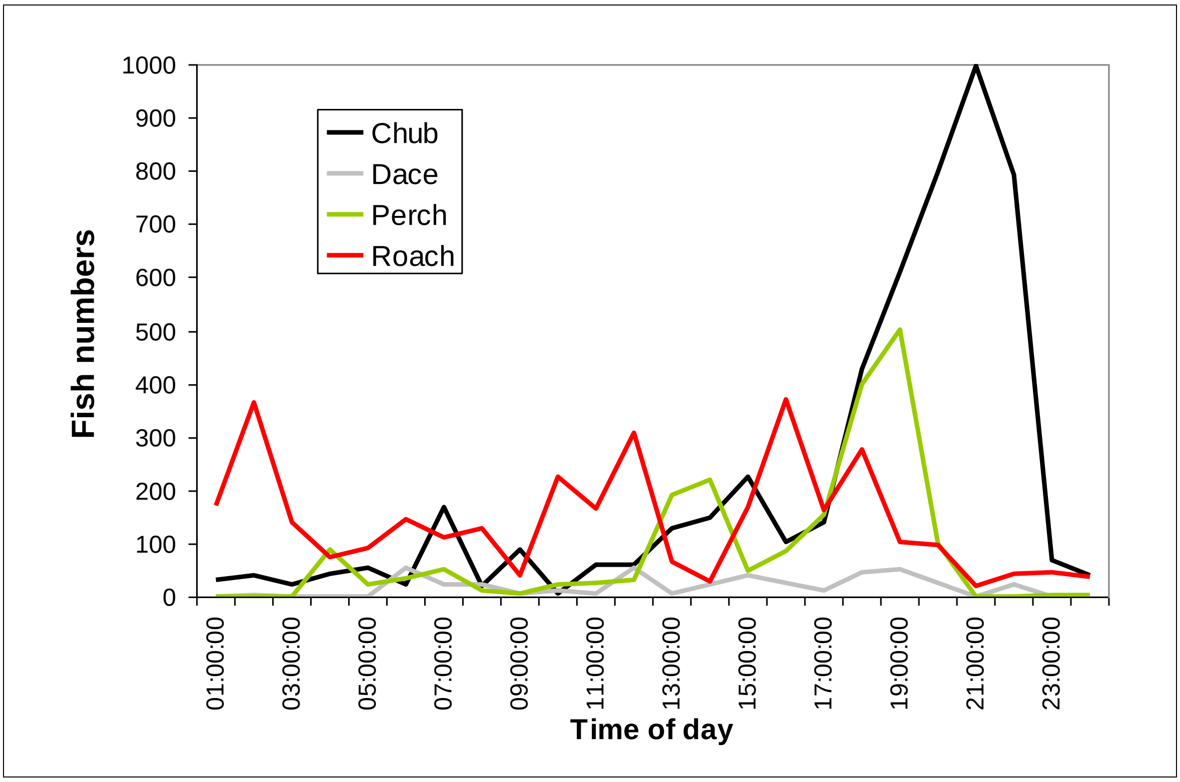


Figure 3.15 **Number of detections per species throughout the day, all weir antennae combined.**

Figure 3.15 shows the number of detections on antennae 1,2 and 3 combined, categorised by species. Each species appeared to have a different pattern of daily activity. Roach detections occurred throughout the day and the night, with sporadic peaks occurring in both day and night. Dace maintained a relatively constant level of detection between the hours of 05:00 and 22:00. Perch were detected between 03:00 and 21:00, with a peak in activity around dusk, from 17:00 to 20:00, similar to chub, which showed a big peak in detections in late afternoon and evening.

3.2.5 Attractiveness to different species

Table 3.4 and Figure 3.16 show the total number of individuals detected at each antenna. In total, 110 individual fish were detected moving into the approach channel of the weir (antenna 1), out of 157 (68 per cent). Of those fish, 37 were chub, 3 were dace, 13 were perch and 57 were roach. Out of the remaining 47 fish, 42 more individuals were detected on the downstream antenna, and never made any recorded attempt to move upstream. Only five fish (3 per cent) were not detected on any antenna. These may have remained in the weir pool and not approached any of the antennae, or moved upstream or downstream during periods when antennae were out of order, then subsequently remained out of range of any of the antennae.

Recordings at antennae 0 suggest that most fish explored the lower section of the river below the weir pool. However, it was evident that a smaller proportion of chub and dace were detected at antennae 1 and 2, compared with the percentages of perch and roach (52 and 33 per cent of chub and dace at antenna 2, compared with 63 and 72 per cent of perch and roach respectively). One explanation may be that chub and dace were generally more successful at progressing up through the baffles and thus collectively spent rather less time around the lower part of the weir. Higher percentages of chub and dace reached antenna 3 at the top of the weir: only one roach, and no perch, were detected. It is perhaps noteworthy that the roach that was successful in reaching antenna 3 was relocated from the river upstream of the weir. Thirty per cent of the total chub and 33 per cent of the total dace were successful in reaching antenna 3 at the top of the baffles.

Table 3.4 Individual fish detected at each antenna by species*.

Species	Total number of individuals tagged	Individuals at each antennae			
		Antenna 0	Antenna 1	Antenna 2	Antenna 3
Chub	63	60 (95%)	37 (59%)	33 (52%)	19 (30%)
Dace	9	9 (100%)	3 (33%)	3 (33%)	3 (33%)
Perch	16	15 (94%)	13 (81%)	10 (63%)	0
Roach	69	68 (92%)	57 (77%)	54 (72%)	1 (1%)
Total	**157**	**152**	**110**	**100**	**23**

***some fish were detected on more than one occasion.**

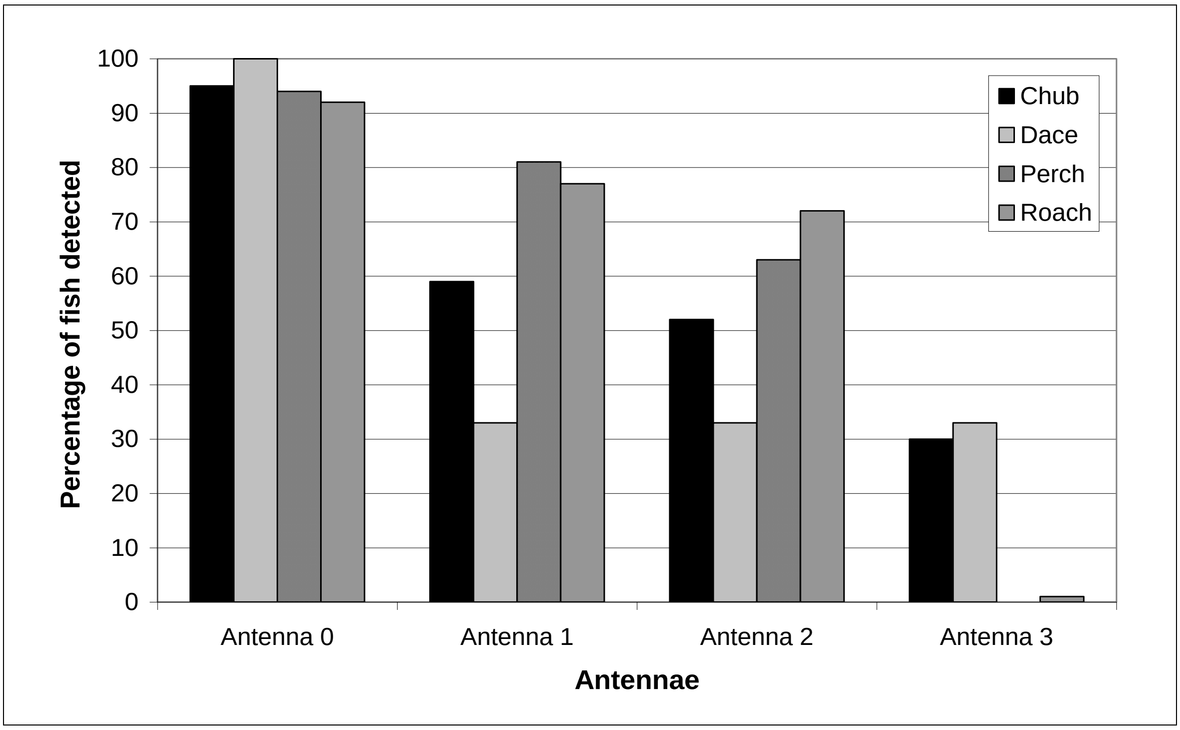


Figure 3.16 Percentage of each species detected at each antenna.

3.2.6 Effect of capture site on motivation to ascend the weir

Table 3.5 and Figure 3.17 show the activity of individuals from each capture site at each antenna. Once again, most of the fish from each area were detected at downstream antenna 0. As the fish enter the weir channel, there is a reduction in the number of fish from all capture sites, particularly those from downstream. Only 33 per cent of downstream fish make it to antenna 2. However, fish from The Chase (the upstream online lake), mainly roach, showed considerable motivation to ascend the pass, though none were recorded at antenna 3. With the exception of one fish from downstream which ascended twice, all the chub that reached antenna 3 had been captured upstream. They were the largest fish in the study, (and therefore perhaps the most able with the greatest motivation to return to the upstream reaches of the river to spawn, however some smaller chub were also successful as were dace (all relocated from the river upstream of the weir) and a riverine roach of 244mm.

Table 3.5 Individual fish detected at each antenna by capture site
(Percentages of original numbers of each category tagged are shown in brackets)

Capture site	Total number of individuals	Individuals at each antenna			
		Antenna 0	Antenna 1	Antenna 2	Antenna 3
Upstream	61	59 (97%)	40 (66%)	35 (57%)	22 (36%)
Downstream	18	17 (94%)	7 (39%)	6 (33%)	1 (1%)
The Chase	68	67 (92%)	56 (77%)	53 (73%)	0
Blakes trap	10	9 (90%)	7 (70%)	6 (60%)	0
Total	**157**	**152**	**110**	**100**	**23**

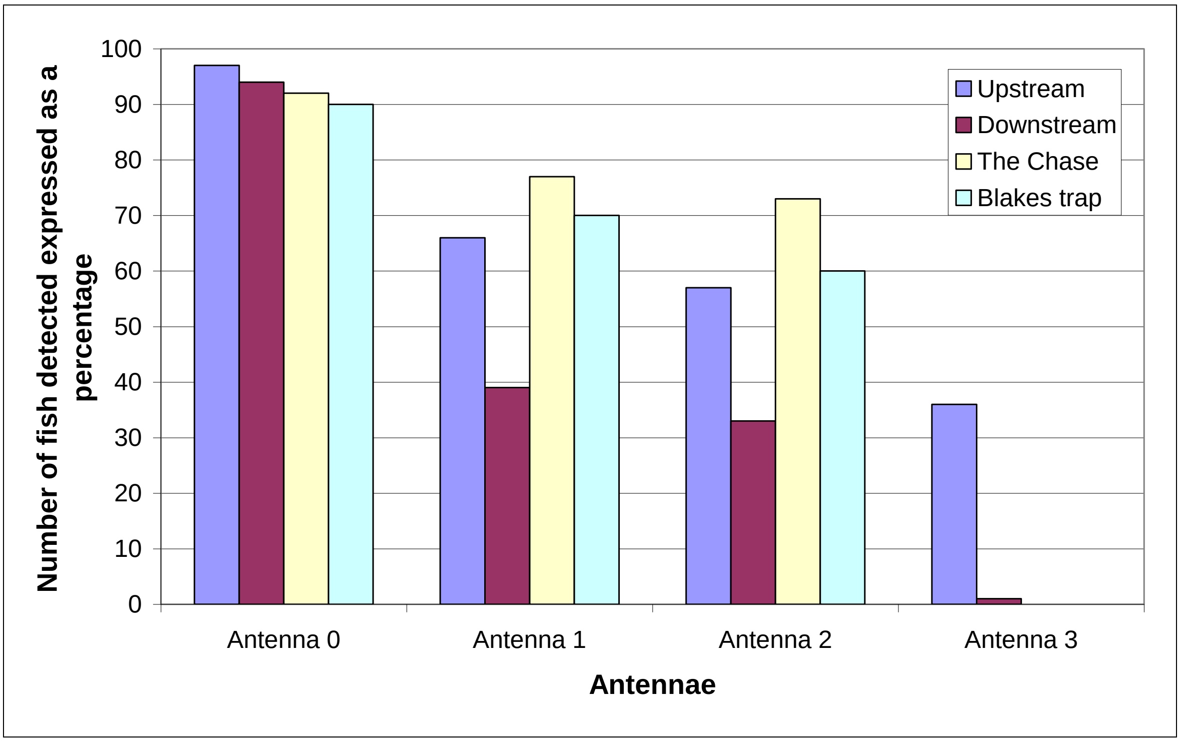


Figure 3.17 Number of fish detected at each antenna by site of capture

3.2.7 Comparative statistics

The number and species of coarse fish introduced into the weir pool are shown in Table 3.2. The numbers obtained vary considerably between species and capture site, such that only a limited number of comparative assessments could be made.

Initial examination of the data showed extensive variation in the behaviour of individual fish in their attempts to ascend the weir across all species for which there were sufficient data to make a judgement. Some individuals made frequent attempts to ascend while many made no attempts. This made evaluation of propensity (that is, desire to ascend the weir) problematic. The analysis was simplified by treating the situation as a binary problem, by regarding individual fish as falling into one of two groups: those that made at least one attempt to ascend (recorded at antenna 2) and those that made no such attempts (Table 3.6). Propensity to ascend the weir could then be judged on the relative proportions of these groups within each population.

This analysis assumes that every fish has an equal opportunity to ascend the weir and its choice is independent of that made by other fish. In practice this assumption may not hold absolutely for some species, particularly those that shoal readily, consequently the outcome should be treated with some caution.

Only one valid comparison was possible, which was between chub from upstream of the weir compared with the chub from downstream. Fisher's Exact Test was used to obtain the p-value for the difference in proportions. The results indicated that the test of a difference between proportions (two tailed test) is not significant ($p>0.05$) but the test that the proportion from upstream is greater than from downstream (one tailed) returns a p-value almost exactly 0.05 and provides evidence of a difference in origin influencing the number of chub ascending the weir. The choice of a one-tailed test is justified on the basis that fish are likely to exhibit a homing instinct and the natural drive of both groups would tend only to cause the proportion of upstream fish ascending the weir to exceed that of the downstream fish.

Table 3.6 Contingency table for chub.

	Upstream Chub	Downstream Chub	Total
At least one attempt	28	6	34
No attempt	17	12	29
Total	45	18	63

Attempts and ascents at the weir

In this study, an attempt is defined as an entry into the fish pass, which corresponds to a detection at antenna 2. It is possible that recordings at antenna 2 that do not culminate in detection at antenna 3 are due to fish finding the habitat in the immediate vicinity of antenna 2 favourable to reside/feed/seek refuge in. However, given that antenna 2 is situated on the fourth baffle up the weir in a very turbulent environment, it is unlikely that these fish species would choose to remain there and thus it is reasonable to assume that the fish detected here made a positive decision to attempt to move upstream.

Not all detections at antenna 2 were associated with discrete attempts to pass. All repeat detections occurring within 60 seconds of each other were removed, as they were very likely to be the result of fish movement within the vicinity of the antenna after the initial detection. Those fish that made it all the way up and over the weir are referred to as 'successful ascents'.

Table 3.7 shows the number of individual fish that attempted to pass the weir, and the total number of attempts each made. The numbers in brackets show the values as a percentage of the total number present. The greatest percentage of individuals attempting to pass up the weir are from The Chase (73 per cent), which is upstream of the weir. Fifty-nine per cent of the fish from upstream made attempts, along with 60 per cent of the fish from Blakes trap and 33 per cent of the fish from downstream. Fifty-two fish (52 per cent of all those detected at antenna 2) made more than five attempts to ascend the weir.

Table 3.7 Number of individuals attempting the weir, by species and capture site. (Percentages of original numbers of each category tagged are shown in brackets)

	Chub	Dace	Perch	Roach	Number of individuals	Total number of attempts
Upstream	28 (62%)	3 (33%)	3 (60%)	2 (100%)	**36 (59%)**	**324**
Downstream	6 (33%)	0	0	0	**6 (33%)**	**86**
The Chase	0	0	1 (100%)	52 (72%)	**53 (73%)**	**294**
Blakes trap	0	0	6 (60%)	0	**6 (60%)**	**61**
Total number of attempts	**331**	**30**	**99**	**305**		**765**

Table 3.8 Number of ascents of the weir, by species and capture site. (Percentages of original numbers of each category tagged are shown in brackets)

	Chub	Dace	Perch	Roach	Number of individuals	Total number of ascents
Upstream	18 (40%)	3 (33%)	0	1 (50%)	**22 (36%)**	**27**
Downstream	1 (6%)	0	0	0	**1 (6%)**	**2**
The Chase	0	0	0	0	**0**	**0**
Blakes trap	0	0	0	0	**0**	**0**
Total number of ascents	**25**	**3**	**0**	**1**	**23**	**29**

In total, 23 fish (22 from upstream and 1 from downstream) made 29 ascents of the weir. These fish effectively negotiated the baffle pass and reached antenna 3 (Table 3.8). All the fish that reached the last antenna are referred to in the above analysis as an ascent, regardless of whether or not they continued up a further 1.2m to reach the crest and make it upstream. This was because they had negotiated their way up the baffle pass, which is a positive result. It is highly likely that these individuals would have passed upstream if the baffles were all the way up to the crest (that is, on a non-gauging weir).

Table 3.9 contains the details of every discrete ascent (a detection at antenna 3). Out of the 29 attempts made by 23 fish, 18 individuals had antenna 3 as their last detection, indicating that they reached the crest and successfully made it over the weir. These fish are highlighted in yellow.

The predicted water velocity at the point just before the first baffle was calculated for each detection. Each fish would have had to swim against this water velocity in order to reach the weir crest. The mean burst speed figure is the mean maximum speed that fish can swim at for up to 20 seconds, which is most likely to be the mode of swimming needed to ascend the baffles. An estimate of the mean burst swimming speed of each fish was calculated by inputting the temperature, water velocity and fish length information for all the fish into SWIMIT version 3.3. This model was constructed using the data produced from the swimming speeds research by Clough and Turnpenny (2001). SWIMIT provides an estimate of fish swimming speeds and endurance for different species of different sizes in flumes set to varying water velocities. Any data that falls outside the range of the empirical data (temperature and fish size) used to construct the model is flagged up. In this study, all fish that are greater than 230mm (79 per cent of the total that reached antenna 3), are larger than those used in the experiments, so their mean burst speeds should be viewed with caution.

Relationship between successful ascent, flows and velocities

A large number of ascents (17 fish – 59 per cent of the total number of detections at antenna 3) occurred in the high flows between 30 April and 1 May. During this time, the exact flows at which these fish were detected ranged from $5.07m^3s^{-1}$ to $9.39m^3s^{-1}$ ($>Q_5$). The water temperature ranged from 9.06˚C to 10.42°C. Ten of these 17 fish made it over the weir. One other fish, a 221mm chub, made it over the weir in high flow conditions on 3 June. The remainder of the fish made it to the top of the baffles when the flows were considerably lower and the temperatures were higher. Eight out of these 11 fish successfully reached the crest of the weir and passed upstream during flows that ranged from $0.94m^3s^{-1}$ to $2.48m^3s^{-1}$, (approximately Q40-Q15) and in temperatures ranging from 11.13˚C to 16.10˚C. Under these lower flows, antennae 1 and 2 were still fully operational.

Table 3.9 Details of each detection at antenna 3 (successful ascents are highlighted).

