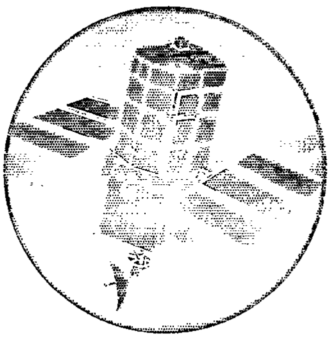
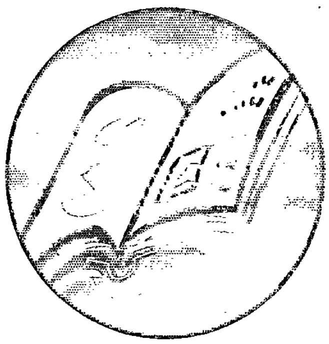
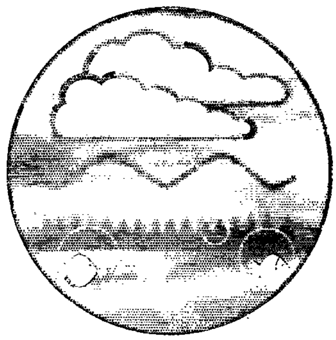
Calibration of Gauging Stations Using Portable Ultrasonics

Research and Development

Technical Report
W189

ENVIRONMENT AGENCY

Calibration of Gauging Stations Using Portable Ultrasonics

R&D Technical Report W189

A M Bennett,

Research Contractor:
Scotia Water Services

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Statement of use
This report is aimed at those interested in the measurement of river flows using ultrasonic (time of flight) gauges. It is a practical guide for use by hydrometric staff and managers, based on field experience and the analysis of the results. It describes the application of portable gauges to calibrate structures of gauging stations, particularly at high flows and under non-modular conditions.

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Peter Spencer, Environment Agency, North WestRegion

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EXECUTIVE SUMMARY

This report presents the results of an Environment Agency R&D Project that was commissioned to determine the feasibility of using portable ultrasonic flow gauges working on the time of flight principle to calibrate structures, particularly at high flows and/or non modular conditions. The research was to determine the limitations on use, accuracy and optimum configuration for gauge deployment, and arose from an increasing need for good quality hydrometric data, both by the Agency and outside users, and the increasing availability of portable equipment that can be moved from site to site.

The report provides a background to the development and use of ultrasonic flow gauges, which have themselves evolved over a number of years. The respective advantages and disadvantages of different gauge configurations are discussed, together with an introduction to some of the theoretical uncertainties that are associated with this approach to flow measurement. A comparison between the performance of twin-path and multi-path gauge configuration is presented in the report, which shows that whilst the twin-path system may not be as accurate as one using more paths, the decrease in performance might not be as large as previously thought. In particular, it was found that deploying the two transducer paths within two identified vertical 'zones' would decrease the uncertainty in the derived flows. The recommendations for setting the twin-path transducer levels to give optimum performance are:

Lower path	deployed at less than 0.3 of the design water depth
Upper path	deployed at between 0.45 and 0.7 of the design water depth

During the course of the Project three twin-path gauges were deployed as stand alone units at a total of six different gauging stations and operated in a number of different ways. Using the experience gained from these field studies a series of recommendations have been made regarding gauge installation and commissioning. These recommendations include aspects of site survey, mounting systems, power supplies, transducer selection and gauge parameter settings. Whilst a 'typical' installation may take approximately 30 staff hours to complete, more complex or larger sites may take up to 40 hours and a relatively compact site could be completed in 20 hours.

The data collected from the gauges was used to calculate flows by three different approaches:

1. Using the gauge as a twin-path system to calculate flows and derive rating curves;

2. Operating the gauge data to derive stage-velocity relationships from which stage-discharge relationships were then calculated;
3. Operating the gauge to measure flows in real time at sites where there is no single, stable relationship between level and flow.

The first of these approaches demonstrated that, with the exception of high sediment loads at the peak of some events at some of the field sites, the equipment performs well under a range of flow conditions. Using data collected at three of the field sites it is demonstrated that the gauge is able to calculate flows to within a typical uncertainty (within the recorded range) of ±10% using the manufacturer's default parameter settings. This uncertainty can be reduced to under ±7% by setting one of the parameters to a revised value, and can be further reduced to ±5% by optimising the parameter on site when commissioning the equipment. The typical equipment costs of operating the gauge in this manner are approximately £1,300 per site, plus up to 70 staff hours on site, plus any additional travel time and costs in excess of normal travel.

If the stage and velocity data collected by a gauge are used to develop stage-velocity and stage-discharge relationships, the analysis presented in the report demonstrates that the total uncertainty in the derived flows can be reduced to between ±2.5 and ±5%. In addition to reducing the uncertainty in the derived flows, this approach removes any anomalies in the derived flows that may arise if one of the velocity paths should fail during a specific event. The additional cost of these benefits is assessed at almost 20 staff hours per site, or three days work, with the equipment costs being similar to those of the straightforward twin-path approach.

An essential pre-requisite of using the ultrasonic gauge to derive stage-discharge ratings is a stable relationship between level and flow. Where this is not the case, the gauge may be used as a permanent installation to monitor flows in real time. The work presented in this report demonstrates that the gauge is sensitive enough to be able to measure river velocities under differing hydraulic conditions, and detect the onset of non-modular flows. Operational costs are similar to those of more conventional techniques currently used by the Environment Agency such as crest tappings, with the advantage that the gauge can retrospectively installed at a site that does not have a tapping.

In addition to the three identified methods used to calculate flows at a given site, the report also presents the results of alternative approaches that were evaluated during the course of the Project. These include reflector systems, multi-level operation during an event, and non-horizontal transducer paths. In all cases it was found that whilst the gauge may work using these approaches they are less robust that the more conventional configurations. It is thus concluded that these approaches should only be adopted if site conditions dictate that they are the only viable method.

Finally, the report provides recommendations for implementing the results of the Project at both the National and Area level. Specific issues are identified for consideration by the National Hydrometric Group and/or Area Water Resources and Flood Defence management teams, and guidance is provided on selecting the appropriate approach to using the equipment. Recommendations for further research are also made, and include an assessment of the relationship between gauge performance and sediment load.

KEY WORDS

Ultrasonic gauge, time-of-flight, gauging station, flow measurement, twin-path, multi-path, rating curves, stage-velocity relationships, stage-discharge relationships, non-modular flows.

ACKNOWLEDGEMENTS

The author would like to thank the many individuals and organisations who have provided assistance throughout the duration of the Project. In particular, thanks go to the Environment Agency staff who provided assistance and guidance in site selection, and to those who routinely forwarded flow data collected by the Agency. Tom Poodle of Diptone Ltd, and Dr Andrew Black of the University of Dundee, provided assistance and feedback during the early stages of the Project, whilst Jim Waters (formerly of the Environment Agency) assisted with notes and discussion on the evolution of the ultrasonic gauge network in the Midlands Region. Reg Herschy proved to be of great assistance in untangling the background to the development of the ultrasonic approach, and Dave Gibbard and his staff at Peek Measurement provided invaluable assistance and feedback during the course of the Project, as well as providing spare parts for the gauges and additional transducers for evaluation. The South Area of the North West Region loaned a gauge to the Project for use at Blackford Bridge, whilst Thames Region provided software developed in house to enable the gauge data to be logged on a standard Psion II. Finally, I would like to thank all members of the Project Board for their considerable input and feedback, with particular thanks going to Peter Spencer for his continued enthusiasm and patience.

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CALIBRATION OF GAUGING STATIONS USING PORTABLE ULTRASONICS

1 INTRODUCTION

1.1 Background to the Project

This Technical Report presents the results from the Environment Agency R & D Project W6/i646, calibration of gauging stations using portable ultrasonics, which was undertaken between November 1995 and March 1999. The Project was initially to finish in late 1997 but the very dry winters of 1995/96 and 1996/97 resulted in it being extended.

Hydrometric data is a cornerstone of the Environment Agency operations, being used by all functions in fulfilling corporate plan objectives. It is both an operational and planning tool for Water Resources, Flood Defence, Pollution Control and Fisheries. Research and Development in this area will, therefore, ultimately have widespread application through the use of the data.

The quality of hydrometric data is highly dependent on the stage-discharge relationships that are used by the Agency to derive flows from recorded river levels. Whilst this is usually considered to be of primary interest to open channel sites, ie those where there is no formal structure or other control in the river channel, the calibration of structures to derive the stage-discharge relationship is also very important. Whilst this is especially so for non-standard structures, it is also important in confirming the theoretical relationship at standard gauging structures under high and non-modular flow conditions.