Number	Date	Time	TagID	Species	Capture Site	Length (mm)	Mean burst swim speed (m/s)	Number of attempts	ADF (cm^3/s)	Flow at detection (cm^3/s)	Stage at detection (m)	Temp (^oC)	Water Velocity at top baffle (m/s)
1	26-Apr-08	03:39:48	09610058	Chub	US5	422	1.63	1	0.91	0.94	0.28	11.13	2.92
2	30-Apr-08	21:47:18	0960FFDA	Dace	US3	198	1.46	Antenna 2 off	6.73	9.01	0.85	9.34	3.58
3	30-Apr-08	23:52:44	0960FFB2	Chub	US6	489	1.63	Antenna 2 off	6.73	9.30	0.86	9.41	3.62
4	01-May-08	00:18:25	0960FF4E	Dace	US3	204	1.47	Antenna 2 off	4.67	9.35	0.87	9.41	3.63
5	01-May-08	01:02:05	09610062	Chub	US5	440	1.60	Antenna 2 off	4.67	9.39	0.87	9.39	3.63
6	01-May-08	02:00:34	0960FF94	Chub	US5	423	1.59	Antenna 2 off	4.67	9.34	0.87	9.34	3.63
7	01-May-08	03:04:21	0960FF58	Chub	US3	431	1.59	Antenna 2 off	4.67	9.23	0.86	9.26	3.62
8	01-May-08	03:38:42	0960FFB2	Chub	US6	489	1.63	Antenna 2 off	4.67	9.06	0.85	9.24	3.60
9	01-May-08	04:11:37	0960FF3F	Chub	US4	389	1.56	Antenna 2 off	4.67	8.86	0.84	9.21	3.57
10	01-May-08	04:34:14	09610005	Chub	DS1	213	1.38	Antenna 2 off	4.67	8.72	0.83	9.16	3.61
11	01-May-08	04:36:00	0960FF93	Chub	US6	423	1.58	Antenna 2 off	4.67	8.72	0.83	9.16	3.61
12	01-May-08	05:55:59	0960FF3E	Chub	US6	396	1.56	Antenna 2 off	4.67	7.84	0.78	9.11	3.54
13	01-May-08	06:24:51	0960FF7E	Chub	US3	472	1.61	Antenna 2 off	4.67	7.46	0.76	9.09	3.55
14	01-May-08	06:35:41	0960FF77	Chub	US4	438	1.59	Antenna 2 off	4.67	7.46	0.76	9.06	3.55
15	01-May-08	07:38:34	0960FFA6	Chub	US6	468	1.61	Antenna 2 off	4.67	6.69	0.72	9.09	3.50
16	01-May-08	14:50:21	0960FFB5	Chub	US5	443	1.62	Antenna 2 off	4.67	4.85	0.61	10.00	3.34
17	01-May-08	16:04:06	0960FF70	Chub	US6	402	1.60	Antenna 2 off	4.67	5.00	0.62	10.37	3.36
18	01-May-08	16:40:31	0960FF93	Chub	US6	423	1.61	Antenna 2 off	4.67	5.07	0.63	10.42	3.37
19	04-May-08	18:06:24	0960FF70	Chub	US6	402	1.65	Antenna 2 off	1.67	1.69	0.38	12.75	3.01
20	05-May-08	15:42:43	09610005	Chub	DS1	213	1.47	Antenna 2 off	2.18	2.48	0.45	13.23	3.28
21	05-May-08	15:52:42	0960FF54	Chub	US4	399	1.66	Antenna 2 off	2.18	2.48	0.45	13.23	3.28
22	05-May-08	19:46:03	0960FFA9	Chub	US6	478	1.71	Antenna 2 off	2.18	2.36	0.44	13.47	3.30
23	07-May-08	19:52:28	0960FFE1	Chub	US6	445	1.72	1	1.29	1.30	0.34	15.22	2.95
24	08-May-08	18:32:20	0960FFE1	Chub	US6	445	1.73	1	1.12	1.13	0.32	15.61	2.91
25	09-May-08	18:27:37	09610058	Chub	US5	422	1.72	1	0.99	1.00	0.30	16.10	2.93
26	25-May-08	11:15:26	0961005C	Chub	US5	382	1.64	1	1.13	1.37	0.35	12.90	2.99
27	25-May-08	14:56:36	0960FF30	Dace	US6	206	1.53	1	1.13	1.35	0.34	13.06	2.98
28	03-Jun-08	13:07:30	0960FF37	Chub	US7	221	1.49	Antenna 2 off	13.10	9.88	0.88	13.74	3.66
29	08-Jun-08	19:11:59	0960FF3B	Roach	US7	244	1.60	1	1.12	1.12	0.32	15.53	2.91

Table 3.10 below is a summary of the hydrological conditions for the attempts and ascents at the pass.

Table 3.10 Summary of average conditions present during attempts and ascents at the weir.

	Attempts	Ascents
Total detections	765	29
Total individuals	100	23
Mean flow (m^3s^{-1})	0.95 (+/- 0.18)	5.60 (+/- 3.48)
Mean size of fish (mm)	297 (120-510)	380 (198-489)
Mean stage (m)[1]	0.28	0.63

Notes: [1] amount of water over weir crest

Figure 3.18 shows that fish made attempts at a broad range of flows, with some suggestion of bi-modality in the distribution of successful attempts with respect to flow.

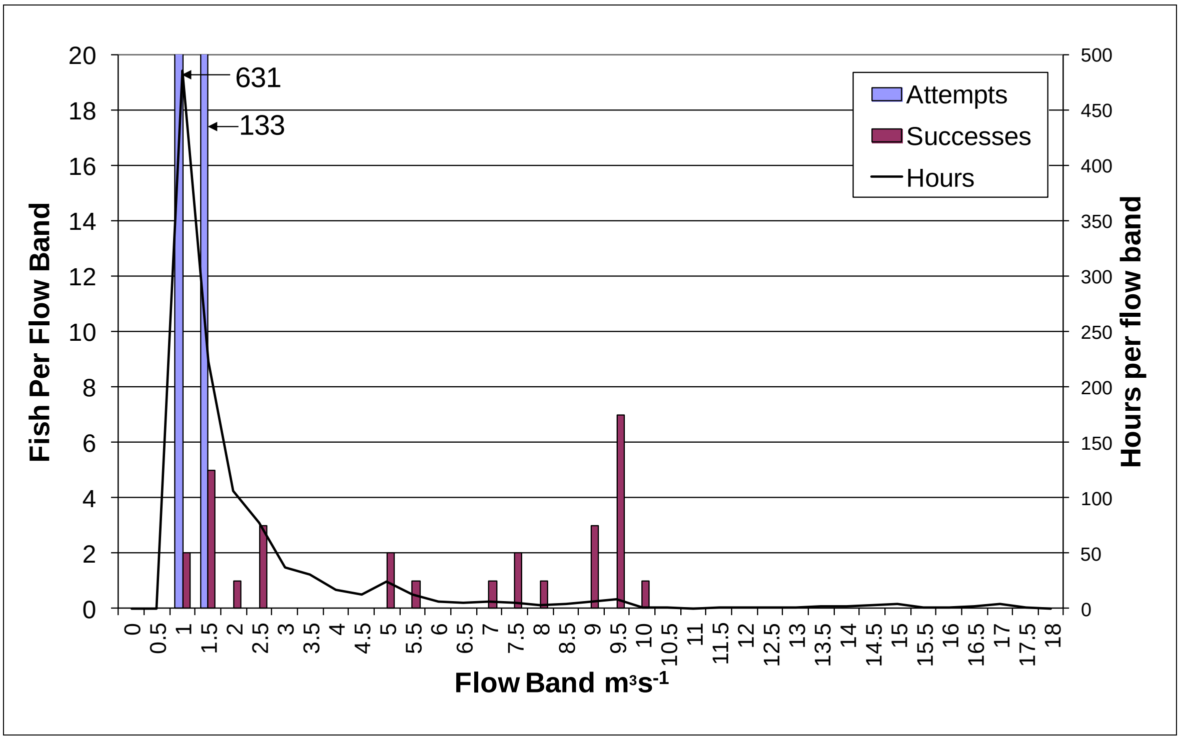


Figure 3.18. Numbers of attempts per flow band.

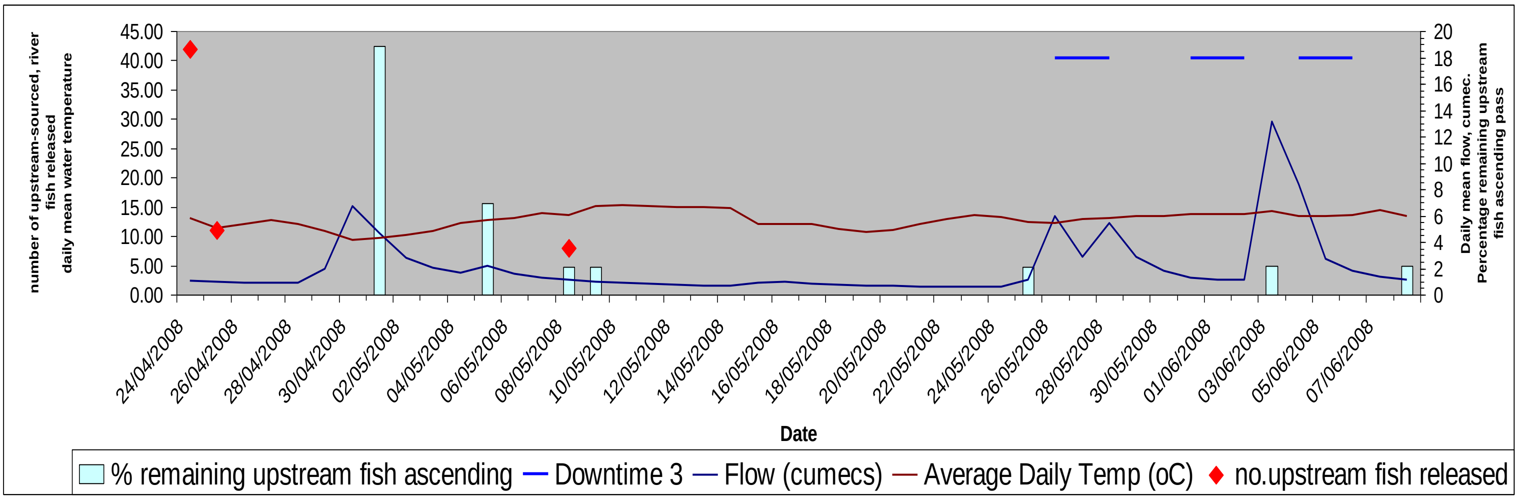


Figure 3.19 Number of ascents of the fish pass by upstream-sourced river fish, in relation to daily mean flow and average daily temperature for the study period.

Figure 3.19 shows the relationship between average daily temperature and average daily flow with the number of successful ascents (antenna 3 as last detection) by the most relevant group of fish – namely those translocated from the main river upstream of Brimpton Weir. The main period of activity is during the period of receding flows after a spate and increasing temperatures, between 6 and 12 May. Other individual fish also ascended during periods of higher flow; just two fish were successful when the river was close to its base flow for the study period – at around 1 m^3s^{-1}. It should be noted that the lower flows during the study period were nevertheless untypical for that time of year.

Effectiveness and efficiency of the baffles

Given that Brimpton Weir was previously judged to be an impassable barrier to fish at most flows, this PIT tagging study appears to show that this low cost baffle arrangement is effective at passing fish over a wide range of flows. A measure of the efficiency of the pass is given quantitatively by calculating the proportion of tagged individuals that successfully ascend the baffle fish pass. This can be assessed using the equation adapted from Travade and Larinier (2002):

$E = 100\ (n_p/CN_m)$

Where

E = The efficiency of the pass, expressed as a percentage

n_p = Number of marked fish that migrate through the pass

N_m = Number of marked fish that attempt to ascend the pass

C = A coefficient ($0<C\leq1$) expressing any influence of marking (mortality and handling and so on)

100 per cent tag retention is assumed along with zero mortality of tagged fish resulting from handling or natural mortality.

From the total 157 tagged fish that were released into the weir pool, 100 made at least one attempt to ascend (registered on antenna 2); 23 were recorded at antenna 3, having successfully negotiated the pass. Hence:

E (Percentage of individuals attempting successfully reaching top baffle) = 100 (23/100) = 23 per cent.

Out of these 23 fish, we can be reasonably sure that 18 of them (16 chub, 1 dace, 1 roach) successfully ascended the fish pass and carried on upstream (last detection on antenna 3).

However, this does not take into account the effort spent in attempting to ascend the pass. When taking all detections into consideration, a large proportion of attempts resulted in a failure to ascend. There were 765 discrete attempts at antenna 2 and 29 successful ascents at antenna 3. The efficiency for the total number of attempts (not individuals) would then be:

E (number of attempts) = 100 (29/765) = 3.8 per cent

Therefore the probability in an attempt resulting in a success would be 3.8 per cent, which is low. If we look purely at fish that were successful, on average 7.5 attempts would be needed (measured by recordings of that individual on antenna 2) before they successfully ascended. This indicates that even for individual fish with the determination and ability to ascend the weir, it still represented a considerable effort in time and energy.

These calculations are a simplistic indication of the efficiency of the pass. They do not take into account the differences between species or between fish from different capture sites.

Figure 3.17 and Tables 3.5, 3.6 provide clear evidence that fish translocated from upstream of the weir showed the greatest motivation to ascend the weir. Although roach from The Chase showed considerable interest in the fish pass, as lake fish they would have had generally poorer swimming ability than river roach of similar size and were apparently unable to ascend the pass. If efficiency of the fish pass is assessed based on the groups that would naturally be expected to use the pass, namely river fish from upstream, the efficiencies are generally higher.

For upstream chub, E= 100(15/28) = 54 per cent

For dace E= 100(1/3) = 33 per cent

For upstream riverine roach E= 100(1/2)= 50 per cent

None of the five perch relocated from upstream were successful in reaching antenna 3, although attempts to ascend were made by three of them.

Note that these figures are for fish whose last detection was on antenna 3; that is, those that we are most certain did ascend the weir-crest and proceed upstream. These percentages are therefore slightly lower than those for total numbers of fish that reached antenna 3, as some of these came back down the pass and then remained below the weir.

For dace and roach the samples sizes are clearly so small that no firm conclusions should be drawn.

These should be regarded as minimum estimates of efficiency since it is likely that significant numbers of fish went through the pass later on in the study period when antenna 3 was disabled by high flows.

Size-selectivity of successful ascent

Figure 3.21 shows the length-frequency histograms for chub tagged and released below Brimpton Weir, those that were detected at the various antennae, and those that were judged to have ascended the fish pass successfully.

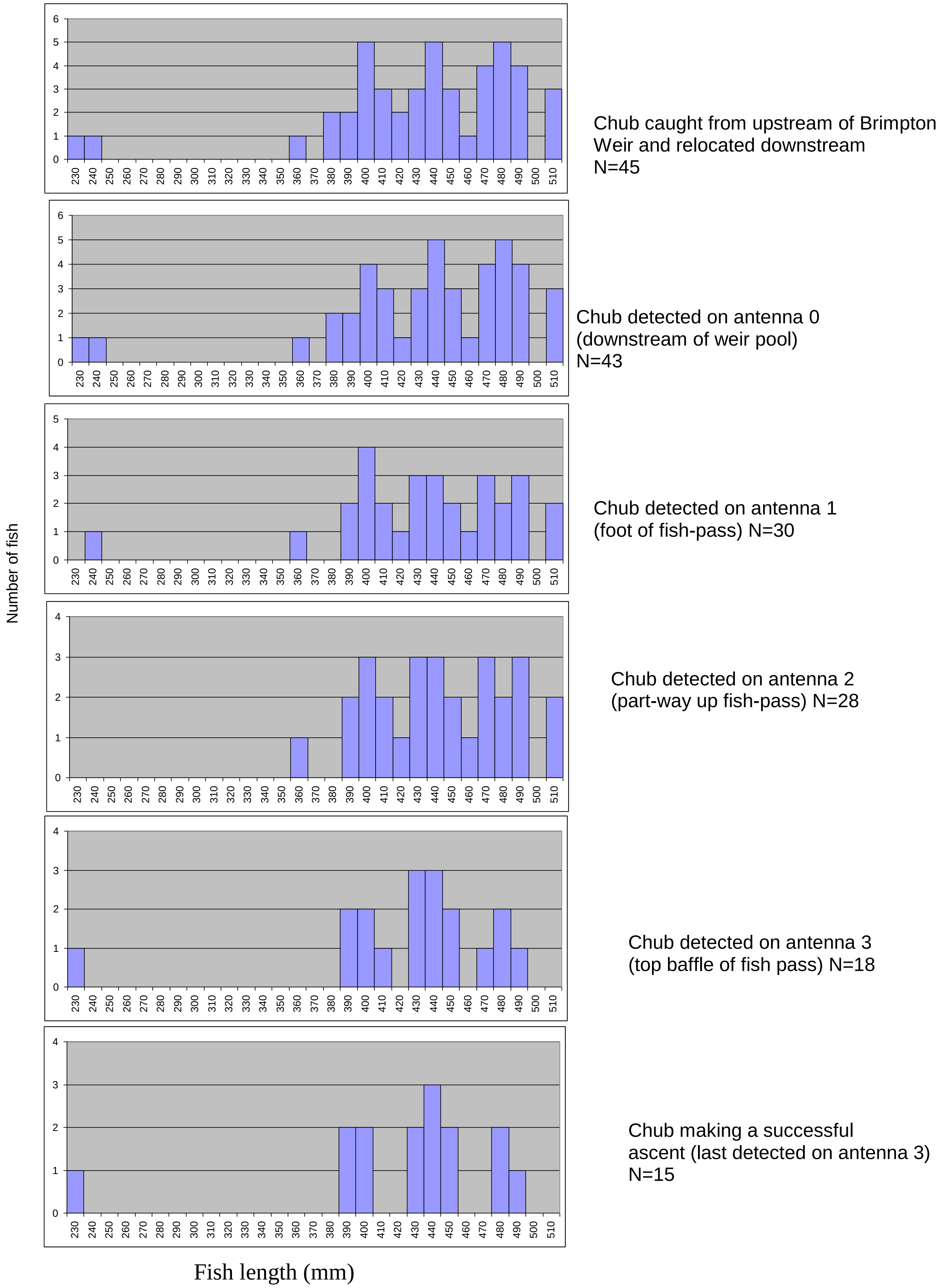


Figure 3.21 Length-frequency histograms of chub detected in the vicinity of Brimpton Weir

3.2.8 In-slot velocities – field evaluation

Table 3.11 shows the velocities actually measured in the field in April 2009.

The measured velocities were significantly higher than those predicted by the laboratory testing and modelling (for flows recorded on 9 April 2009 - see Figure 4.68 in Servais, 2006,). In many areas of the baffle-array these velocities exceeded the maximum burst speeds documented for cyprinid fish.

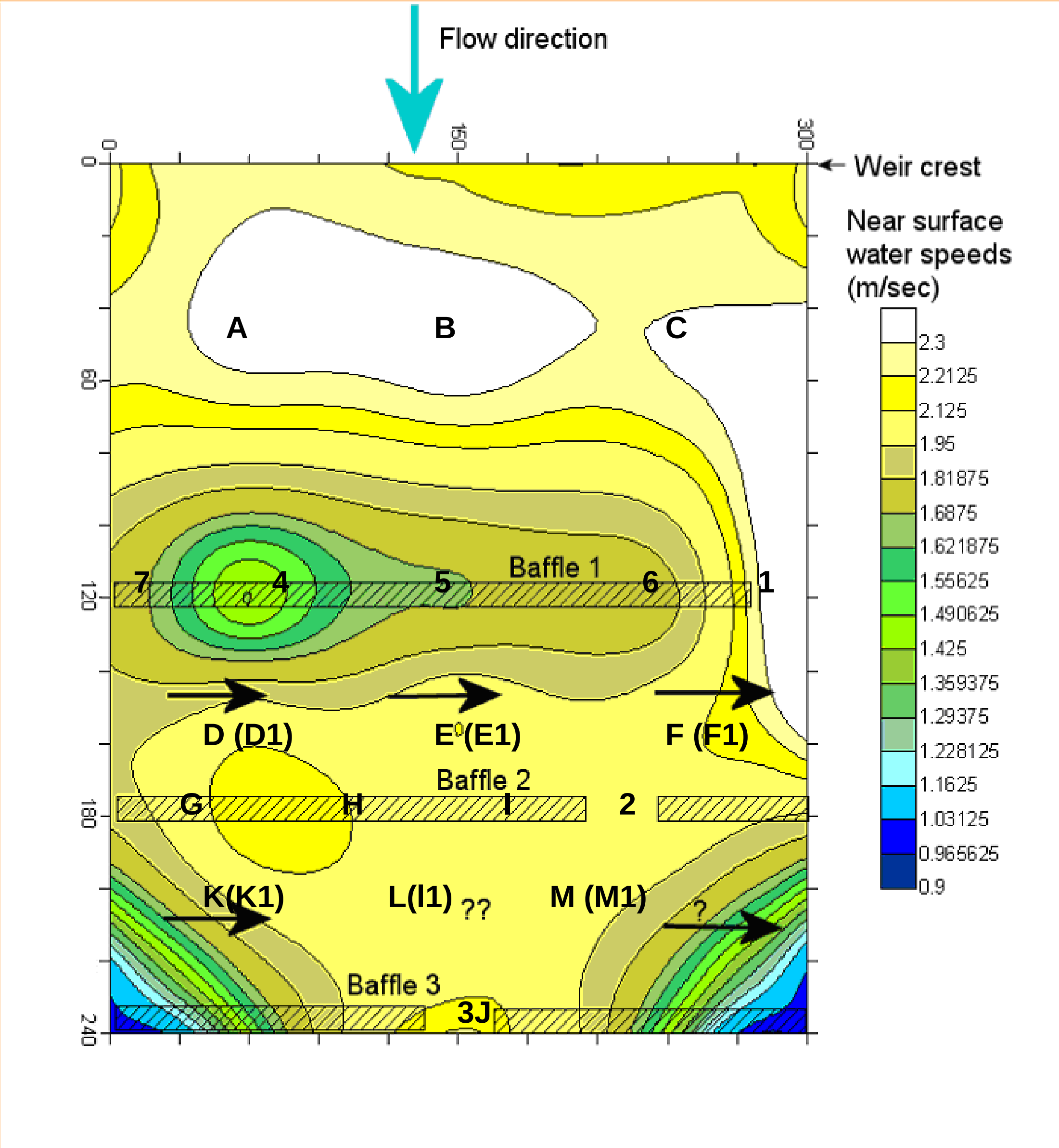
Table 3.11 Velocity measurements at various depths and positions in the upper part of the baffle array, taken with rotating propeller current meter, April 2009. The positions where measurements were taken are shown in Figure 3.22

Date	09-Apr-09					
Location	Brimpton					
Prop No.	3					
Time (time)	60					
Location	Time	Counts	Vel (m s^{-1})	Depth (cm)	% time backwards	Flow direction
1	11.41	570	2.397	20	0	us/ds
2	11.42	51	0.223	34	30	us/ds
3	11.47	316	1.334	30	0	us/ds
4	11.50	338	1.426	16	0	us/ds
5	11.52	399	1.681	17	0	us/ds
6	11.53	424	1.786	12.5	0	us/ds
7	11.55	405	1.706	19	0	
A	11.57	542	2.279	12	0	us/ds
B	11.59	554	2.33	12	0	
C	12.00	545	2.292	11.5	0	
D	12.02	478	2.011	38	0	
E		502	2.11	36	0	
F	12.05	492	2.07	32	0	
G		522	2.196	13		
H		479	2.016	11		
I		528	2.22	10		
J		493	2.07	SURFACE OF SLOT		
K		71	0.31	35		
L		172	0.73	36		
M		88	0.378	38		
e1		27	0.123			Flow left to right 10%, right to left 90%
D1	12.21	30	0.135	30		Right to left
F1		38	0.168			Right to left 90%
K1		94	0.403			Right to left 90%
L1		50	0.219			Undetermined direction
M1		229	0.969			Right to left (probably)

Figure 3.22 Brimpton Weir – Water speeds on weir and baffles, 9 April 2009, when flow was 0.89 m^3s^{-1}

Water velocities measured just below surface, Current meter 61309, impellor no.3.