In many cases pre-existing weirs and other structures are used as long-term gauging stations by the Agency, or often serve as flood warning sites. There is frequently a need to rate such structures as part of the hydrological and hydraulic calibration of river models which are then applied to a range of applications, including assessment of standards of service against flooding and the design of flood defence schemes. It is thus important that the stage-discharge relationships extend accurately to high flow conditions.

Calibration of structures under high flow conditions using conventional methods such as current metering is frequently problematic. During high flow events hydrometric staff are limited in the number of sites which they can visit. Where the response to rainfall is rapid it may not be possible to reach the site in time to gauge the highest flows, and changing water levels during the period of gauging may produce inaccuracies in the results. Calibration of structures for short-term studies will rarely justify the costs of installing a full cableway, and there may be no suitable bridge from which gaugings can be carried out. Furthermore, current meter gauging during high flows may require, or be prevented by, safe working practices to meet Health and Safety requirements. There is thus a definite need for an improved method to gauge high flows.

The ultrasonic time-of-travel approach is an established technique used at a number of permanent Agency gauging stations. Equipment which may be moved from site to site provides the possibility of calibrating structures without many of the problems of conventional methods described above, although it does have problems of its own. In particular, the equipment is vulnerable to vandalism, and the equipment is only suitable for measuring flows contained within the main channel. This Project was therefore initiated to determine the feasibility of using portable ultrasonic gauges to calibrate gauging stations. If successful, the Project will allow the Agency to use non-standard structures where they cannot be used at present, and to establish stage-discharge relationships in a comparatively short time and in a cost effective manner.

1.2 Organisational Details

The Project was undertaken by Scotia Water Services, in collaboration with Diptone Ltd and Dr Andrew Black. The Environment Agency Project Board which managed the Project consisted of:

Peter Spencer	Project Manager, North West Region
Dr John Adams	Topic Leader, Midlands Region (to 1998)
Scott Ferguson	Topic Leader, Southern Region (from 1998)
Alison Hanson	North West Region
Richard Iredale	Midlands Region
Ray Moore	North West Region
David Stewart	North East Region
Irene Gize	R&D Support Officer

Anybody requiring further information relating to the Project is asked to contact Peter Spencer in the first instance.

1.3 Aims and Objectives

The Project PID stated that the overall aim of the Project was 'to determine the feasibility of using temporary ultrasonic flow gauges to calibrate structures, particularly at high flows and/or non modular conditions. To determine limitations on use, accuracy and optimum configuration for application.' The specific objectives were identified as:

(a) To identify practical problems of application and limitations on the method.

(b) To determine the accuracy of the equipment under a range of conditions from ideal to the borderline of application.

(c) To determine the optimum configuration.

(d) To recommend a standard practice where this is feasible.

(e) To note areas of remaining uncertainty in the accuracy of results.

(f) To assess typical costs of the method based on realistic equipment costs and life, and manpower requirements.

(g) To test and report on the performance of ultrasonic equipment at structures over a range of mainly high flows and non-modular conditions. The structures will have an existing accurately known modular rating and will also be typical sites for future application.

(h) To use any existing suitable ultrasonic gauging stations in a manner which replicates the portable equipment.

(i) To produce a Report on each site tested, and incorporate this in the final Project Record.

(j) To produce:-

A Project Record;

A Technical Report;

An R&D Note.

1.4 Structure of this Report

The structure of this Report is as follows:

Chapter 2 **Technical Background** An introduction to the ultrasonic method, together with a review of its development as reported in the literature. This is then followed by specific details of the equipment used for the Project.

Chapter 3 **Gauge Installation and Commissioning** A brief summary of the sites used for the Project, the reasons why these were used, and an overview of the results that were obtained at each site. The mounting systems designed and used for the Project are also described. Full details of the work undertaken at each site are included in the Project Record, whilst Appendix B contains summary data sheets for each of the field sites.

Chapter 4 **Using the equipment as a twin path system.** This is the simplest gauge configuration. By providing examples from the Site Reports this chapter evaluates the use of the gauge with the transducers deployed at a fixed level throughout the entire survey period. It includes:

- Typical performance of the gauges, illustrated by examples;
- An assessment of the uncertainties associated with this method of deployment;
- Limitations of the approach;
- The use of data collected from multi-path gauges to try to identify an 'optimum' set of levels for the two paths;
- Typical operational costs of this approach.

Chapter 5 **Using the gauge to replicate a multi-path instrument** This chapter follows a similar structure to chapter 4, but addresses the use of the gauge at more than two levels during the survey period.

Chapter 6 **Operating the gauge in real time.** The approaches described in chapters 4 and 5 depend on the assumption that there is a fixed and stable relationship between river level and flow. This chapter will present the results from using the equipment at a site where this is not the case.

Chapter 7 **Alternative approaches and studies** A number of 'one-off' studies have been included in the project, including the use of reflectors, non-horizontal transducer paths, multi-path deployment during a specific event etc. These studies and their associated results are described in chapter 7.

Chapter 8 **Conclusions and summary findings** The Project results are summarised, and compared to the original objectives in order to evaluate the success of the Project.

Chapter 9 **Recommendations for implementation** Finally, chapter 9 details a number of recommendations regarding the implementation of the findings of the Project. These recommendations apply at both the national and local scale.

2 TECHNICAL BACKGROUND

2.1 The ultrasonic time of travel method

(Much of this section is based upon the information contained in ISO 6416: 1992 (E), and in the handbooks for ultrasonic gauges provided by the manufacturers of the equipment). *Italicised numbers in brackets indicate the appropriate section in ISO 6416: 1992 (E).*

British Standard 3680 Part 3E: 1993 (also ISO 6416: 1992 (E)), 'Measurement of discharge by the ultrasonic (acoustic) method', provides a comprehensive account of the establishment and operation of an ultrasonic gauging station for the measurement of discharge in an open channel or closed conduit with a free water surface. It also describes the basic principles on which the method is based, and the operation and performance of associated instrumentation. As with this Project, it is limited to the 'time of travel of acoustic pulses' technique, and does not apply to systems that depend on the 'Doppler shift' or related techniques. Unlike some Standards, it is surprisingly readable and it is recommended that any reader wishing to implement the technique should first familiarise themselves with the document.

2.1.1 Underlying principle *(2.1)*

The ultrasonic 'time of travel' approach is based on the following principle, quoted from ISO 6416: 1992 (E):

> *'If the time taken for a sound pulse to travel a measured distance between two reference points in one direction is compared with the time taken to travel between the same two points in the opposite direction, the difference observed is directly related to the average velocity of the element of water in the "flight path" bounded by the two reference points. This is referred to as the "path velocity".'*
>
> *Paragraph 2.1.2, ISO 6416: 1992 (E)*

The speed of sound in water is approximately 1450 metres/second; so fast that the 'line of flight' is not significantly bent by the movement of the water body. Whilst the difference in time is very small, only a few millionths of a second at most for a narrow channel, it can be accurately measured by modern electronic processors.

This basic principle, when combined with appropriate instrumentation, allows the accurate measurement of water velocity along the 'path' between the two transducers. Whilst it falls short of being a fully representative measurement of total flow, it does provide a significant step forward from the single point-measurements associated with current meters.

2.1.2 The elements of the ultrasonic gauge *(3.2)*

The sound pulses are transmitted and received by transducers mounted at either end of the flight path. The ultrasonic transducers are pulsed and allowed to ring at their designed frequency. The transducer power and frequency is selected depending on the flow and channel width at the site. Similarly, there are theoretical minimum clearances that must be maintained between the flight paths and the river bed and water surface. Table 2.1 below, based on Table 3 in ISO 6416: 1992 (E), gives details of this.

Table 2.1 Recommended transducer frequency and clearances for ultrasonic gauges, together with the theoretical uncertainty in the derived velocities arising due to measurement error by the gauge. Based on Table 3 from ISO 6416: 1992 (E).

Path Length (m)	Typical minimum clearance between flight path and river bed or water surface (m)	Operating frequency (kHz)	Uncertainty in velocity determination due to time of flight measurement error (m/s)
300	3.0 to 1.5	30 to 100	0.005 to 0.0015
150	1.0 to 0.6	100 to 300	0.003 to 0.0013
80	0.5 to 0.35	200 to 500	0.003 to 0.002
30	0.3 to 0.15	300 to 1,000	0.006 to 0.003
10	0.12 to 0.07	500 to 1,500	0.013 to 0.007

The transducers are usually mounted individually on sloping ramps or collectively on vertical poles or piles. Each flight path is treated separately by the gauge, which usually requires path length, angle of the path to the river flow and path height to calculate the flow. Some gauges record river depth directly by means of a separate single transducer, whilst others use an external source such as a shaft encoder or bubbler gauge.