Note: only one reading taken at baffle 3 in slot. Slower velocities shown near banks here are likely to be as a result of how Surfer interprets where there is no data. No measurements were possible directly on the weir-crest or further down the weir due to inaccessibility.



Discussion

The overall objective of the project was to assess whether an obstruction to migration – a small gauging weir on the River Enborne – can be alleviated by installing low-cost baffles, without compromising gauging integrity.

This part of the study provided an assessment of the effectiveness of the baffle fish pass on the compound Crump weir. This was carried out by analysing the movements of PIT-tagged fish translocated into the weir pool from four different locations, to determine whether they were able to use the pass, throughout the spawning season of 2008.

The following sections discuss the outcomes from that study.

3.2.9 The baffle fish pass

Despite the fact that the design of the baffle array for Brimpton was derived using theoretical hydraulics and supported by tests undertaken in controlled laboratory conditions, the structure installed at Brimpton exhibited some features that rendered the fish pass sub-optimal.

When a baffle fish pass is deployed at a gauging station, the first baffle has to be further down the weir-face than would be optimal for fish passage in order to avoid changing the coefficient of discharge by more than 1 per cent. On Brimpton Weir, the calculated distance for the first 200mm-high baffle was 1200mm down from the crest. However, when the baffles were installed, a 120mm baffle was fitted, 1260mm down the weir-face. The first baffle should have been either 200mm high or 120mm high and situated much closer to the weir-crest. The effect of this departure from the intended design would be a longer stretch of faster-flowing water for upstream swimming fish to negotiate after passing the first baffle.

Other features also rendered the as-built pass sub-optimal. According to Servais (2006), the baffles should have been fully rounded (see Figure 3.2a) in order to minimise aeration as water passes over the baffle crest, whereas in fact the timber was delivered un-rounded, and the baffle edges were merely chamfered before installation. In addition, just upstream of the uppermost baffle and adjacent to the low-velocity slot, there are two stop-log slots (Figures 2.43 3.4, 3.10) - these generate aeration, which has been associated with fish disorientation (Larinier, 2002).

3.2.10 PIT and camera equipment

The ability to detect relatively large numbers of tagged fish moving up the weir and remotely monitor them using a system of cameras, in different conditions, day or night, makes this method of assessing fish passage and behaviour at flow gauging weirs very effective. However, conditions during the study period were exceptionally inclement and unseasonal, and limited the techniques used.

At Brimpton, as long as the flows remained lower than $2.6m^3s^{-1}$ all the equipment was functional. That flow value is exceeded approximately 12 per cent of the time (Q_{10} exceedance = 3.063), and at flows above this value, the water level begins to rise above the 1m height of the antennae, thus breaking them sequentially. Antenna 3 was the last to break, at flows of approximately $7m^3s^{-1}$. High river levels were the main cause of downtime, with 15.5 days of data from antennae 1 and 2 lost due to these conditions. There was some evidence of greater utilisation of higher flows for successful fish passage, but the full pattern of fish movement at high flows could not be fully observed, because the PIT equipment was not fully operational across the entire flow range. The height of the top of the antenna loop above water level could not be increased without loss of detection capability.

It was not possible to set further PIT detection sites on the upstream side of the weir, as the water was too deep. In future studies at Brimpton or other sites, it may be feasible to set additional PIT antennae at specific sites further upstream and downstream in the locality of the weir. In retrospect, it would have been beneficial to place antennae on the high flow weir as it was possible (though very unlikely) that some fish may have ascended it at higher flows.

Each PIT antenna was tested regularly using a pole mounted PIT tag. The tag was passed under the antennae at different points and various depths. The detection rate was shown to be 100 per cent on all antennae up to 40cm away from the antennae. In reality, the detection efficiency could not have been 100 per cent at all times, as fish were seen to hold at antenna 0, 1 and sometimes 2. These fish would have inhibited the detection of other fish passing through. Also, it is highly likely that some fish passed through the antennae at an oblique angle, some at the same time as others, or more quickly than the two-second detection cycle. These scenarios would have precluded detection of a proportion of the tags. Where previous studies suggest that detection efficiency is high, at 93 +/-2 per cent (Zydlewski *et al*., 2001; Lucas *et al*., 1999a), it has not been possible to estimate this in the present study.

Several adjustments were made to the camera equipment throughout the study, to obtain the highest quality images of fish passing from the top baffle to the crest, in the day and the night. Unfortunately, at the times of peak fish movement, the water was too turbid to be able to see anything clearly, and even at normal flows reflections from the water surface and turbulence obscured clear views of the water column most of the time. Only one fish was seen clearly emerging from the slot in the top baffle of the fish pass. Cameras positioned in the water, particularly looking across slots of several baffles, would be a useful improvement if any further work is carried out at Brimpton.

3.2.11 Variables affecting successful passage

The relationship between environmental variables (especially flow and temperature) and salmonid migration has been the subject of much study in recent years. River flow is often cited as being the primary environmental factor triggering salmonid migration (Jensen *et al*., 1998; Laine *et al*., 2002), although temperature has also been shown to be influential (Gowans *et al*., 1999. Examples of work exploring the relationship between temperature, flow and migration for non-salmonids are relatively less abundant. Increasing temperature, giving rise to elevated levels of movement (primarily spawning movement) has been reported for shad (Bellariva & Belaud, 1998), barbel (Lucas & Frear, 1997) and various riverine cyprinids (Prignion *et al*., 1998; Lucas & Bubb, 2005).

Temperature

Estimates for the minimum temperature under which cyprinids will migrate vary. Travade *et al.* (1998) suggest that 9-10°C is the minimum temperature allowing cyprinids to use passes, whereas Prignion *et al*. (1998) suggest 10-12°C represents the minimum temperature for ascent. In the UK, upstream migrations of cyprinid fish have been observed at similar temperatures to these (Lucas *et al*., 1999b). Throughout the study period, temperatures ranged from 9.36°C to 14.94°C, hence the water temperature was never below the range during which at least some migration could be expected to take place.

There were more fish at antennae 1 and 2 when water temperatures had increased. Peak activity at antenna 2 occurred from 7 to 10 May, when average daily temperatures ranged from 13.52°C to 15.30°C. As fish are ectotherms, metabolism is related to ambient temperature, hence their activity and swimming ability increases in the warmer temperatures, thus explaining increasing frequency of attempts. However, the number of fish at antenna 3 on 1 May occurred at lower temperatures, coinciding with high flows. At such flows the water level downstream of the weir increased as well as the upstream level, potentially reducing the effort required to ascend the weir, so that ascent was possible despite reduced swimming capability. A combination of river flow and temperature might be influencing the propensity of fish to try to ascend the weir and their success in doing so. However, a limited time frame, very variable conditions and variable timing of the introduction of tagged fish make it difficult to draw firm conclusions from this study.

River flows, velocities and fish swimming speeds.

There appeared to be some influence of flow, or related factors such as turbidity, on the number of fish that ascended the weir and reached antenna 3. The maximum in a single day of 14 individual fish was detected at antenna 3 on 1 May, which coincided with the first high flow event. While less fish were detected on antennae 1 and 2 on this occasion, this probably reflected equipment failure rather than a real drop in activity, as these antennae ceased to function above flows of 2.6 m^3s^{-1}. This prevented the real picture of fish behaviour in the weir channel from being fully assessed across the whole flow range.

The mean flow under which fish ascended the weir to baffle 3 was much higher than that at which most fish attempted to ascend (Table 3.10). The fish that made a positive ascent and reached the top of the baffle pass appeared to fall into two distinct groups in their relationship with flow: those that ascended in flows between 1m^3s^{-1} and 2.5m^3s^{-1}; and those that ascended in flows between 5m^3s^{-1} and 10m^3s^{-1} (Figure 3.18). Flows were below 2.5m^3/sec for a large proportion of time during the study period. Thus, fish would have had more opportunities to attempt the pass under these lower flows, which would be expected to result in more successful ascents. Conversely, those fish that ascended in the higher flows had a very narrow time window yet enjoyed a relatively high success rate, which suggests that high flows were more favourable to fish passage. The fish that ascended in the lower flows are likely to have navigated their way through the fish pass slots designed for low velocity passage (rather than over the top of the baffles) to reach the top of the weir. Indeed the one fish observed using the pass on the cameras, (a 382mm chub) swam through the exit of the baffles and up over the weir on 25 May. At that point, the flow was 1.37 m^3s^{-1} and the stage level was 0.35m.

The above observations suggest that the fish may have utilised the baffle pass in different ways in order to ascend. Those fish that ascended in the lower flows are likely to have used the slots, while those that ascended on the higher flows could have swum just above the baffles, using the reduced velocities created by the baffles to make their way. The baffles create complex hydrodynamic conditions on the downstream face of the weir, which creates slow-moving boundary layers and areas of re-circulating flow, or eddies. Fish exploit these conditions as they are able to perceive very slight variations in hydrodynamic conditions (McLaughlin & Noakes, 1998) A fish using the baffle pass at Brimpton might take advantage of the boundary layers as well as a combination of re-circulating flows generated by the baffles and the slower water velocities in-between each baffle in order to ascend. On the other hand, the high turbulence caused by the baffles may also negatively impact on their ability to ascend, since these environments increase drag forces on fish swimming, restrict generation of forward thrust and may also cause difficulties in orientation (Larinier *et al*., 2002). Further studies with cameras are required to determine whether the fish that pass through in the lower flows and stage bands are passing through the baffle slots or over the top of the baffles.

To make a successful ascent, fish that have made it to the top of the baffle pass, have then to ascend a further 1.2m to reach the crest of the weir. Eighteen out of the 157 tagged fish made it over the weir on the basis that if the last detection of a fish was at antenna 3 (and has not been picked up on any other antenna for the remainder of the study) then that fish had successfully ascended the pass. When the majority of these fish passed antenna 3, antenna 2 was compromised, hence some fish may have ascended the baffles and dropped back down again without being detected. A true estimate of the proportion of successful attempts by comparing fish presence on antenna 2 with antenna 3 was therefore not possible.

According to SWIMIT, no fish less than 30cm in length should have been capable of ascending the weir on the basis of the velocities calculated for the flows at which the fish were attempting to pass. While SWIMIT cannot accurately predict the capabilities of fish over 30cm, the model suggests that these too should not have been able to pass.

All velocities on the weir-face, including in the slots, were beyond the 90 per cent sustained swimming speed, hence fish must be using their burst capability. Servais (2006) predicted that velocities in the slots would, at seasonal median flows, be low enough to enable fish to pass. For most of this study, flows were unseasonably high, but some fish clearly were able to ascend the weir using the fish pass.

It is widely acknowledged that fish exhibit substantial variability in maximum swimming speeds either through differences in physiological capability, or differences in the behavioural motivation to swim at high speeds (Priede & Holliday, 1980).
Peake (2004) showed that there are alternative modes of fish swimming (volitional swimming) which cannot be elicited in flume tests, which can deliver higher velocities than burst swimming. It is highly likely it is that capability which was successfully invoked by fish that ascended the pass.

Photoperiod and diel activity

Photoperiod is important in stimulating migration (Lucas & Batley 1996; Prignion *et al*., 1998; Fredrich *et al*., 2003). Lucas and Batley (1996) studied radio-tracked barbel and found that their upstream movement increased with increasing day length. Figures 3.11 and 3.12 show that during the present study, increasing photoperiod initially coincided with increasing activity, but photoperiod continued to increase when fish activity began to reduce after 10 May. It is possible that photoperiod acts as a trigger to initiate upstream fish movement, though once migration has started, other factors determine its progress.

The movements and activity of many fish species are affected by circadian rhythms. Lucas (2000) states that entry into a fish pass on the River Derwent was mainly nocturnal, and Lucas and Frear (1997), Lucas *et al*. (1999) and Prignion *et al*. (1998) all report behavioural or physical inhibition to travelling over obstructions in daylight. Results from the chub and perch in this study agree with these findings, as they clearly had a preference to attempt to ascend the weir during the hours of dusk and darkness, between18:00 and 23:00 (Figure 3.14), though there was very minimal movement from 00:00 to 05:00 when it was also dark. On the other hand, the results suggest that roach and dace were less crepuscular, as the majority of their detections were recorded during daylight.

The effects of capture site on motivation to ascend

The experimental design was compromised by the unexpectedly low numbers of fish available from upstream of the weir.

The ideal dataset for this study would have been 96 or more fish of each of the four species evenly spread throughout each group, as efficiencies would have been calculated to a precision on +/-10 per cent (Zar, 1984) (Section 3.2.7). Unfortunately, electric fishing at the River Enborne revealed that there were very few fish available for this study. Previous surveys revealed that the river was impoverished in places, but overall it had been found that biomass and densities were satisfactory. The particularly low densities seen in this study may have been attributable to the very high flows and numerous flooding events that occurred in 2007 and early 2008. It is suspected that many young fish were washed down into the main river, and that Brimpton Weir would have been one of the main obstacles that prevented them from returning to the upper reaches of the Enborne.

Due to the numbers and species of coarse fish introduced into the weir pool varying considerably between species and capture site, only a limited number of comparative assessments could be made. The results show that, with the exception of one chub from downstream, all the fish that reached antenna 3 were caught upstream of the weir. Most of the fish from upstream that made it to antenna 3 were chub, with an average length of 420mm (range 221mm-489mm). Twenty-eight of the chub attempted to ascend the weir and 15 (54 per cent of those attempting, 33 per cent of total upstream chub) of those reached the third antenna and were not detected again. Three others from that group of chub reached antenna 3 but were subsequently detected again downstream of the weir, suggesting that either they failed to reach the weir crest and fell back downstream, or that they ascended the weir, then returned to the weir pool by choice.

Chub may have been more successful because they have been shown to be faster swimmers than the other species (Turnpenny *et al.,* 2001), and this combined with their larger size may have given them a better chance of negotiating the pass. Fisher's exact test showed that there was a statistical difference in the number of attempts each fish made to ascend the weir between the chub that were caught upstream and the chub that were caught downstream of the weir, suggesting that the upstream fish were more highly motivated. This agrees with the view that coarse fish display homing behaviour when displaced to a different location (Lucas *et al*., 1999; Clough & Ladle, 1997). Although present in very small numbers, upstream riverine roach and dace also appeared successful in passing – three of the nine dace attempted the pass, three reached antenna 3, but two were last recorded below the weir. Both roach taken from the river upstream of the weir attempted to pass and one was successful.

The high percentage of fish from The Chase making it to antenna 2 (73 per cent) indicates a desire for these fish to return upstream. However, the small size and reduced swimming ability of these lacustrine fish may have precluded full ascent of the weir (Broughton & Goldspink, 1978). A significant proportion of downstream-sourced chub appeared on antenna 2 and this may have reflected the general tendency to move upstream in spring to search for spawning areas distant from their overwintering habitats (Lucas *et al*., 1999b; Fredrich *et al*., 2003). Perch from Blakes Trap (33 and 60 per cent respectively), also appeared on antenna 2, surprising perhaps because they were taken from the main River Kennet approximately 15km downstream of Brimpton, but these were fish that had already ascended a Larinier fish pass prior to capture and so were clearly motivated to move upstream. Most of these perch were small, however, and their swimming ability was apparently insufficient to enable them to ascend the baffle pass.

Inter-specific differences

Real differences between species are difficult to elucidate due to the different origins of the fish and their varying size.

The results indicate that the only species capable of reaching antenna 3 at the top of the baffles in significant numbers are chub and dace (rheophilic species with good swimming capabilities), and possibly roach.

The majority of chub tagged were over 400mm in length, which naturally would have given them a better chance of ascending the baffles, though smaller chub were also successful. The small sample sizes of dace and roach mean that their ascent rate should be interpreted with caution, however their success indicates that smaller fish (dace of 198mm, 204mm, 206mm and roach of 244 mm) are capable of reaching antenna 3.

None of the five perch translocated from the river upstream of Brimpton ascended the pass. The sample size was again small, but four of the fish were of comparable size to the dace, roach and smaller chub that were successful in ascending the pass, and it is possible that perch may have more difficulty in dealing with the flow patterns created in the baffle pass. Published data on perch swimming speeds are few (Wolter & Arlinghaus, 2003) but these indicate that perch have slightly better swimming capability than roach, and on that basis some of the riverine perch would have been expected to ascend the pass.

Movement studies of many freshwater fish, including perch and roach, demonstrate that not all artificially or naturally displaced fish return to their initial location of capture when displaced from upstream (Halvorsen & Stabell, 1990; Lucas & Baras, 2000). Several authors attributed this to motivational differences between individuals and the occurrence of a stationary and mobile component within a fish population (in other words, the non-mobile part of the population returns to their home ranges while the more mobile fish, which are not attached to any particular part of the river, stay where they were put or explore the new environment) (Stott *et al*., 1963; Halvorsen and Stabell 1990). Therefore the failure of some fish from upstream of Brimpton Weir to attempt to ascend the weir and return to point of capture does not necessarily reflect the inadequacy of the baffle system as a fish pass.

3.2.12 Is the ‘rotated V’ baffle arrangement effective at passing fish?

Of all the tagged fish, at least 64 per cent made an attempt at passing the weir. Some of these fish made many attempts, while others did not. It is calculated from the results that only 3.8 per cent of total attempts resulted in a successful ascent. However, success varied between groups of fish.

The groups translocated from river sites upstream of Brimpton Weir were the fish that would be expected to be most persistent and successful in ascending the pass on the basis of their homing instinct and swimming ability. Forty-seven per cent of all river fish translocated from upstream of Brimpton Weir that attempted to return were successful. Fifty-four per cent of chub were successful. Conversely, none of the five perch translocated from the river upstream of the weir were successful in reaching antenna 3, although three of those fish tried.

It should, however, be recognised that these estimates of efficiency are minima, since many more fish may have attempted and successfully ascended the weir during periods when the antennae were not working or due simply to the failure of the antennae to detect them when multiple fish were present (section 3.1)

Currently, fish pass efficiency for coarse fish species has not been formally defined in terms of minimum standards. For salmonids, it is generally considered that efficiencies should be 90-100 per cent (Lucas & Baras, 2001). Larinier *et al*. (2002) propose that the passage of a ‘certain number’ of cyprinid fish, in ‘reasonable proportion to the size of the population’ should be considered a success. In other words, a pass could be considered effective for coarse fish if it enables sufficient fish to negotiate an obstacle, reach spawning and nursery areas and produce sufficient progeny to maintain a viable population. However, if the weir is preventing the majority of fish from reaching feeding or other seasonally-important areas then it may still seriously constrain the population.

Based on Larinier’s proposition, the baffle pass on the compound Crump weir at Brimpton would be efficient enough to make it a reasonable success, as a minimum of 36 per cent of the tagged individuals originating from upstream of the weir were able to ascend the pass.

Bearing in mind that in the present study a number of fish got as far as baffle 3 and subsequently fell back and remained downstream, if the baffles had been positioned all the way to the top of the weir (which could be done on a non-gauging weir) and the design not been compromised in any other way, the efficiency would have been higher.

This study provides evidence that despite the compromised installation of the baffles at Brimpton, three species of fish (chub, dace and roach) are able to ascend a Crump gauging weir using the baffle pass. Conversely, there was no evidence that perch were able to use the pass. It appears that fish may have used the pass in different ways under different conditions (suggested by the bi-modal distribution of successful attempts in relation to flows), to negotiate what was previously a barrier to upstream movement. This is the first time that this design of baffled fish pass has been trialled in the field.

4. Louds Mill Weir – a retrofitted Larinier Super-Active baffle Fish Pass

4.1 Materials and methods

A full description of the location and hydro-geological characteristics of the Frome and Louds Mill Gauging Weir is given in chapter 2.

4.1.1 Fish populations in the River Frome

Louds Mill lies some 28km upstream of the River Frome's tidal limit and the fish populations in this area are dominated by brown trout, grayling and juvenile salmon. There are some coarse fish including dace, roach, gudgeon, perch and pike, but Louds Mill is close to the upstream limit of the distribution of these species in the Frome. Adult salmon tend to reach this area of the Frome during late autumn once increasing river flows have triggered their upstream migration, adult sea trout occasionally penetrate this far up the catchment but not in significant numbers.

In 2000, David Solomon assessed the weir structure at Louds Mill with regard to fish passage and concluded that it presented a significant obstacle to the upstream passage of migratory salmonids and a total obstruction to other fish species (Solomon, 2000). Low numbers (<50) of salmon would successfully ascend the structure each year, but this was dependant on good river flows during late Autumn and early Winter. If low river flows were experienced at this time then the ability of any fish to ascend the structure was further compromised.

The River Frome is bifurcated at this location and therefore other potential migration routes do exist. However, due to the flow configurations of these channels at their return to the main river, the majority of salmon were attracted to the Louds Mill site.

4.1.2 Fish pass design and construction

A three-unit, super-active 100mm high baffle Larinier fish pass with its crest level at 75mm below the level of the crest of the existing main weir was recommended in order to achieve the minimum desired fish pass attraction flow of $0.3m^3/s$ (10 per cent ADF) and a minimum depth over the crest (H_a) at Q95 of 0.16m. This configuration was chosen for Louds Mill because it provides a good balance between the hydrometric and fishery needs. The fish attraction flows are adequate throughout the flow range on the river Frome and the chosen type of fish pass has a satisfactory calibration for hydrometric requirements.