The final element of equipment required for flow measurement is the gauge itself. This is capable of controlling all flight paths, and synchronising the sound pulses to enable the flow (and, where applicable, depth) measurements to be taken. It will also undertake diagnostic tests, such as signal amplification and wave form analysis, before calculating the actual flow.

2.1.3 Typical configurations of the ultrasonic flight paths *(2.4)*

The configuration of the ultrasonic flight paths is usually based on one of four 'standard' options. These are described in turn, and illustrated in Figure 2.1.

Single path systems *(2.4.2)*

At their most basic, ultrasonic gauges can perform satisfactorily with a single pair of transducers deployed at either end of a single flight path (Figure 2.1(a)). The ability of the gauge to calculate flows under this configuration is influenced by four factors:

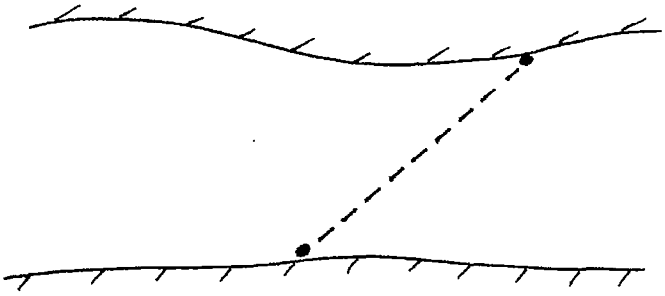
1) The range in water levels at the site, with higher ranges usually reducing the reliability and accuracy of the gauge.
2) The degree to which the relationship between the flight path velocity and either the velocity profile or mean cross-sectional velocity is known. The greater the uncertainty in this relationship, the greater the uncertainty in the derived flows.
3) The stability of the velocity profile at a given site under the whole range of flow conditions. Should the site be susceptible to backwater conditions then a single path gauge is unlikely to produce consistently accurate results.
4) The uniformity of the approach channel, and the presence/absence of skewed flow.

A number of variations to this exist, involving the movement of the flight path in the vertical plane. This might be as simple as altering the flight path level on a seasonal basis in response to changing flow regimes, or determining velocity profiles by operating the flight path at a number of levels under the same flow conditions. This will then allow the gauge operator to set the flight path at the optimum level.

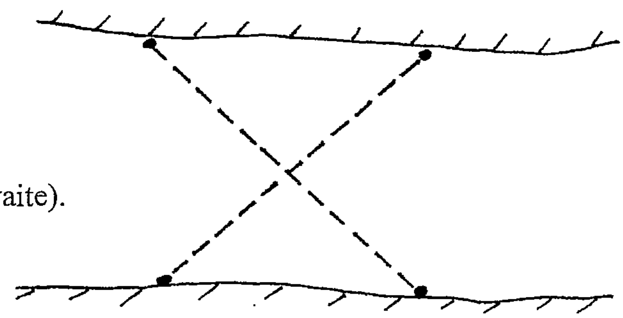
During the tender process for the Project the simplest ultrasonic gauge had two velocity paths. OTT have since introduced the Affra gauge, which can be supplied as a single path unit.

Crossed path systems *(2.4.4)*

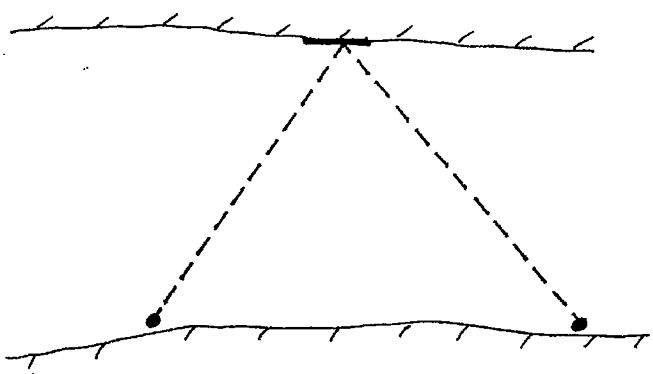
In practice it may be difficult to determine the true direction of flow at a given site. This may be because the channel geometry at low flows is different to that when levels are higher, or due to skewed flow in a channel. In order for the ultrasonic gauge to determine the flow it needs to know the angle of the flight path to the direction of flow. Any error in the determination of this angle is then magnified in the discharge computation, by as much as 3% per degree error.



(a) Single path installation
Most of the field installations used two paths deployed one above the other in this configuration.



(b) Crossed path installation
This was used at one of the Project field sites (Low Nibthwaite).