Details of the configuration are as follows:

- A single flight, super active Larinier fish pass with 100mm baffles set within the existing left hand flank of the weir (abutment), with the entrance jet pointing down the line of the bank.
- Three Larinier units, each 600mm width, separated by 100mm high longitudinal partitions. Baffle-to-baffle spacing (upstream-downstream) is 260mm, centre to centre. Total width of the pass is 1800mm.
- The crest level of the transverse section of the uppermost baffle within the fish pass to be set at 51.05m AD, the same level as the crest of the mill leat weir on the right bank, giving H_a at Q95 of 0.160m and at Q10, 0.42m.
- The longitudinal slope of the fish pass is 15 per cent.
- The length of the baffle section of the fish pass is 6.7m with the elevation of the crest of the most downstream baffle at 50.05m AD, so that at Q95 (winter) the tail is drowned to a depth of 0.17m.
- The upstream exit section to the fish pass is 3.8m long from the topmost baffle to the end, measured along the centre line. It has a concrete invert with an elevation of 50.50m AD (giving a depth of 0.71m at Q95) and the entry walls to the upstream exit channel have a radius of 0.3m to give smooth entry conditions. Velocities in the exit channel are $0.17ms^{-2}$ at Q95 and $0.5ms^{-2}$ at Q10.
- Downstream of the fish pass, the invert of the entrance channel is set at current bed level 49.50m AD. This is drowned to a depth of 0.15m at winter Q95 and 0.31m at summer Q95
- The pass spans the stilling basin of the weir, which is short and turbulent.
- A semi-floating trash boom across the mouth of the upstream exit channel, which rises and falls with the water level.
- Mean water velocity in the pass is $1.03\text{-}1.4ms^{-2}$ at Q95 and Q10 respectively.

This retrofitted fish pass was installed on the main gauging weir in September 2008 (see Figure 4.1) potentially making an additional 24km of good quality spawning habitat freely accessible to salmon (an increase of 40 per cent). It also allows other fish species to move more freely.

Figure 4.1 Super active Larinier fish pass

4.1.3 Fish monitoring

Fish capture and tagging

On 17 March 2009 a team from the Environment Agency, assisted by members of Dorchester Fishing Club, caught over 300 brown trout and grayling. Wading electric fishing with twin anodes was used, powered by an Electracatch pulsed D.C. machine set at pulse frequency 50Hz, from a 2km stretch of the main River Frome upstream of Loud's Mill Weir in the outskirts of Dorchester. No coarse fish other than a small pike and a gudgeon were seen or caught, these were not retained for tagging.

The fish were brought in aerated tanks back to the weir pool where they were fitted with intraperitoneal PIT half-duplex tags (Wyre Micro Designs) following the same procedure as described for the study at Brimpton in 3.1.4.

After recovering fully from the surgical procedure, the fish were released around 100m downstream of the weir pool. The tagging and release of fish was complete by late afternoon. A small number of fish did not recover from the anaesthetic and were removed from the site.

PIT detection array

Three half-duplex PIT detection antennae were deployed at Louds Mill weir.

The first was installed beneath a small footbridge situated approximately 200m downstream of the weir, where the river narrows to around 8m with a depth of approximately 40cm. This system was powered by three 110A-h, 12V batteries and the antenna was set in a loop crossing the river bed and returning approximately 20cm above the water surface, anchored to the concrete bridge buttresses. The total length of the antenna was approximately 17.2m

The second was installed at the foot of the Larinier baffle fish pass and was mounted in a glass-fibre conduit running along the base of the fish pass channel and back along a glass fibre beam set approximately 0.30m above the water surface, forming a loop approximately 1.8m wide by 0.5m high, with a total length of 4.6m. The antenna loop connected to a reader mounted on the beam and this in turn was connected to the logger, housed in the gauging station instrumentation hut and fed by mains power. The third and upstream-most antenna was arranged in a similar way and installed at the foot of the upstream face of the Crump weir, approximately 60cm upstream of the uppermost baffle of the fish-pass (Figures 4.2a & 4.2b), total antenna length was approximately 5m. Plans to locate a fourth antenna some distance upstream of the weir in order to register fish moving onwards from the weir were abandoned due to the lack of a suitable, secure location.

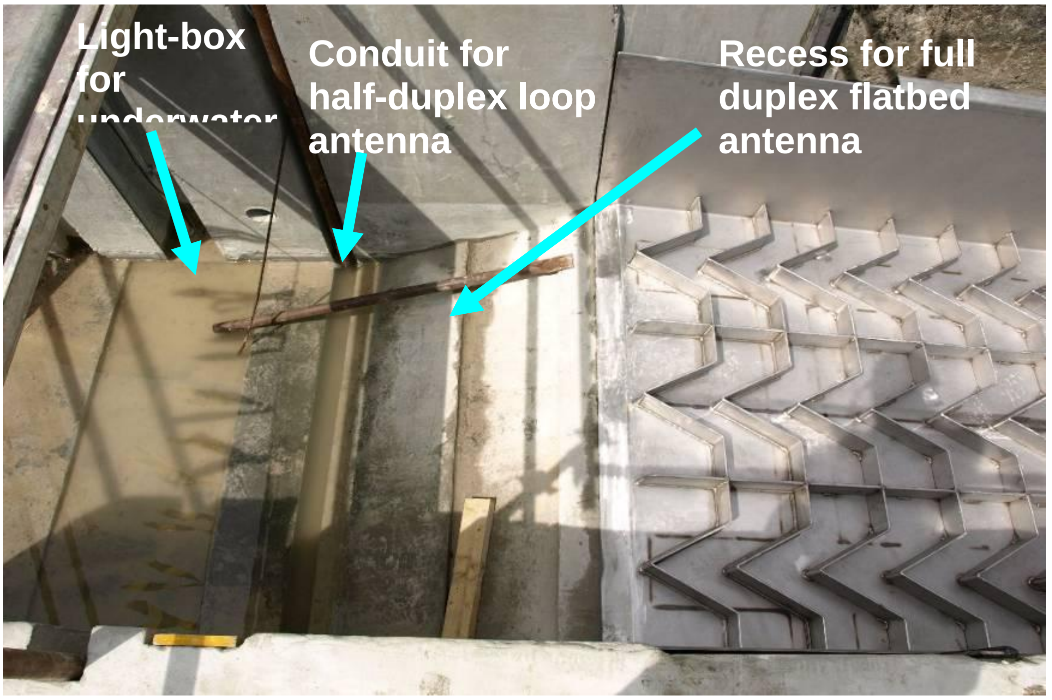


Figure 4. 2a Arrangement of the fish telemetry elements in the channel immediately upstream of the Larinier fish pass, summer 2008

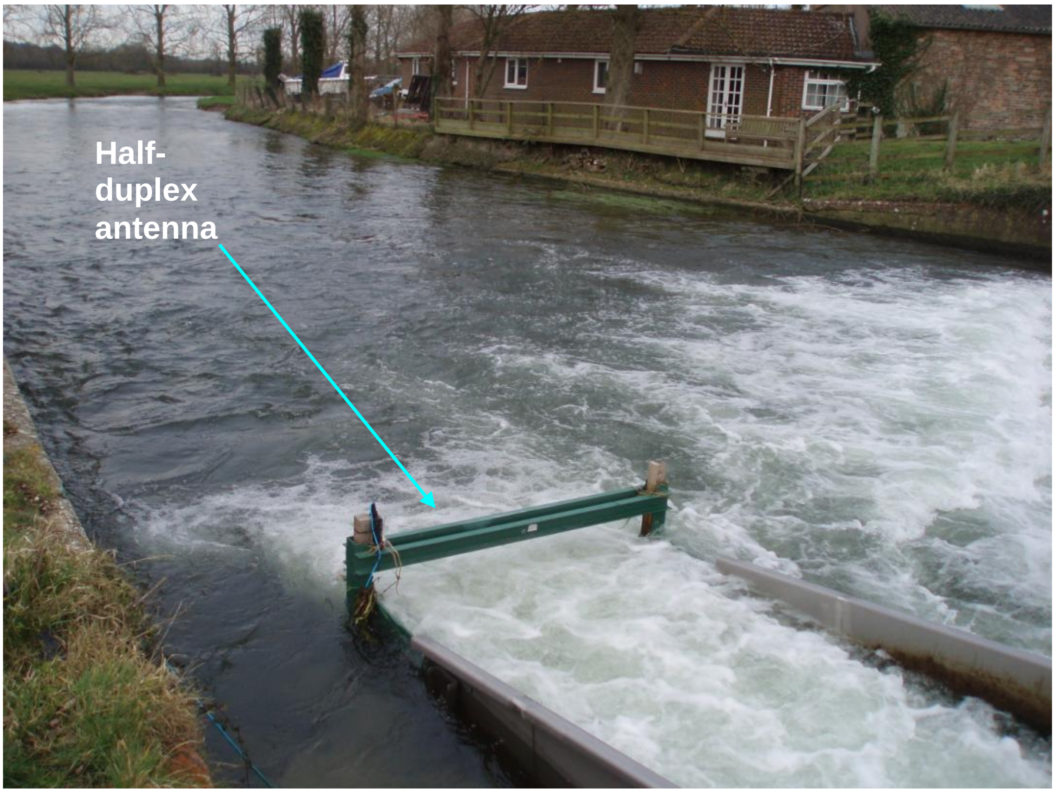


Figure 4. 2.b Location of the half-duplex antenna at the foot of the fish pass

Video monitoring

Video monitoring was used to provide additional data to complement the PIT tag systems. A digital video array (Clabburn *et al.,* 2008) was located in the upstream exit of the fish pass, mounted in specially recessed, water-tight slots at each side of the channel beneath water level, their field of view illuminated by an infrared light-box positioned in the bed of the channel, just upstream of PIT antenna 3 (see Figure 4.2a above). The array consisted of two cameras looking across the channel at mid-depth from opposite sides, and two looking down onto the left and right-hand sides of the fish pass crest.

This system monitored and recorded fish activity in the exit channel immediately upstream of the Larinier fish pass. The data generated by this system was managed using FISHTICK software, which uses motion detection software to indicate fish movement. Outputs are in the form of .AVI files which display all movements detected during specified time slots. Video footage from the three days prior to the release of translocated fish and three days afterwards were viewed; all fish movements were logged, with fish identified by species and direction of travel recorded.

An upstream movement is defined as a fish entering the downstream portion of the field of view and then passing the upstream boundary, likewise a downstream movement is defined as a fish crossing the upstream boundary of the field of view and then crossing the downstream boundary. Holding behaviour was characterised by a whole or part of the fish entering the field of view from either upstream or downstream and then leaving the field of view in the direction whence it came.

Salmon monitoring

In addition to the trout and grayling tagged on 17 March 2009, salmon parr are captured and tagged with 12mm full duplex PIT tags every summer as part of the Centre for Ecology & Hydrology (CEH)/Game & Wildlife Conservation Trust (GWCT) studies of salmon populations on the Frome (Ibbotson *et al* , 2004; Beaumont *et al*, 2006). The parr are caught from various locations in the upper catchment (including upstream of Louds Mill) and released where they were caught. In order to detect these fish as they return as adults, a full duplex flat-bed antenna was installed immediately upstream of the top of the fish pass, half-way down the upstream slope, and this was also operated from the instrumentation hut using mains power. It was not possible to operate both the full-duplex and half duplex systems simultaneously due to mutual interference, so the full duplex system was activated in the autumn of 2008 and switched off at the commencement of the half-duplex sampling programme in March 2009, resuming operations again in autumn 2009 after the half-duplex had been switched off.

4.2 Results

4.2.1 Fish tagged and relocated

201 brown trout and 91 grayling were successfully captured, PIT-tagged and released downstream of Louds Mill Weir on the afternoon of 17 March 2009.

The brown trout ranged in length from 88mm to 392mm fork-length (mean 235mm) and the grayling from 138mm to 438mm (mean 287mm). Length-frequency histograms of the fish released are shown in Figures 4.3 & 4.4.

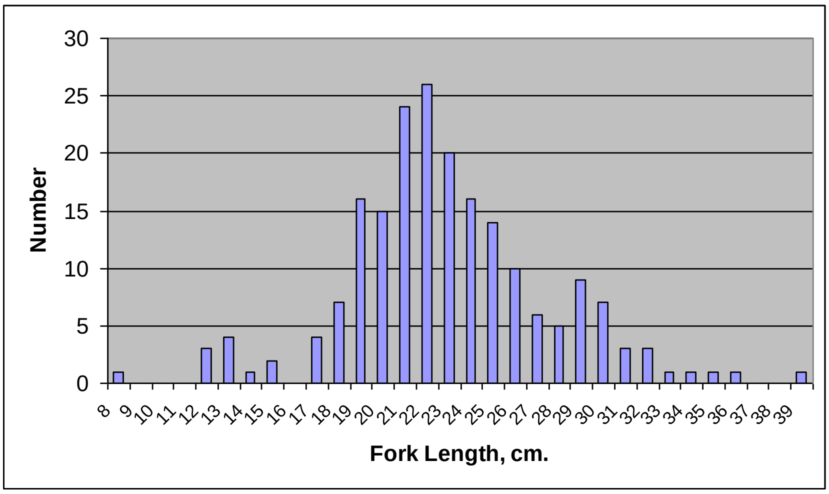


Figure 4.3 Length frequency histogram of brown trout tagged and released downstream of Louds Mill Weir, 17 March 2009.

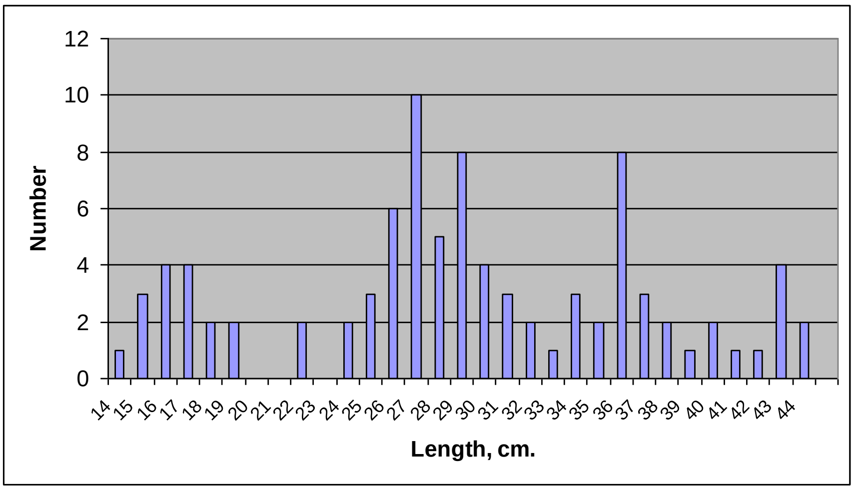


Figure 4.4. Length frequency histogram of grayling tagged and released downstream of Louds Mill Weir, 17 March 2009.

The length composition of the trout catch suggested that the majority of fish were three-year-olds, with a small number of older trout, probably four and five years old, and some yearlings. A number of the fish in the 18-23cm range were very silvery and are likely to have been sea trout smolts.

The length frequency histogram for grayling indicates a number of distinct age groups, with two-year-olds being the most numerous but with a number of older grayling up to specimen size present. Grayling were close to their spawning period and most of the larger fish showed the distinctive dark colouration associated with spawning.

4.2.2 Fish activity in relation to time after release, flow and temperature

Of the 91 grayling originally tagged and released, 74 (81 per cent) were detected subsequently by the PIT system, as were 182 (90.5 per cent) of the tagged trout.

Figure 4.5 shows the total number of fish detections on all three antennae both fish species combined, for the duration of the study.

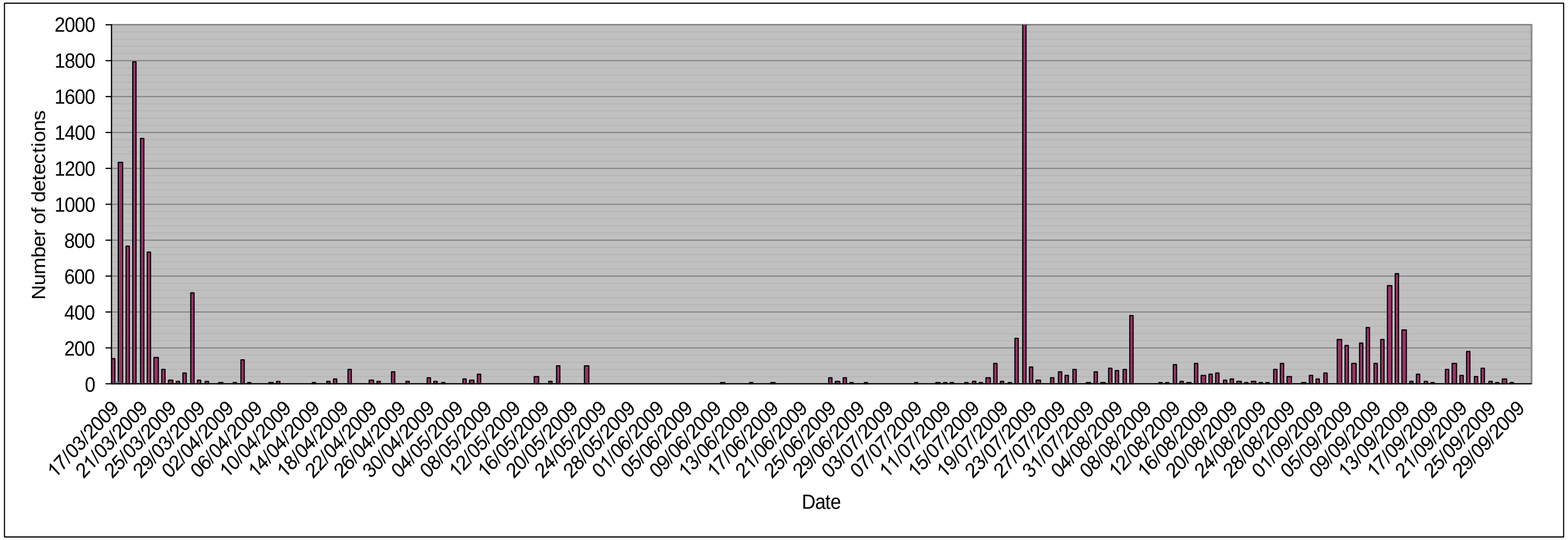


Figure 4.5 Number of fish detections, all readers, both species, March to September 2009 at Louds Mill.

The majority of activity was during the first few days of the study in mid to late March. It should be noted that the computer recording the detections from all antennae was inoperable between 8pm on 17 March when the fish were tagged and released and 8.00am the following morning. There is evidence that numbers of fish passing all readers are likely to have been high during this period (numbers of detections both before and after the outage were high, and video recordings (see Figure 4.8) also indicated lots of activity during that period). It is therefore highly likely that some fish dispersed from the release site without being detected on any of the antennae. In addition, reader 1, under the footbridge downstream of the weir and operating from a battery power source, was out of action for most of the time beyond the end of March, hence any fish that moved downstream away from the weir after that point are likely not to have been detected.

The peak in detections in late July were the result of a single trout that took up residence immediately downstream of the lower entrance to the fishway (reader 2); this individual was joined by another similar fish in September.

Figures 4.6 and 4.7 show the number of ascents of the fishway made by trout and grayling respectively during the study period. If a fish reached reader 3 (situated 0.6m upstream of the top baffle of the fishway) then it was judged to have successfully negotiated the fishway and to have reached an area of lower water velocities through which it would be able to swim on upstream if it so desired.

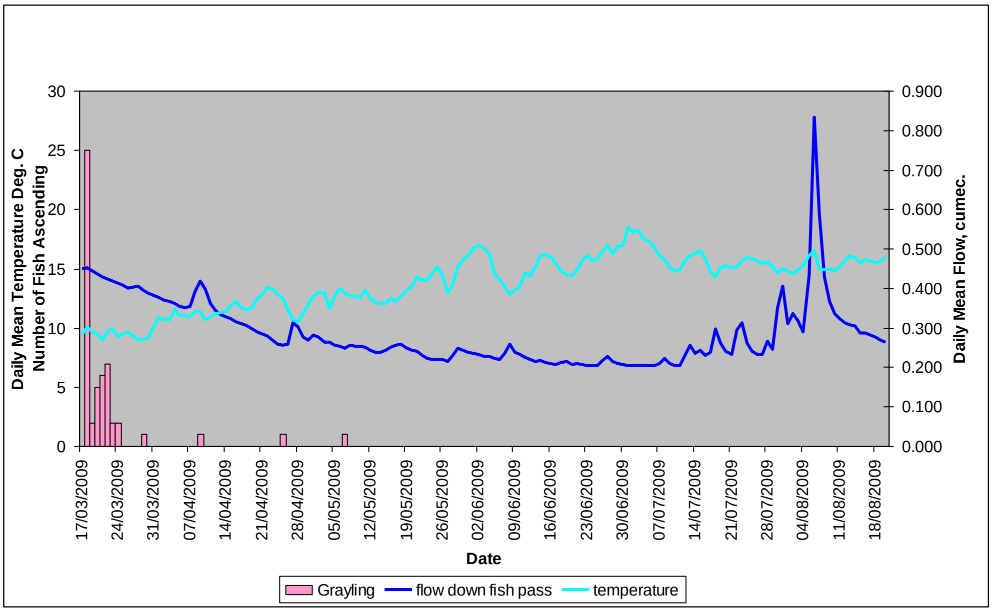


Figure 4.6 Numbers of grayling per day ascending Louds Mill fish pass, spring 2009, in relation to date, temperature and flow.

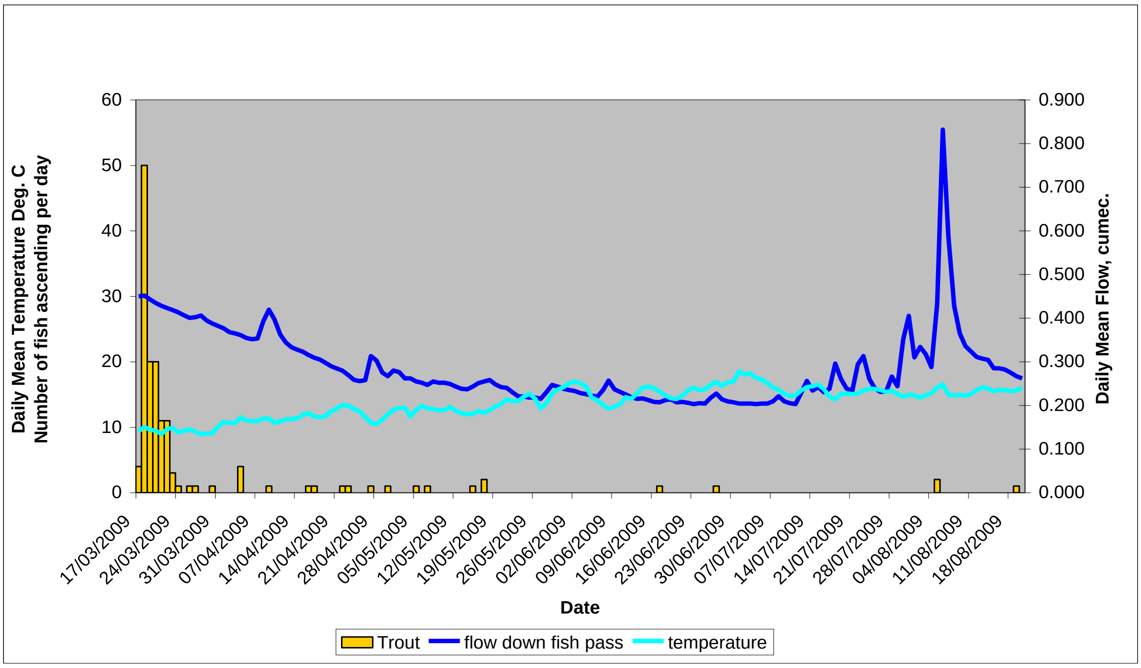


Figure 4.7 Numbers of trout per day ascending Louds Mill fish pass, spring 2009, in relation to date, temperature and flow

Shortly after the system was returned to functionality early in the morning on 18 March, individual fish that had not been recorded on any of the readers appeared on reader 3 in the channel upstream of the fish pass. These fish must have ascended the fish pass during the previous night (between 8pm and 8am) and so have been recorded as 17/18 March.

For both species the vast majority of ascents occurred in the first few days after tagging and relocation. However the grayling waited a little longer before ascending the fish pass – no grayling were observed to ascend to reader 3 before the system went down on the evening of 17 March whereas three trout made the journey.

A minimum of 49 grayling (54 per cent of those tagged and released) and 143 trout (71 per cent) were judged to have successfully negotiated the pass. A number of these fish (seven trout and two grayling) ascended the pass, returned downstream and re-ascended: one trout did this three times.

Of the fish that ascended the pass at least once, 42 grayling (46 per cent of those tagged and released) and 122 trout (60.6 per cent) were judged to have left the fish pass area and continued on upstream (last registration was on antenna 3 upstream of the fish pass crest). The remainder ascended, came down again and did not ascend again during the period of the study.

Video evidence

There were a total of 617 fish sightings – 385 trout, 18 grayling, 4 other species and 210 unidentified - during the period 14 to 20 March inclusive, encompassing the period immediately before release of translocated fish, the day of release, and the three days after the release event.

Figure 4.8 shows the pattern of total fish sightings recorded by the video cameras during an eight-day period around the time of release of translocated fish. In practice, only the sideways-viewing cameras were effective in capturing fish images as the downward-pointing cameras captured too much surface reflection from the smooth water immediately upstream of the baffle crest. Not all images could be positively identified as a particular fish species either because of poor imagery due to water turbidity and the build up of algae on the viewing window and light box, or unfavourable angle of fish movement. It was difficult to recognise the shape of some fish if they approached the camera at 60° to 90 ° - diagonally or directly across the current. Some fish were simply too far away from the camera or moved too quickly to enable identification. Consequently such fish were recorded as ‘unidentified’.

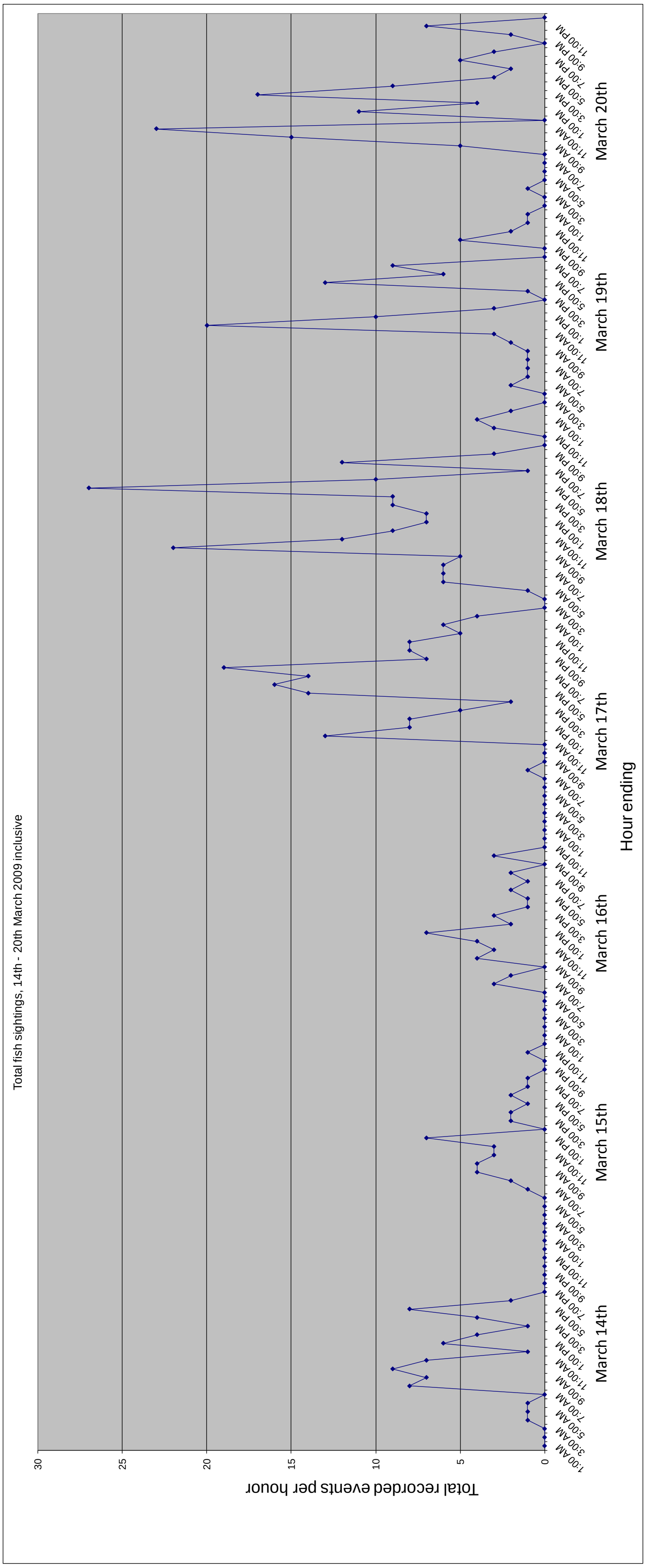


Figure 4.8. Daily patterns of fish activity recorded by video camera at upstream entrance to fish pass Louds Mill

Most images recorded were of trout. Figure 4.8 shows that there was considerable activity around the fish pass even before the tagging and translocation work on 17 March, however there was a step change in the number of trout sightings after the release of the tagged fish in the afternoon of 17 March. Grayling were not seen around the pass until after the translocation exercise. A single pike and three perch were also seen moving upstream through the fish pass channel. There was a diurnal pattern of fish sightings, with little or no activity during the middle hours of darkness, though this pattern was less marked after the fish translocation.

During periods of high fish activity numbers of fish were recorded ascending, descending, and holding in the fish pass channel. On most days both pre- and post-translocation, there was a net movement of fish upstream, and this net movement was greatest after the translocation (Figure 4.9).

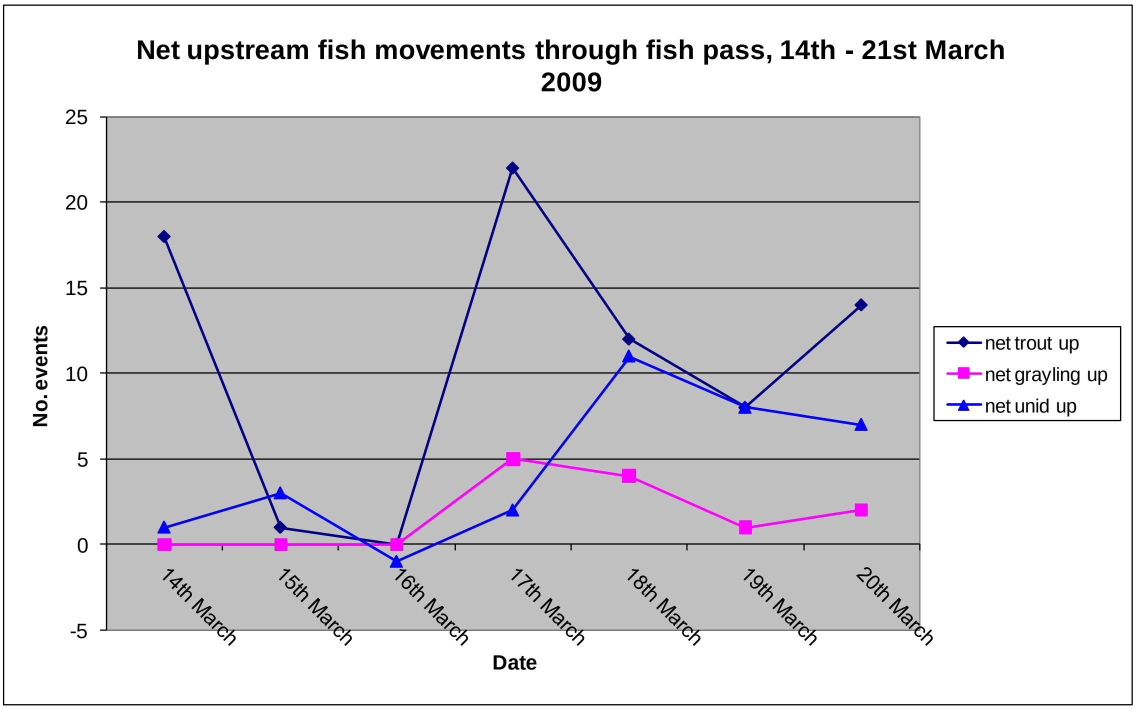


Figure 4.9 Net movements of trout and grayling past video cameras in the upstream entrance to Louds Mill Fish Pass, mid-March 2009

These results need care in interpretation since the video images cannot distinguish between individual fish, so the number of net movements in either direction relate strictly to movements, not numbers of fish. A record of a fish moving upstream cannot be taken as proof that that fish has ascended the fish pass; many of the fish sightings are clearly fish that are loitering in the fish pass channel and are moving up and down past the cameras.

4.2.3 PIT detections - fish movement and time of day

Figure 4.10 shows the total number of detections (all readers, both species) per day for a selection of days early in the post-release period when all readers were functional (18 March from 8.00am only). Fish activity recorded by PIT antennae varied greatly from day to day and was not confined to particular periods; on some days activity was maximal during the middle hours of daylight, on others the peaks of activity were during the middle hours of darkness.

However, when we consider the patterns of successful ascents of the fish pass, (Figure 4.11), it can be seen that for both species, few ascents are made during the very early hours of the morning – trout ascended the pass throughout the daylight hours and into the late evening, whereas grayling ascents were more concentrated in late afternoon and early evening. This corresponds more closely with the pattern of video detections in the vicinity of antenna 3. A significant number of ascents by both species took place but were not properly recorded: fish were detected on reader 3 before they were recorded on reader 2, indicating that the fish had passed reader 2 without being recorded and then either remained close to reader 3, or gone upstream for a period and returned to reader 3. These events could therefore not be considered in relation to temporal patterns of ascent of the fish pass.

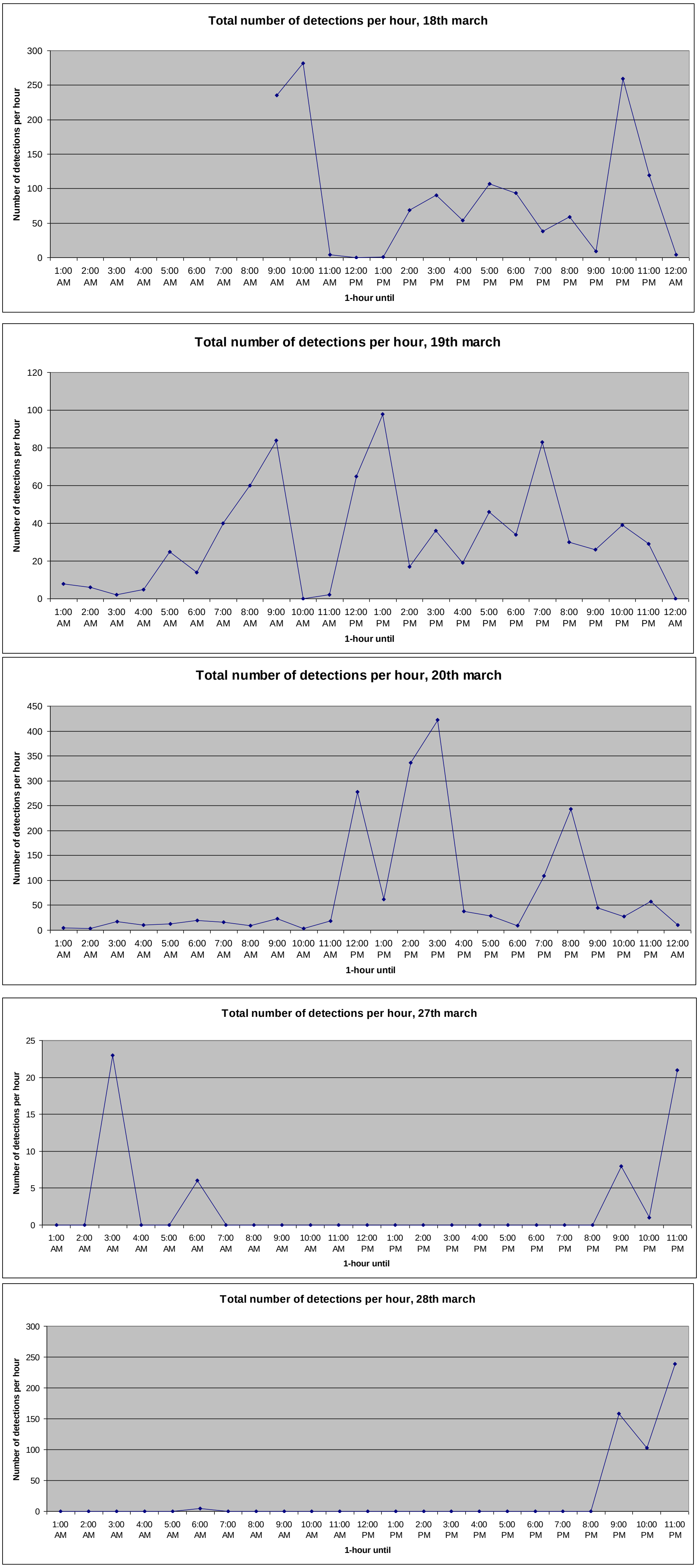


Figure 4.10 Diel patterns of detections of PIT readers around Louds Mill Weir in March 2009, all readers and species combined.

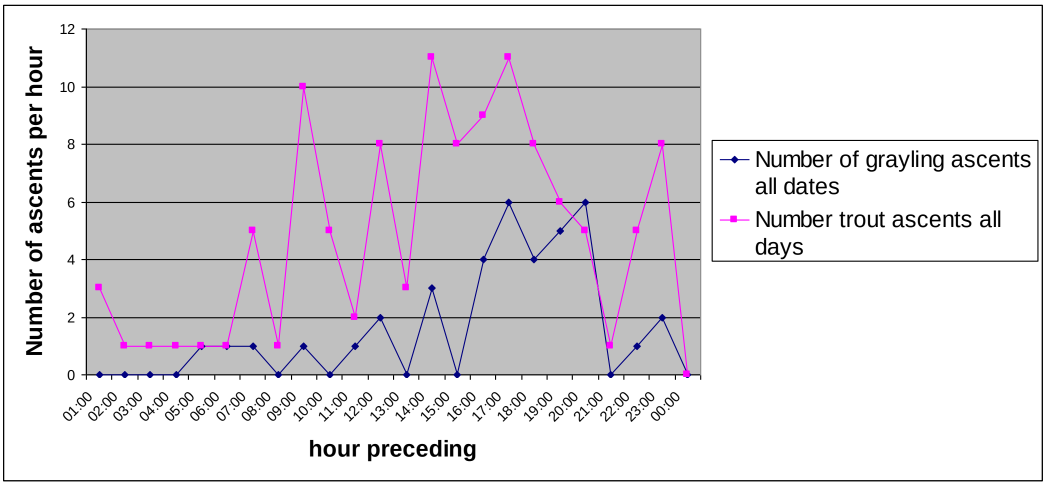


Figure 4.11 Diel pattern of ascents of Louds Mill fish pass, spring and summer 2009.

4.2.4 Passage times

Despite clear demonstration that the majority of relocated fish were able to use the fishway to return to their original home ranges upstream of the weir, the weir and its fish pass still have the potential to interrupt and delay a fish's upstream journey, and the ease with which individual fish are able to negotiate the fishway itself must still be addressed.

The time a fish took to pass the entire structure was regarded as the period from the beginning of the fish's last continuous presence on antenna 2 (at the foot of the fish pass) to its final departure from the vicinity of antenna 3 (in the channel upstream of the fishway itself. Often, fish would disappear from antenna 3 for short periods then return, and for the purposes of this study an arbitrary cut-off time of five minutes was applied to decide whether the fish was likely to have left the area during that period and then voluntarily returned, or it was resting after having ascended the pass.

Figures 4.12 and 4.13 show the pattern of times taken for grayling and trout to clear the fish pass complex.

Thirty-nine grayling ascending the fish pass were detected on both reader 2 and reader 3, enabling their transit time to be measured. As noted in 4.2.3, other fish ascended the fishway without detection on reader 2 and so their timings could not be determined; those incidents have not been included in this analysis. Figure 4.12 shows that a significant number of grayling spent relatively little time around the foot of the fishway immediately before swimming up it, and left the upstream channel quickly after arrival at the top of the pass. The whole journey took less than 30 seconds, with one large grayling completing the journey in only three seconds, equating to a speed of 2.67ms^{-1} , considerably faster than the maximum burst speed of around 1.9ms^{-1} estimated by the

SWIMIT model (Turnpenny et al, 2004). However the majority of grayling took between two and five minutes to clear the structure, with just two fish taking much longer at 14 to 15 minutes.

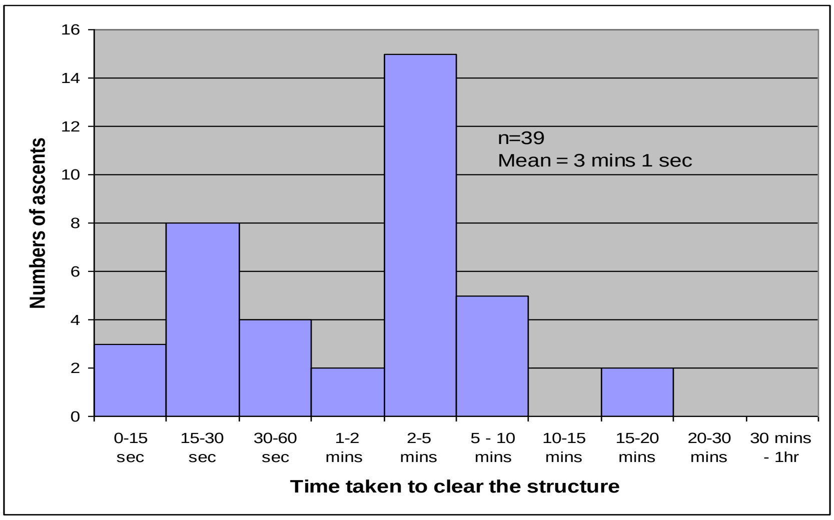


Figure 4.12. Pattern of times taken for grayling to negotiate Louds Mill fish pass complex, spring 2009

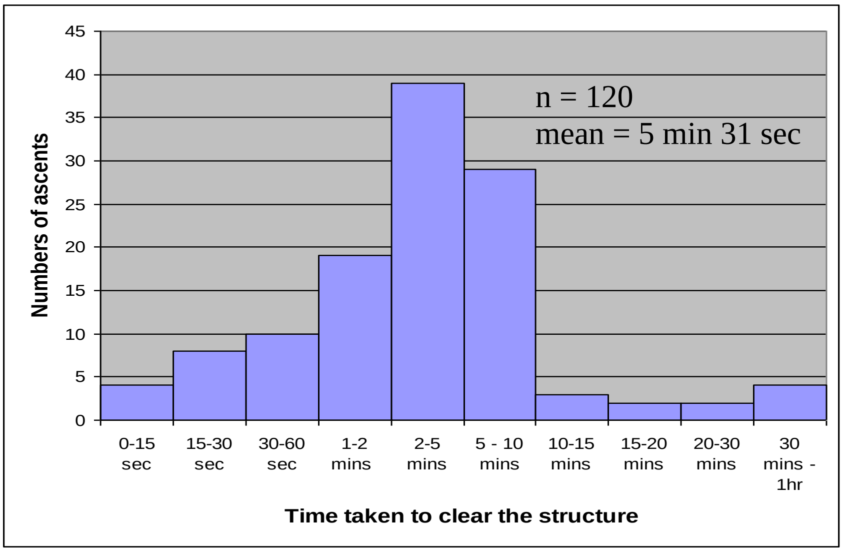


Figure 4.13. Pattern of times taken for trout to negotiate the fish pass complex, Louds Mill, spring 2009

A number of trout also ascended the fish pass complex very quickly (again, one fish negotiated it in three seconds). However, like grayling, the majority of trout waited for short periods at the foot of the pass before ascending, and then loitered in the vicinity of the upstream approach channel before moving on upstream, taking several minutes to complete the journey. Some trout stayed close to reader 3 much longer, and took almost an hour to leave the area after their ascent. The average passage time for trout (5 minutes 30 seconds) was actually longer than for grayling (3 minutes 1 second) and this appears to be mainly due to a greater tendency to remain in the channel immediately upstream of reader 3 (a conclusion supported by the video observations).

Figures 4.14 and 4.15 show the times taken to swim up the Larinier itself (the time between last detection on reader 2 and first on reader 3) for the two species.

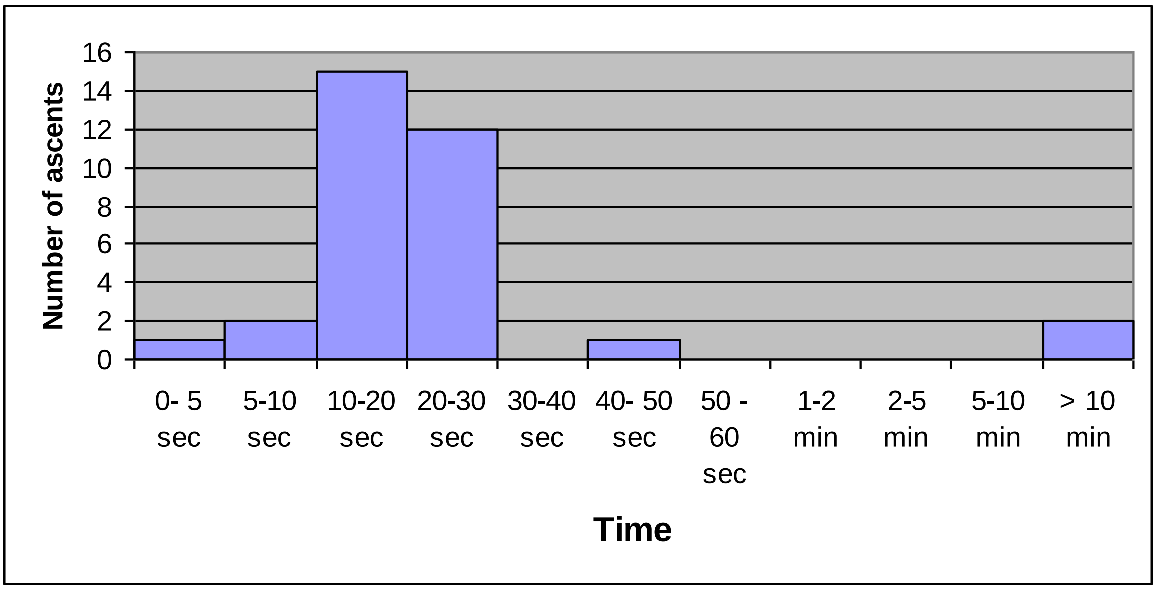


Figure 4.14 Pattern of times taken to swim through the Larinier fishway, grayling.

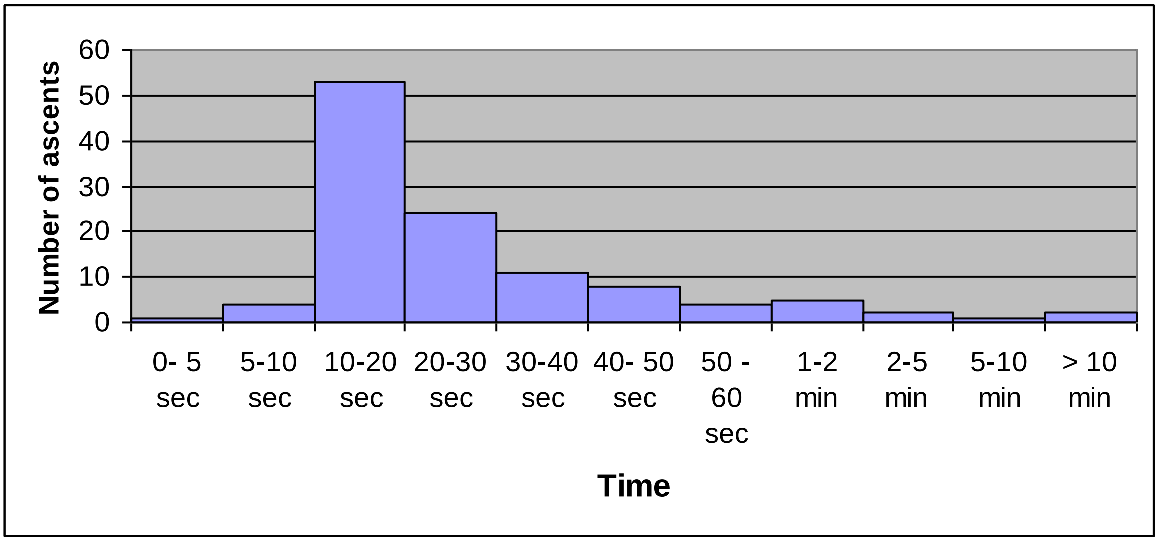


Figure 4.15 Pattern of times taken to swim through the Larinier fishway – trout.

Both species showed a similar pattern of passage times between reader 2 and reader 3. The majority of fish of both species swam through the fishway in between 10 and 30 seconds, and all but a small number took less than a minute. Interestingly, a small number of both trout and grayling took longer than ten minutes to move from reader 2 to reader 3, suggesting that they spent a considerable time in the fishway itself.

Size differences in passage times and ascent success

Figure 4.16 and 4.17 show the relationship between fish length and time taken to negotiate the entire structure for both grayling and trout.

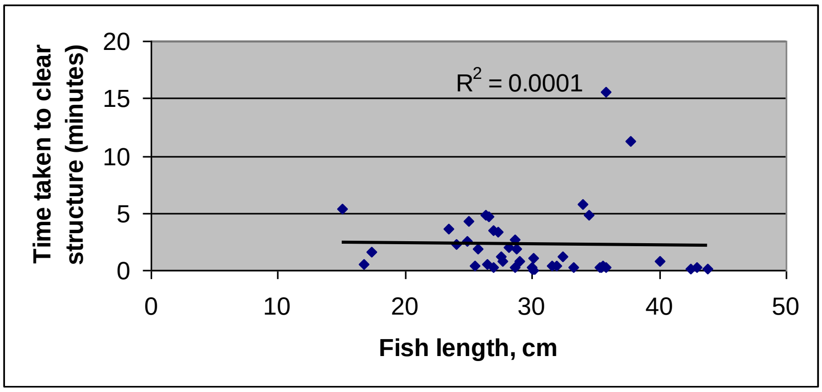


Figure 4.16 Time taken to clear the fish pass complex at Louds Mill in relation to fish length – grayling.

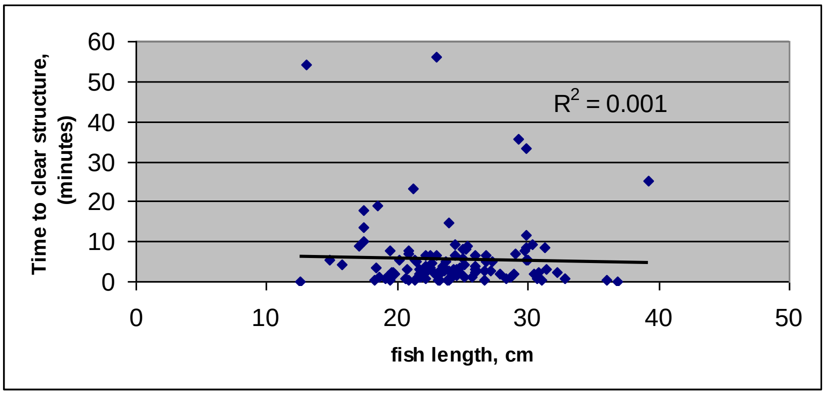


Figure 4.17 Time taken to clear the fish pass complex at Louds Mill in relation to fish length – trout

There appears to be little or no relationship between the length of time a fish took to negotiate the structure and the size of the fish, for either species.

Figures 4.18 and 4.19 show the time taken to swim the Larinier fishway itself (the time between last detection on reader 2 and first subsequent detection on reader 3) in relation to fish length. For grayling, there was a very weak positive relationship between time taken to swim the Larinier and fish size, and only a weak, inverse relationship for trout. None of these relationships were significant.

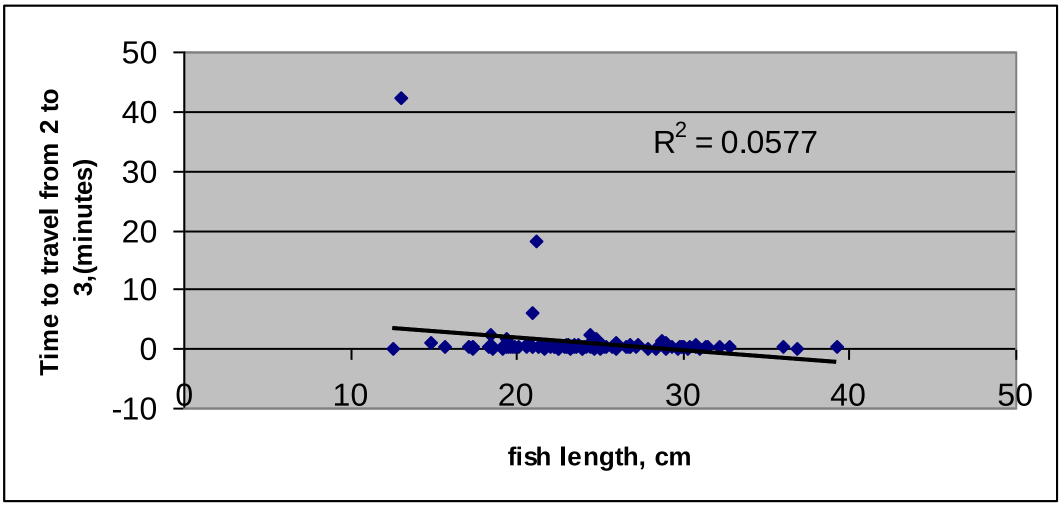


Figure 4.18 Time taken to swim the Larinier fishway, Louds Mill, in relation to fish length – grayling.

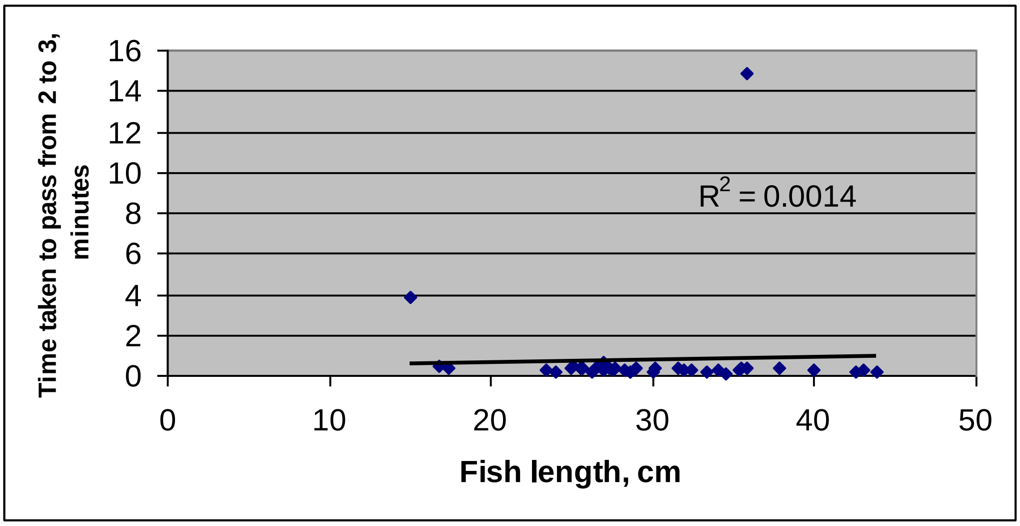


Figure 4.19 Time taken to swim the Larinier fishway, Louds Mill, in relation to fish length – trout.

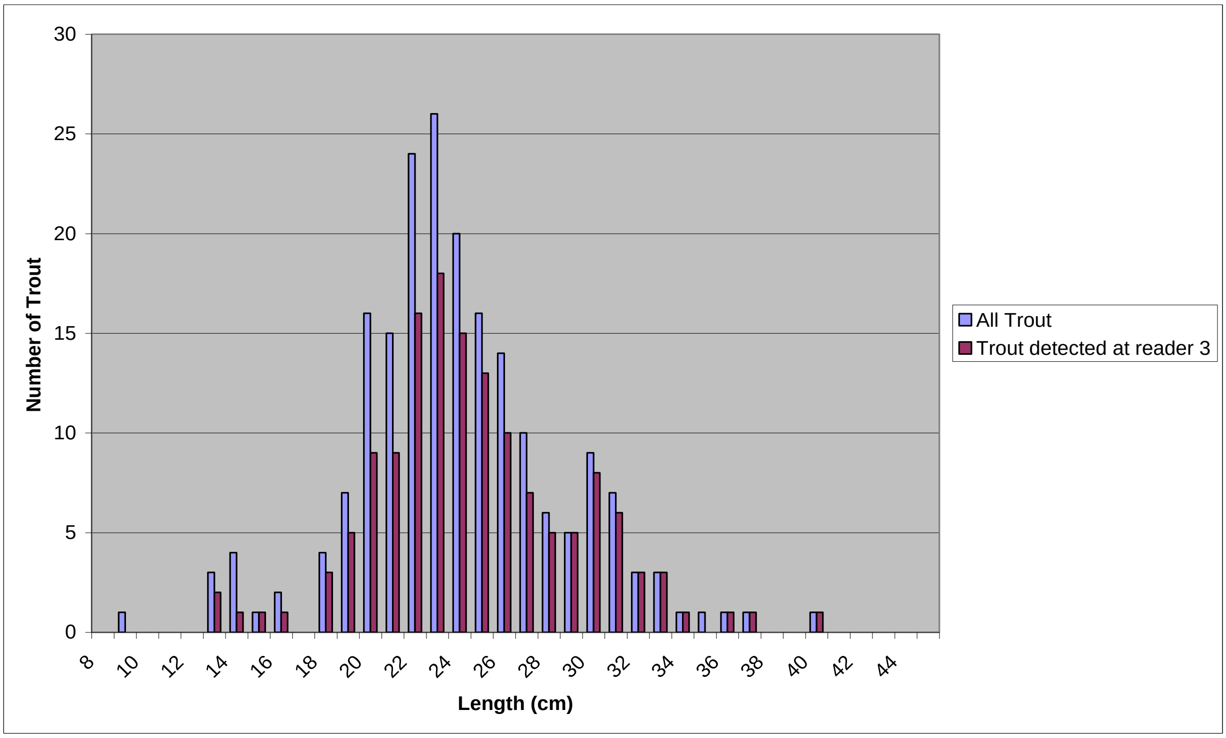


Figure 4.20 Length frequency histogram of brown trout reaching antenna 3 compared to that of all trout released downstream of Louds Mill Weir.

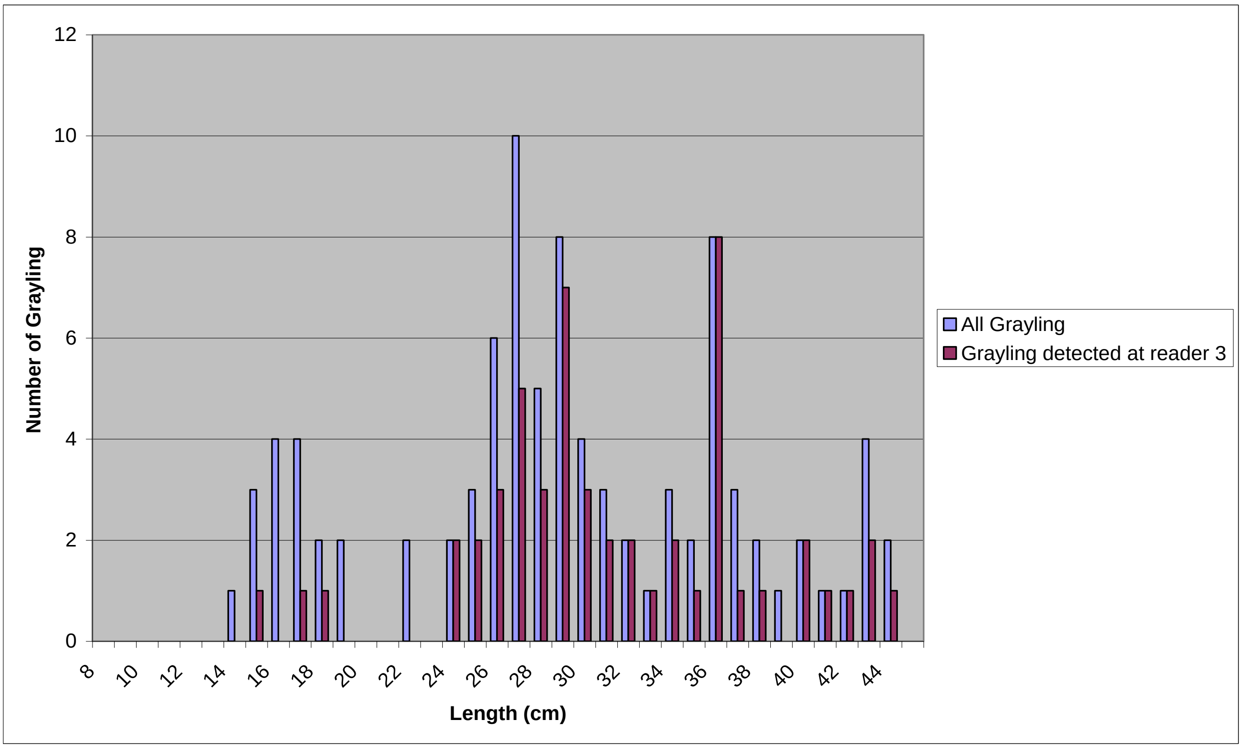


Figure 4.21 Length frequency histogram of grayling reaching antenna 3 compared to that of all grayling released downstream of Louds Mill Weir.

The mean length of grayling ascending the pass was 30.9cm compared to a mean length of 28.7cm for the total tagged sample. However a t-test of the two samples failed to yield a significant difference (df=139, p= 0.072) between the means.

A Kolmogorov-Smirnov two-sample test also showed that the frequency distribution of the fish ascending (Figure 4.21) was not significantly different from that of the total tagged sample (D=0.1456, p= 0.48).

For trout (Figure 4.20), the difference between the sample of fish ascending and the original tagged population was even less.

4.2.5 Fish activity and fishway ascent in relation to flow and temperature

In contrast to the study at Brimpton Weir, temperature and flow conditions at Louds Mill varied relatively little during the study period. Flows fell very gradually throughout the period, characteristic of the normal pattern of chalkstream flows, which tend to be high in late winter and spring due to winter recharge then fall gradually towards the autumn. There were occasional peaks in flow due to surface water runoff after rainfall events, notably in early August when a Q5 flow event was recorded. Water temperatures rose fairly steadily towards mid summer, falling only very slightly through August. However, there were significant fluctuations, with temperatures sometimes falling by as much as three degrees in a matter of days due to changing weather.

Fish activity and fish ascent for both species were highly concentrated in the first few days after tagging and release. During this period, temperatures were around 10°C and flows were above average (approximately Q30-Q45) but were gradually falling after winter. Head (Ha) over the fish pass invert during this period was 0.25m-0.27m. While flow and temperature only changed slightly over the following few days (24 -31 March), fish ascents reduced to a low and sporadic level throughout the rest of the study.

4.2.6 Salmon

Very soon after the fish pass and associated telemetry became fully functional in August 2008, small numbers of adult salmon began to ascend the fish pass and these were recorded both on the full duplex PIT system and the cameras. Seven salmon were recorded on the full-duplex system between 2 and 10 November 2008, and approximately 30 images of upstream migrating salmon were captured during the winter of 2008/9. There is some evidence from redd counting that the number of salmon spawning in the reaches of the Frome upstream of Louds Mill has increased significantly in recent years (Figure 4.22), though this improvement began in the year prior to the construction of the pass. Parr surveys (Figure 4.23) have not reflected this improvement.

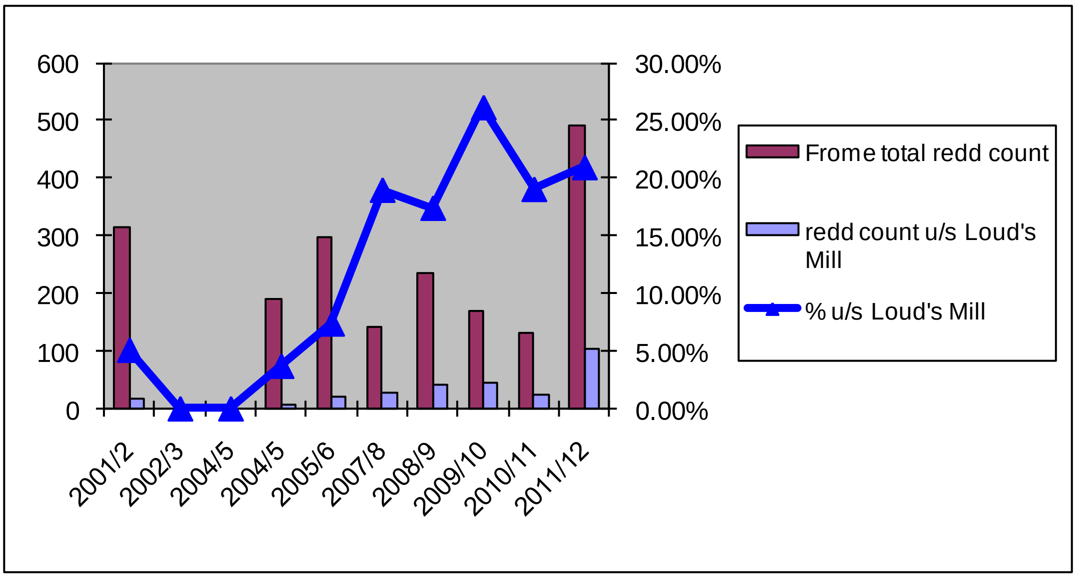


Figure 4.22 Annual salmon redd counts in the river Frome, 2001 – 2011

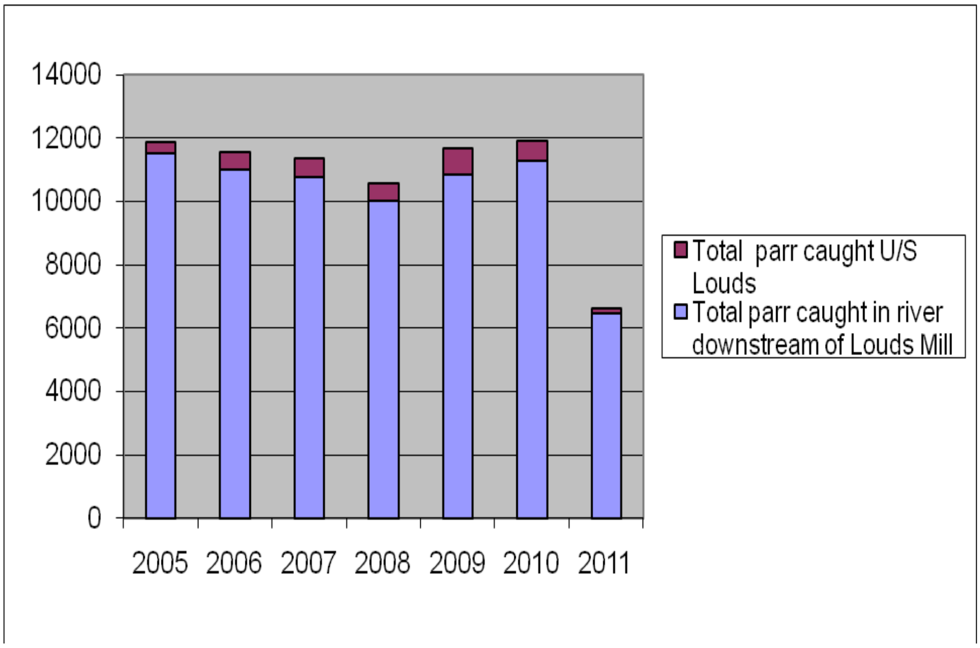


Figure 4.23 Salmon parr catches, GWCT electric fishing surveys, upper Frome, 2005-2011

4.2.7 Comparative statistics

It is not possible to use the same approach for assessing fish pass efficiency as for the Brimpton study, simply because it was not possible to identify distinct attempts to ascend the fish pass. Because the Larinier pass was constructed of stainless steel, it was not possible to install an antenna part-way up the fishway, hence we relied upon the antennae at the foot of the fishway and in the upstream exit channel to monitor fish passage. A detection at antenna 2 cannot be taken as an attempt to ascend the pass since tagged fish taking up position close to it in order to feed or shelter would also have been recorded. Hence efficiency can only be assessed as:

$E = 100^* n_p/N_m$

Where n_p = number of fish ascending the pass; Nm = number of marked fish potentially available to ascend.

The simplest approach for expressing a minimum efficiency would be therefore to state that for trout:

E=100* 143/201 = 71 per cent

And for grayling

E= 100* 49/91 = 56 per cent

4.3 Discussion

4.3.1 Efficiency of the Larinier Super Active Baffle Fish Pass

In 4.2.7 above, the efficiency of the fish pass was calculated as 71 per cent for trout and 56 per cent for grayling. However, these should be considered minimum estimates.

It is legitimate to suggest that if a fish was only ever seen on antenna 1 (at the footbridge 400m downstream of the weir) then it had left the site without attempting to ascend the fish pass; six grayling and one trout fell into this category.

In addition, 19 trout and 16 grayling were not recorded on any of the antennae and these too could be considered as having left the area without attempting to ascend the fish pass. However, it is equally plausible that some of those fish did ascend the weir during the night of 17 March when the PIT recording system was inoperable, since there is evidence from the video recordings of a great deal of fish activity at the weir crest during that period. Twenty upstream movements of trout (but no grayling) through the exit channel were recorded on video during the period when the PIT system was inoperative. Other fish may have swum downstream past antenna 1 during the various periods when it was out of order. A number of the trout caught were very silvery in colour and there was a suggestion that these may have been sea trout pre-smolts, which would have been pre-disposed to continue moving downstream. In fact, none of the 17 individuals indicated as possible sea trout were seen on any of the antennae, strongly suggesting that they made no attempt to ascend the pass.

We can therefore conclude that there were a number of fish that either became unavailable to ascend the fish pass, or ascended successfully without being recorded. In either case this leads to the conclusion that real efficiency was actually higher than the above minimum estimates.

4.3.2 Size and species selectivity of the pass

The lack of strong relationships between time taken to swim through the Larinier fishway and fish size suggests that swimming capability (greater for larger fish (Turnpenny *et al*., 2001)) is not limiting fish ability to ascend the pass. Equally, there is no evidence that smaller fish took longer to negotiate the entire structure than did larger ones. However, when the respective length frequency histograms for fish successfully reaching antenna 3 (top of fishway) is compared to that for the total number tagged and released at the start of the experiment, there is a suggestion of size-selectivity in fish successfully ascending the pass – this is more noticeable for grayling. However, these distributions were not significantly different.

A smaller proportion of tagged grayling were successful in ascending the pass compared to trout. There is only weak evidence that this was purely due to the lower swimming ability of grayling, since of the fish that were successful in ascending, grayling and trout were able to swim through the Larinier in broadly similar times – most fish of both species took 10-20 seconds.

There may be behavioural differences between the two species that account for lower representation of grayling. Video recordings provide some evidence of this. Grayling were not seen at all on the video camera prior to grayling being translocated to the weirpool, whereas lots of trout were seen in the days prior to the release. Even after grayling were released in the weir pool, only 18 sightings of grayling in the channel upstream of the fish pass were recorded on the camera, although there is evidence from the PIT tag monitoring than many more than this ascended the pass. Grayling were always seen moving upstream or holding, none were ever seen moving downstream despite PIT tagged fish being recorded as doing so. The field of view of the video cameras is limited to the lower part of the water column and so many fish recorded on PIT antenna 3 may have passed through the area close to the surface, out of view of the cameras. This suggests that grayling may move at a higher level in the water column than trout, this may either render them less susceptible to being detected by the PIT antennae or cameras, or less able to negotiate the Larinier baffles, though the mechanism for this is not obvious.

4.3.3 Influence of flow, temperature and light levels on fish movements and ascents of the fish pass

Both fish activity (Figure 4.5) and ascents (Figures.4.6 and 4.7) of tagged fish at first sight appear to be positively associated with flow and inversely related to temperature, but they are most likely to be simply a function of time after release. There is some suggestion from the data (Figures 4.6 and 4.7) that ascents made subsequently to the initial movement of large numbers of fish shortly after release were associated with sporadic increases in flow (short-lived peaks varying in magnitude between Q30 and Q5) , however the numbers were too small to ascertain a clear link.

Fish activity in relation to daylight showed a broadly similar pattern according to both PIT detections and video recordings, with peak activity generally greatest at dawn and dusk and mimimal activity in the middle hours of the night, very similar to the observations at Brimpton. However, there was variation from day to day and on some days the only activity was at night, while on other days, fish movements continued sporadically throughout the daylight hours rather than being concentrated at dawn and dusk. These variations may have been driven by small variations in weather, such as cloud cover, or marginal changes in temperature or by moonlight, which were not monitored during the project. The video cameras recorded the majority of fish movements on the right hand side of the fish pass channel (as seen looking downstream), which tended to be in relative shade during daylight hours due to its north-facing aspect. These observations support the general view that fish activity of many kinds favours low light intensities.

4.3.4 Salmon

No fully quantitative assessment of salmon passage through the Larinier fish pass was undertaken. Only fish that had been tagged as parr with full-duplex 12mm PIT tags as part of CEH/GWCT studies would have registered on the array; seven of these fish were seen in the first week of November 2008. In addition, around 30 adult salmon were certainly seen ascending the pass, recorded on the video cameras, during the first autumn after installation of the fish pass. No figures are currently available for subsequent seasons. Redd counts in the Frome upstream of Louds Mill have shown a general upward trend since installation of the pass, though there were indications that this began prior to its installation, influenced possibly by the very high flows in the summer of 2007 which may have rendered Louds Mill Weir temporarily passable. Parr surveys have not reflected the apparent increase in numbers of adults, possibly because of the low summer flows since 2009, which may have impacted on parr survival, as was indicated by Solomon and Lightfoot (2009), perhaps especially in 2011.

5 Conclusions and further work

5.1 Low cost baffle solution on gauging weirs

5.1.1 Effectiveness of the low cost baffle fish pass

In terms of the fisheries-related objectives of this study – assessment of the efficiency a low cost baffle pass on a gauging weir – it has been possible to give preliminary indications of the suitability of this design to passage of a cross-section of coarse fish species and sizes.

It is clear from the results that three species of coarse fish, roach, chub and dace, of sizes ranging from 198mm to 489mm, are able to successfully negotiate the pass under a range of flows and temperatures in significant numbers. This is despite modification of the original, optimum design. The optimum design for a low cost baffle fish pass, outlined in Servais (2006) is inevitably compromised when fitted to a flow gauging weir, because whatever is fitted to the face of the weir must not raise the water level measured over the weir crest. In addition, the baffle array was installed incorrectly, the top-most baffle being 80mm lower than specified. Both of these factors compromise effectiveness of the fish pass. Overall, of the 157 tagged fish released below the weir, 23 reached top of the pass, 18 of which (11 per cent) traversed the weir crest and continued upstream.

Considering only fish that attempted to negotiate the fish pass, the most successful group of fish (chub translocated from upstream of the weir) achieved a 54 per cent success rate. For the reasons outlined in sections 4.1 and 4.4, these estimates of efficiency are probably conservative. Nonetheless, the results indicate that this unique baffle design may provide levels of passage sufficient to prevent the isolation of populations of coarse fish above and below the obstruction, and allow two-way mixing between populations, at least for some species (though not perhaps perch). This new pass may also help to offset the effects of downstream displacement, which is very common on a flashy river like the Enborne, by facilitating upstream homing.

5.1.2 Impacts on flow gauging accuracy

The available data suggests that the operational performance of the low flow Crump weir at Brimpton is not adversely affected by the presence of the baffles, within the observed stage range (0.353m-0.746m). While this conclusion may be considered valid for the range of stages monitored, it is based on a very limited number of gaugings. It is therefore recommended that further field-based research is undertaken to confirm the impact of the baffles on flow measurement accuracy over the full stage/flow range.

The presence of the baffles has been observed to lead to a greater risk of debris snagging and also appears to encourage weed/algae growth on the downstream face of the weir, which has the potential to impact on the hydrometric performance of the structure. It is therefore critical that a regular maintenance programme be put in place to ensure that any weed or algae build up is kept in check.

Whilst the conclusions of this project suggest that low-cost baffle arrangements have a limited impact on hydrometric performance, it is critical that sites are well installed, maintained and operated in line with good practice guidelines and the appropriate British and International standards for hydrometric structures, where relevant.

When complete removal of the weir is not practical and when there are no funds available to install a fish pass that completely bypasses the weir, this low cost design is the best solution currently available for coarse fish passage, as it has been shown that with careful design it causes less than 1 per cent variation in the coefficient of discharge. Pre-barrages (small subsidiary weirs built a short distance downstream of the main gauging weir that reduce the head-difference) can be used in conjunction with low cost baffle systems or separately, to improve fish passage in certain situations.

Turnpenny et al (2002a) estimated 88 Crump weir sites in England and Wales where there are problems for fish passage and the true figure is likely to be higher. Many of these sites could benefit from installing this low cost baffle pass (if it was found not to affect gauging), at a cost of around £10,000-£20,000 per site compared to approximately £200,000-£400,000 per site for a conventional fish pass. This highlights the importance of Hydrometry and Fisheries working together, to try to employ a way of successfully alleviating these obstructions to coarse fish passage, while maintaining accurate and reliable flow data. Ultimately, previously inaccessible upstream reaches will be opened up to many species of coarse fish, improving the habitat and diversity of many rivers throughout the country and enabling Water Framework Directive targets for good ecological status to be met.

5.1.3 Future work with low-cost baffle fish passes

Further work should include installing baffles on other gauging structures and undertaking a full pre- and post-performance study on fish passage, and further field-testing of hydrometric performance should be undertaken to confirm the findings from Brimpton over a full range of flows and at sites with different configurations (in terms of crest width, height and modular range, for example).

Future work should also include installation of this design on non-gauging weirs, where the baffles would be positioned at the crest of the weir, in line with the optimum design for the baffle solution developed in extensive laboratory trials. With larger samples of fish, extra PIT antennae upstream of the weir, and cameras positioned closer to the baffles, monitoring of behaviour and passage efficiency could be significantly improved.

5.2 Larinier Super Active Baffle Fish Passes

5.2.1 Effectiveness of the Larinier Super Active Baffle Fish Pass

This study has provided good evidence that the Larinier super active baffle fish pass can be very effective in allowing upstream migration of salmon, trout and grayling, with minimum efficiency estimates of 54 per cent for grayling and 71 per cent for trout. Fish of a wide range of sizes were also shown to be able to negotiate the pass with ease. These figures do fall short of the efficiencies recommended by Lucas and Baras (2001) for maintenance of salmonid populations, however this study provided minimum estimates and true values are likely to have been higher.

While there is good evidence from the literature that this design of fish pass will enable passage of non-salmonid species, it has not been possible in this study to compare the efficiencies for salmonids and other species. It is also not possible to provide a direct comparison with the low cost baffle fish passes of the type installed at Brimpton, due to the difference in fish species present at the two sites and the differing hydrological conditions and fish monitoring capability.

5.2.2 Impact of the Larinier fish pass on flow gauging

The installation of Larinier fish passes to improve fish passage at hydrometric structures can be undertaken with some confidence that they will have little or no negative impact on flow measurement performance, provided they are designed appropriately and operating within the specified range. The installation of the Larinier fish pass at this location does not appear to have had any detrimental impact on the overall monitoring accuracy of the gauging station; indeed it is considered that the installation of the Larinier fish pass at this site has actually improved the sensitivity of the structure under low flow conditions.

In terms of its performance as a gauging structure, the Larinier fish pass at Louds Mill, as judged by the fit of the gauged data to the theoretical stage discharge relationship, is considered excellent throughout the majority of the stage range. The difference between the existing Environment Agency theoretical rating and the proposed theoretical rating is less than 1 per cent throughout the full stage range.

There can, however, be additional costs for Area Hydrometry and Telemetry teams in terms of the installation and operation of supplementary flow monitoring apparatus, including separate head measurement. Weed and other debris were observed to accumulate on the fish pass baffles, and although this was demonstrated not to have had any significant impact on flow gauging during the study, there will be an on-going requirement to ensure that debris accumulation is kept to a minimum. Installing cameras to monitor debris on the main weir complex and the approach to the fish pass is considered to provide significant benefit to the successful operation and maintenance of the site.

The project has thus demonstrated that two types of fish pass can be incorporated into flow gauging structures with minimal impacts on flow gauging accuracy and uncertainty, enabling successful ascent of the structure by the majority of fish attempting to do so.

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Appendix A

Details of tagged fish – Brimpton

Tag ID	Date	Time	Species	Length (mm)	Capture Site
0960FFBA	24/04/08	13:00:00	Chub	502	US1
0960FF72	24/04/08	13:00:00	Chub	414	US1
0960FFE6	24/04/08	13:00:00	Chub	474	US1
0960FF9D	24/04/08	13:00:00	Perch	147	US1
0960FFC3	24/04/08	14:00:00	Chub	510	US2
0960FF42	24/04/08	14:00:00	Chub	460	US2
0960FFC6	24/04/08	14:00:00	Chub	473	US2
0960FFEB	24/04/08	14:00:00	Chub	376	US2
0960FFBC	24/04/08	14:00:00	Chub	481	US2
0960FFB9	24/04/08	14:00:00	Chub	412	US2
0960FFCC	24/04/08	14:00:00	Dace	220	US2
0960FF47	24/04/08	14:00:00	Chub	394	US3
0960FF55	24/04/08	15:00:00	Chub	470	US3
0960FF58	24/04/08	15:00:00	Chub	431	US3
0960FFC7	24/04/08	15:00:00	Chub	464	US3
0960FF7E	24/04/08	15:00:00	Chub	472	US3
0960FFC9	24/04/08	15:00:00	Chub	398	US3
0960FF90	24/04/08	15:00:00	Chub	371	US3
0960FF4E	24/04/08	15:00:00	Dace	204	US3
0960FFDA	24/04/08	15:00:00	Dace	198	US3
0960FF9A	24/04/08	15:00:00	Chub	507	US3
0960FFE9	24/04/08	15:00:00	Dace	198	US3
0960FF87	24/04/08	15:00:00	Chub	488	US3
0960FF5E	24/04/08	15:45:00	Chub	446	US4
0960FF54	24/04/08	15:45:00	Chub	399	US4
0960FF77	24/04/08	15:45:00	Chub	438	US4
0960FF3F	24/04/08	15:45:00	Chub	389	US4
0960FF60	24/04/08	15:45:00	Dace	216	US4
0960FF81	24/04/08	15:45:00	Dace	217	US4
0960FF4B	24/04/08	15:45:00	Dace	185	US4
0960FF82	24/04/08	16:45:00	Chub	436	US5
0960FFB5	24/04/08	16:45:00	Chub	443	US5
0960FFDD	24/04/08	16:45:00	Chub	409	US5
0960FF94	24/04/08	16:45:00	Chub	423	US5
09610058	24/04/08	16:45:00	Chub	422	US5
0960FF25	24/04/08	16:45:00	Chub	465	US5
0960FF2E	24/04/08	16:45:00	Chub	405	US5
0960FF75	24/04/08	16:45:00	Chub	488	US5
09610062	24/04/08	16:45:00	Chub	440	US5
0961005C	24/04/08	16:45:00	Chub	382	US5
0960FF64	24/04/08	16:45:00	Chub	434	US5
0960FF41	25/04/08	12:00:00	Chub	485	DS1

Tag ID	Date	Time	Species	Length (mm)	Capture Site
0960FF57	25/04/08	12:00:00	Chub	476	DS1
0960FFB0	25/04/08	12:00:00	Chub	415	DS1
0960FF68	25/04/08	12:00:00	Chub	456	DS1
0960FF97	25/04/08	12:00:00	Chub	442	DS1
0960FFD5	25/04/08	12:00:00	Chub	456	DS1
09610005	25/04/08	12:00:00	Chub	213	DS1
0960FFDF	25/04/08	12:00:00	Chub	153	DS1
0960FFC2	25/04/08	13:00:00	Chub	429	DS2
0960FFF0	25/04/08	13:00:00	Chub	463	DS2
0960FFE3	25/04/08	13:00:00	Chub	421	DS2
0960FFBD	25/04/08	13:00:00	Chub	478	DS2
0960FF5A	25/04/08	13:00:00	Chub	429	DS2
0960FF50	25/04/08	13:00:00	Chub	424	DS2
0960FF76	25/04/08	13:00:00	Chub	435	DS2
0960FFBF	25/04/08	13:00:00	Chub	382	DS2
0960FFD3	25/04/08	13:00:00	Chub	212	DS2
0960FFFE	25/04/08	13:00:00	Chub	461	DS2
0960FFAE	25/04/08	16:00:00	Chub	475	US6
0960FFE1	25/04/08	16:00:00	Chub	445	US6
0960FF70	25/04/08	16:00:00	Chub	402	US6
0960FFB2	25/04/08	16:00:00	Chub	489	US6
0960FF3E	25/04/08	16:00:00	Chub	396	US6
0960FF93	25/04/08	16:00:00	Chub	423	US6
0960FFA9	25/04/08	16:00:00	Chub	478	US6
0960FF44	25/04/08	16:00:00	Chub	396	US6
0960FF30	25/04/08	16:00:00	Dace	206	US6
0960FF9B	25/04/08	16:00:00	Dace	240	US6
0960FFA6	25/04/08	16:00:00	Chub	468	US6
0960FFD0	08/05/08	13:50:00	Chub	353	US7
0960FF71	08/05/08	13:50:00	Perch	222	US7
0960FFFB	08/05/08	13:50:00	Perch	283	US7
09610009	08/05/08	14:15:00	Perch	224	US7
0960FFF1	08/05/08	14:15:00	Roach	240	US7
0960FFA2	08/05/08	14:15:00	Perch	227	US7
0960FF3B	08/05/08	14:45:00	Roach	244	US7
0960FFBE	08/05/08	14:45:00	Chub	237	US7
0960FF37	08/05/08	14:45:00	Chub	221	US7
0960FF31	08/05/08	16:30:00	Roach	156	The Chase
096100A1	08/05/08	16:30:00	Roach	222	The Chase
0960FF8B	08/05/08	16:30:00	Roach	156	The Chase
0961009C	08/05/08	16:30:00	Roach	159	The Chase
09610068	08/05/08	16:30:00	Roach	166	The Chase
096100AB	08/05/08	16:30:00	Roach	169	The Chase
0960FF7B	08/05/08	16:30:00	Roach	178	The Chase
09610091	08/05/08	16:30:00	Roach	161	The Chase
0960FF78	08/05/08	16:30:00	Roach	165	The Chase
0960FFED	08/05/08	16:30:00	Roach	184	The Chase
0960FFE0	08/05/08	16:40:00	Roach	173	The Chase
09610037	08/05/08	16:40:00	Roach	180	The Chase
0960FFD9	08/05/08	16:40:00	Roach	158	The Chase
09610066	08/05/08	16:40:00	Roach	163	The Chase
0960FFAF	08/05/08	16:40:00	Roach	166	The Chase
09610084	08/05/08	16:40:00	Roach	178	The Chase

Tag ID	Date	Time	Species	Length (mm)	Capture Site
0961000B	08/05/08	16:40:00	Roach	142	The Chase
0960FF6C	08/05/08	16:40:00	Roach	169	The Chase
0960FFC0	08/05/08	16:40:00	Roach	163	The Chase
0960FFF5	08/05/08	16:40:00	Roach	175	The Chase
0961000C	08/05/08	16:50:00	Roach	161	The Chase
0960FF5B	08/05/08	16:50:00	Roach	158	The Chase
0960FFFA	08/05/08	16:50:00	Roach	155	The Chase
0960FF22	08/05/08	16:50:00	Roach	158	The Chase
09610007	08/05/08	16:50:00	Roach	173	The Chase
0960FF91	08/05/08	16:50:00	Roach	153	The Chase
060FFEC	08/05/08	16:50:00	Roach	152	The Chase
0960FFB6	08/05/08	16:50:00	Roach	160	The Chase
09610001	08/05/08	16:50:00	Roach	178	The Chase
0960FF59	08/05/08	16:50:00	Roach	170	The Chase
0960FF8C	08/05/08	17:00:00	Roach	154	The Chase
0960FFFC	08/05/08	17:00:00	Roach	158	The Chase
09610002	08/05/08	17:00:00	Roach	166	The Chase
0960FFE2	08/05/08	17:00:00	Roach	191	The Chase
0960FF3C	08/05/08	17:00:00	Roach	158	The Chase
0960FFF8	08/05/08	17:00:00	Roach	162	The Chase
0960FF24	08/05/08	17:00:00	Roach	170	The Chase
0960FF34	08/05/08	17:00:00	Roach	174	The Chase
0960FFD8	08/05/08	17:00:00	Roach	156	The Chase
0960FF7C	08/05/08	17:00:00	Roach	181	The Chase
0960FF84	08/05/08	17:10:00	Roach	180	The Chase
0961005E	08/05/08	17:10:00	Roach	165	The Chase
0960FFD2	08/05/08	17:10:00	Roach	161	The Chase
0960FFE8	08/05/08	17:10:00	Roach	173	The Chase
0961000F	08/05/08	17:10:00	Roach	178	The Chase
0960FFEE	08/05/08	17:10:00	Roach	158	The Chase
0960FFB8	08/05/08	17:10:00	Roach	159	The Chase
0960FFA0	08/05/08	17:10:00	Roach	188	The Chase
0960FFA4	08/05/08	17:10:00	Roach	180	The Chase
0960FF69	08/05/08	17:10:00	Roach	154	The Chase
0960FFAC	08/05/08	17:20:00	Perch	224	The Chase
0960FF21	08/05/08	17:20:00	Roach	171	The Chase
0960FFD6	08/05/08	17:20:00	Roach	198	The Chase
0960FF29	08/05/08	17:20:00	Roach	178	The Chase
0960FF51	08/05/08	17:20:00	Roach	157	The Chase
0961002C	08/05/08	17:20:00	Roach	160	The Chase
0961008A	08/05/08	17:20:00	Roach	175	The Chase
0960FFA3	08/05/08	17:20:00	Roach	161	The Chase
0960FFEF	08/05/08	17:20:00	Roach	158	The Chase
0961004D	08/05/08	17:20:00	Roach	159	The Chase
0960FF5C	08/05/08	17:30:00	Roach	168	The Chase
0960FF61	08/05/08	17:30:00	Roach	201	The Chase
09610043	08/05/08	17:30:00	Roach	162	The Chase
0960FF3D	08/05/08	17:30:00	Roach	161	The Chase
0960FF9F	08/05/08	17:30:00	Roach	164	The Chase
0960FF74	08/05/08	17:30:00	Roach	179	The Chase
0960FF63	08/05/08	17:30:00	Roach	167	The Chase
0960FF65	08/05/08	17:30:00	Roach	193	The Chase
0960FF45	08/05/08	17:30:00	Roach	162	The Chase

Tag ID	Date	Time	Species	Length (mm)	Capture Site
0961000A	08/05/08	17:30:00	Roach	170	The Chase
0960FF2B	08/05/08	17:30:00	Roach	177	The Chase
0960FFFF	08/05/08	17:30:00	Roach	156	The Chase
0960FF8E	08/05/08	17:30:00	Roach	170	The Chase
0960FFF6	13/05/08	14:00:00	Perch	219	Blakes trap
0960FF9E	13/05/08	14:00:00	Perch	195	Blakes trap
0960FF79	13/05/08	14:00:00	Perch	120	Blakes trap
0960FFB4	13/05/08	14:00:00	Perch	138	Blakes trap
0960FF2F	13/05/08	14:00:00	Perch	146	Blakes trap
0960FF33	13/05/08	14:00:00	Perch	123	Blakes trap
0960FF35	13/05/08	14:00:00	Perch	129	Blakes trap
0960FFE4	13/05/08	14:00:00	Perch	128	Blakes trap
0960FFE5	13/05/08	14:00:00	Perch	126	Blakes trap
09610035	13/05/08	14:00:00	Perch	120	Blakes trap

Appendix B

Details of Tagged Fish, Louds Mill

All fish captured 17/03/09 approximately 10.00 am - 3.00 pm from upstream of Louds Mill Weir

All fish released 17/03/09 between weir and footbridge d/s weir, 1.00pm - 6.00pm

Number	Tag ID	Species	Length (cm)	Comment	Comment 2
1	000965D181	Grayling	35.8		
2	000965D09F	Grayling	33.3		
3	000965D0B8	Grayling	34.4		
4	000965D100	Grayling	42.2		
5	000965D0DF	Trout	29.7		
6	000965D0ED	Trout	26.6	silvery	
7	000965D0B1	Trout	22.2		
8	0007FB5B63	Grayling	28		
9	000965D0E5	Trout	20.9		
10	000965D0D8	Trout	19.4		
11	000965D0BA	Trout	20.6		
12	000965D097	Grayling	25.7		
13	000965D13D	Trout	19.3		
14	000965D0F9	Trout	26		
15	0007FB5B86	Grayling	24.9		
16	000965D158	Trout	23		
17	000965D098	Trout	23.9		
18	000965D0AA	Trout	21.3	silvery	
19	000965D0E2	Trout	24.5		
20	000965D0F5	Trout	18.6		
21	000965D0C2	Trout	21.4		
22	000965D0DA	Trout	19.1	silvery	
23	000965D0FA	Trout	22.4		
24	000965D0E3	Trout	26.8		
25	000965D0A1	Trout	27.3		
26	000965D141	Trout	27.6		damaged tail
27	000965D10E	Trout	22.2		
28	000965D109	Trout	21.6		
29	000965D0BC	Trout	21.3		

30	000965D12F	Trout	27.4		
31	000965D0AF	Trout	24.8		
32	000965D167	Trout	22.9		
33	000965D15D	Trout	20.8		
34	000965D0B7	Trout	20.9	silvery	
35	000965D101	Trout	20.7	silvery	
36	000965D0C6	Trout	21.7	silvery	
37	000965D17B	Trout	19.7		
38	000965D0D9	Grayling	29.5		
39	000965D0F6	Grayling	34.5		
40	0007FB5228	Grayling	35.8		
41	007FB5B65	Grayling	27.6		
42	000965D0D1	Grayling	39.6		
43	000965D0C1	Grayling	35.4		
44	000965D0A4	Grayling	27.5		
45	000965D0AE	Trout	23.1	silvery	
46	000965D11F	Grayling	28.6		
47	000965D0FF	Grayling	38.3		
48	000965D0DC	Grayling	26		
49	000965D0B5	Grayling	35.5		
50	000965D0DB	Trout	24.2	silvery	
51	000965D0E8	Trout	24.8		
52	000965D0C4	Grayling	29		
53	000965D179	Trout	21.3		
54	000965D0A6	Trout	22.2		
55	000965D0C8	Trout	21.5	silvery	
56	000965D189	Grayling	37.03		
57	000965D154	Trout	30.7		
58	000965D13C	Trout	24.5		
59	000965D121	Trout	22.4		
60	000965D13B	Grayling	28.6		
61	000965D123	Trout	25		
62	000965D17E	Trout	29.2		
63	000965D19D	Grayling	32.4		
64	000965D165	Trout	26.6		
65	000965D0B2	Trout	25.8		
66	000965D0F1	Trout	24		
67	000965D0B4	Grayling	40		
68	000965D0A3	Grayling	34		
69	000965D151	Grayling	35.2		
70	000965D10D	Grayling	35.3		
71	000965D118	Grayling	31.6		
72	000965D168	Grayling	30		
73	000965D139	Trout	14.8		parr
74	000965D137	Trout	22		
75	0007FB5B8A	Trout	22.2		

76	000965D0EC	Rainbow trout	36.4		damaged tail
77	000965D0C5	Trout	26		
78	000965D178	Trout	31.3		
79	000965D138	Grayling	28.2		
80	000965D0FB	Trout	24	silvery	
81	000965D115	Trout	26.7		
82	000965D14F	Trout	21.7		
83	000965D11B	Trout	27.4		
84	000965D107	Trout	29.9		
85	000965D112	Trout	25		
86	000965D096	Trout	24.2		
87	000965D173	Trout	23.5		
88	000965D188	Trout	30.3		
89	000965D15C	Trout	23		
90	000965D0AD	Trout	21.2	silvery	
91	000965D187	Trout	22.6		
92	000965D126	Trout	22.8		
93	000965D186	Trout	19.4	silvery	
94	000965D0D2	Trout	20.2		
95	000965D12D	Grayling	24.6		
96	000965D208	Trout	15.3		
97	000965D11A	Grayling	30.1		
98	000965D1F0	Grayling	15.4		
99	000965D1BB	Trout	13		
100	000965D128	Trout	13		
101	000965D1D9	Trout	21.7		
102	000965D1AA	Trout	26		
103	000965D200	Trout	26.7		
104	000965D20B	Grayling	13.8		
105	000965D1D3	Trout	36.9		
106	000965D1C1	Trout	27.1		
107	000965D1BA	Grayling	31.9		female
108	000965D205	Trout	23.4		
109	000965D1BD	Trout	28.9		
110	000965D1BE	Grayling	26.5		
111	000965D1F8	Trout	22.4		
112	000965D1EA	Trout	23.1		
113	000965D1EF	Trout	21.2	silvery	
114	000965D1B6	Trout	31.6		
115	000965D1CF	Grayling	15.5		
116	000965D1E1	Trout	26		parr
117	000965D147	Trout	13.5		parr
118	000965D1DD	Trout	18.5		
119	000965D19A	Trout	23		
120	000965D106	Grayling	42.2		

121	000965D175	Grayling	26.3		
122	000965D199	Grayling	24		
123	000965D129	Grayling	18.2		
124	000965D1FF	Trout	13.6		
125	000965D18B	Trout	22		
126	000965D1A3	Grayling	18.8		
127	000965D105	Trout	8.8	silvery	
128	000965D1AC	Grayling	29.4		
129	000965D20A	Trout	13.6		
130	000965D1F7	Grayling	15		
131	000965D1FA	Grayling	16.8		
132	000965D1F1	Trout	19.8		
133	000965D12C	Grayling	23.4		
134	000965D1A7	Trout	19.5		
135	000965D1F2	Trout	24.1		
136	000965D1E6	Grayling	15.1		
137	000965D14A	Trout	23.5		
138	000965D1B9	Trout	21.7		
139	000965D18E	Trout	26		
140	000965D1B7	Trout	20.7		
141	000965D1A8	Trout	22.3		
142	0007FB5B81	Trout	18.4		
143	000965D180	Trout	25.2		damaged dorsal
144	000965D1C0	Trout	25.1		
145	000965D1AB	Trout	22		
146	000965D1DA	Trout	18.3		
147	000965D1C7	Trout	25.3		
148	000965D135	Trout	18.9	silvery	
149	000965D1D0	Trout	21.7		
150	000965D1B8	Trout	21.6		
151	000965D1F3	Trout	25.9		
152	000965D1CC	Grayling	21.3		
153	000965D1FB	Trout	28.8		
154	000965D1B2	Trout	23		
155	000965D1C6	Trout	23.9		
156	000965D1D8	Grayling	16.8		
157	000965D197	Grayling	21.8		
158	000965D0DD	Grayling	27.3		
159	000965D1DB	Trout	18.7		
160	0007FB5B85	Grayling	17.6		
161	000965D1AF	Trout	19.6		
162	000965D1F9	Trout	24.5		
163	0007FB5B80	Trout	15.7		
164	000965D18D	Trout	23.4		
165	000965D0CF	Trout	24.4		

166	000965D1B5	Trout	21.6		
167	000965D1D4	Trout	19.6		
168	000965D0CD	Trout	20.3		
169	000965D1F4	Trout	17.1		
170	000965D1E8	Trout	21.3		
171	000965D1DF	Trout	21.8		
172	000965D18C	Trout	21.2	silvery	
173	000965D174	Trout	19.8		
174	000965D15F	Trout	20.1		
175	000965D20C	Trout	17.4		
176	000965D1C2	Grayling	36.2		
177	000965D1C5	Grayling	30.8		
178	000965D1A5	Grayling	28.8		
179	000965D1CD	Grayling	15.9		
180	000965D1BC	Grayling	14.7		
181	000965D1B4	Trout	27.9		
182	000965D1E0	Trout	31.4		
183	000965D1A2	Trout	22.2		
184	000965D1A6	Trout	20.9		
185	0007FB5B7F	Trout	25.1		
186	000965D1EC	Grayling	26.5		
187	000965D206	Grayling	43.6		
188	000965D1D6	Grayling	37.8		
189	000965D1A9	Grayling	25.5		
190	000965D1E4	Trout	17.5		
191	000965D10A	Grayling	33.3		
192	000965D1E9	Grayling	28.3		
193	000965D140	Grayling	25.8		
194	000965D1EE	Trout	26.8		
195	000965D198	Trout	21		
196	000965D192	Trout	19.3		
197	000965D12A	Grayling	36.4		
198	000965D18F	Grayling	15		
199	000965D1EB	Grayling	25.7		
200	000965D201	Trout	26.8		
201	000965D159	Grayling	35.5		
202	000965D1E7	Trout	19.8		
203	000965D142	Trout	20.6		
204	000965D12E	Grayling	16.4		
205	000965D195	Grayling	26.1		
206	000965D1D5	Trout	28.3		
207	000965D209	Grayling	35.6		
208	000965D19F	Grayling	40.2		
209	000965D10C	Grayling	26.6		
210	000965D1BF	Trout	23.9		
211	000965D17A	Trout	33.5		

212	000965D15B	Grayling	27		
213	000965D127	Trout	21.2		
214	000965D1A1	Trout	22.5		
215	000965D146	Trout	30.7		
216	000965D1ED	Grayling	17.4		
217	000965D1CA	Trout	22.7	silvery	
218	000965D1E2	Trout	22.2		
219	000965D194	Trout	25.8		
220	000965D183	Trout	25.4		
221	000965D1AD	Trout	23.5		
222	000965D19B	Trout	29.9		
223	000965D1DE	Grayling	16.2		
224	000965D1B1	Trout	24.7		
225	000965D17D	Trout	23.2		
226	000965D1C8	Trout	21.8		
227	000965D170	Trout	24.3		
228	000965D207	Trout	22.5		
229	000965D1D7	Trout	19.6		
230	000965D203	Trout	21.2		
231	000965D172	Trout	23.8		
232	000965D103	Trout	31		
233	000965D150	Trout	30.4		
234	000965D10F	Trout	23.7		
235	000965D202	Trout	23.2		
236	000965D193	Trout	30		
237	000965D144	Trout	29.8		
238	000965D15E	Trout	22.2		
239	000965D155	Trout	19		
240	000965D177	Trout	24.5		
241	000965D1FE	Trout	24.5		
242	000965D143	Trout	13.5		
243	000965D132	Trout	22.5		
244	000965D0D3	Trout	26.6		
245	000965D1DC	Trout	19.8		
246	000965D1CE	Trout	26.2		
247	000965D136	Trout	29.8		
248	000965D12B	Trout	22.2		
249	000965D176	Trout	32.8		
250	000965D16F	Grayling	37		
251	000965D125	Trout	23.7		
252	000965D13E	Trout	17.8		
253	000965D182	Trout	31		
254	000965D130	Grayling	27		
255	000965D134	Grayling	25		
256	000965D15A	Grayling	26.2		
257	000965D145	Trout	20.3		

258	000965D148	Trout	12.6		
259	000965D19E	Grayling	41.3		
260	000965D1A0	Grayling	43		male
261	000965D17C	Trout	34.8		
262	000965D14D	Grayling	30.8		
263	000965D157	Trout	39.2		
264	000965D1E5	Trout	29		
265	000965D1F6	Trout	20		
266	000965D10B	Trout	23.6		
267	000965D13A	Trout	25.1		
268	000965D16A	Trout	20.2	silvery	
269	000965D1E3	Grayling	42.5		
270	000965D196	Grayling	27.7		
271	000965D1FC	Grayling	29.8		
272	000965D1B3	Grayling	28.8		
273	000965D1AE	Grayling	28.7		
274	000965D19C	Trout	36		
275	000965D14E	Grayling	26.9		
276	000965D166	Trout	20.6		
277	000965D169	Trout	32.2		
278	000965D149	Grayling	26.3		
279	000965D0B0	Trout	22.2		
280	000965D095	Trout	29.2		
281	000965D18A	Trout	32.5		
282	000965D161	Grayling	43.8		
283	000965D160	Grayling	25.4		
284	000965D122	Trout	26.8		
285	000965D0D0	Trout	23.6		
286	000965D16D	Trout	30.8		
287	000965D0BD	Trout	28.7		
288	000965D0CE	Trout	22.6		
289	000965D0A9	Trout	24.4		
290	000965D13F	Trout	23.1		
291	000965D111	Trout	29.3		
292	000965D117	Trout	22.8		
293	000965D164	Trout	19.4		

Appendix C

Glossary of hydrometric terms

Note – This list seeks to define a number of terms that are key to this document and does not seek to provide a comprehensive list of standard terms and abbreviations.

a Constant used in rating application

Abutments The walls that flank the edge of a weir or other hydraulic structure, and which support the river banks on each side of the weir.
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b Constant used in rating application

Baffle An upstand designed to create turbulence favourable for fish migration conditions.

Boundary friction effects Drag influence on water immediately adjacent to the sides and bed of a weir structure.

BS / ISO British or International Standard, generally outlines acceptable practice and presents the theoretically researched guidelines.

C Constant used in rating application

CEH Centre for Ecology and Hydrology.

Crest (of weir) Control section of weir structure. The level of the crest, its length and its cross-sectional shape determine the discharge (flow) characteristics of the weir.

Crump weir A form of weir with a precise triangular profile used for discharge monitoring (after E S Crump, who defined the characteristics of this shape of weir).

Cumec Cubic metres per second (m^3s^{-1}). A measure of rate of flow per unit time.

Deviation Percentage that a gauging lies from the equivalent theoretical flow based on the stage.

Drowning In the context of weir hydraulics, a weir is said to be drowned (or drowned out) when the downstream water level rises to the point where it begins to affect the head of water upstream of the weir.

Fish pass A device provided to allow fish to migrate over or round a weir or other control structure that would otherwise obstruct the movement of fish.

Flow Flow rate or discharge. Expression of a volume of water per unit time.

Gauging The means of determining flow through a series of spot flow measurements.

Head (of water) The height/level of water above a fixed datum (such as the weir crest).

Head loss The change in energy gradient across a weir or other hydraulic structure, usually approximated by change in stage across structure.

HR Wallingford Hydraulics Research Wallingford, consultants

Invert level Level of the lowest point in a natural or artificial channel.

Larinier Fish pass or Larinier Super Active Baffle Fishpass (LSABF) Fish pass type utilising upstream pointing baffles developed by Larinier in France.

Modular flow Condition in which flow is able to discharge freely over a weir resulting in a unique relationship between flow rate and upstream water level

Non-modular flow Condition in which flow is not able to discharge freely over a weir, with the downstream water level influencing the upstream level (i.e. drowned flow).

NRFA National River Flow Archive, hydrological data holding and historical records managed and published by CEH.

P-value Height of crest above the average upstream bed level in the stage measurement section.

POT Peaks Over Threshold, flows above a selected threshold in any one hydrological year (usually five flood events per water year)

Q95 The flow that is exceeded 95% of the time

Q10 The flow that is exceeded 10% of the time

Quadrature Method used for combining uncertainties using independent head measurements. Applied as the square root of the sum of the individual uncertainties squared

Rating A relationship of water level against flow rate for a channel section, weir or other hydraulic structure

Side weir Weir installed in a channel to divert part of the approach flow into a separate spill channel

Stage Elevation of water surface relative to a fixed datum, usually the cease to flow level or invert of a weir crest

Tail-water level Water level downstream of a hydraulic structure

Transposed Relating the stage from one measurement location to an alternative location

Trash Debris and rubbish that lodges on baffles e.g. weed / branches / plastic bags

Weir An artificial obstruction in a watercourse that results in increased water surface level upstream for some, if not all flow conditions. A structure in a river, stream, canal or drain, over which free-surface flow occurs. May be used variously for control of upstream water levels, diversion of flow, and/or measurement of discharge.

Wingwall A wall on a weir or other in-river structure that ties the structure into the river bank. Wingwalls extend from the weir abutments into the river bank.

WISKI Commercial data management system for handling hydrometric time series data and application of ratings

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