(c) Reflector installation
This configuration was evaluated at two of the field sites.

Figure 2.1 Typical configurations of the ultrasonic flight paths. Multi-path gauges can use a combination of these configurations, with the velocity paths stacked above each other.

In order to overcome this problem it is possible to install the transducer flight paths in a crossed configuration, as shown in Figure 2.1(b). Provided that the flow alignment within the gauged section is relatively constant then the true velocity can be obtained by either calculating the mean of the two path velocities when cross-paths are deployed at the same level, or adding together successive 'discharge slices' when the path level and direction is staggered.

Multi-path systems *(2.4.3)*

By increasing the number of different levels at which the velocity paths are installed it is possible to reduce errors in flow determination arising due to the following factors:

1) Wide and frequent range in water levels;
2) Significant risk of backwater effects;
3) Varying flow geometry at differing river levels (for example, at Bewdley);
4) An unusual velocity profile.

Increasing the number of velocity paths will provide a more accurate indication of the mean velocity across the channel section than a single path provides. The number of paths is limited only by the physical constraints of the equipment, and the money available for the installation. A further advantage of a multi-path installation over a single path is that the gauge will continue to function should one of the paths fail.

Whilst the multi-path configuration can be installed with the velocity paths all lying along the same diagonal, they can also be installed in a crossed multi-path configuration should circumstances dictate.

Reflected path systems *(2.4.5 and 3.2.1.2)*

Situations may arise where it is not possible to install transducers on both river banks, for instance where it is difficult to convey the electronic cables across the river, or where access to the far bank is difficult. Under such conditions it may still be possible to deploy an ultrasonic gauge by installing both sets of transducers on the same bank, and 'bouncing' the sound pulse off a reflector on the opposite bank, as shown in Figure 2.1(c).

Reflector configurations may also be used to obtain longer flight paths which will enable low velocities to be determined more accurately. However, in most situations, reflectors usually reduce the performance of the gauge by decreasing the signal strength. A full explanation of factors which affect the acoustic energy is contained in ISO 6416: 1992 (E) *(2.2.3)*.

Computation of flow *(2.8.4-2.8.6, Annex A)*

The mean path velocity v is calculated by:

$$v = \frac{\textit{flight path length x time difference x correction factor}}{(\textit{average time of flight})^2 \times 2 \cos\theta}$$

where θ is the angle between the flight path and the direction of flow, and the correction factor is usually unity.

For the simplest gauge configuration, ie the single path, the computation of flow is simply:

$$Q = fvA$$

where

Q	is the flow rate
f	is an empirically derived function quantifying the relationship between the path and mean channel velocity
v	is the velocity determined along the single path
A	is the cross-sectional area of the channel.

Crossed path configurations which have paths deployed at a single level also compute flow on this basis, but substitute v with the mean of the two path velocities. The greatest single problem with this approach is the determination and application of the empirically derived function f; whilst this can be quantified with only limited uncertainty for a site that experiences a narrow range in river levels, the uncertainty can significantly increase as the range in levels increases.

The computation of flow for multi-path gauges is rather more complicated, and varies from manufacturer to manufacturer. The example quoted here is based on the Sarasota/Peek equipment, which involves dividing the river cross section into a number of different 'slices' and assigning a velocity path to each of the slices, as shown in Figure 2.2. Each slice, with the exception of the lower one, contains one ultrasonic path or crossed path. The boundaries of each slice are:

1) Vertical lines at either end of the ultrasonic path.
2) Mid-way between the working velocity path in the slice and the next one below it. In the case of the slice with the lowest working path this is half way between that path and the river bed, whilst for the lowest slice it is the bed itself.

3) Mid-way between the working velocity path in the slice and the next one above it. In the case of the highest working path, the upper limit is the water surface.

The discharge in each slice is calculated from:

$$Q_{sn} = v_n \, x \text{ slice thickness } x \text{ path length } x \sin\theta$$

where

Q_s is the discharge of the slice

n is the vertical slice number

The total discharge is then obtained by summing the individual slice discharges.

This description, represented in Figure 2.2, is known as the mid-section method, where the ultrasonic path lies in the centre of the horizontal slice. An alternative approach, known as the mean-section method, is described in ISO 6416: 1992 (E) *(2.8.4.4)*. This is based on the boundaries of each slice being defined by the actual velocity paths, with the mean of these two path velocities being used to determine the slice velocity for the calculation of flow.

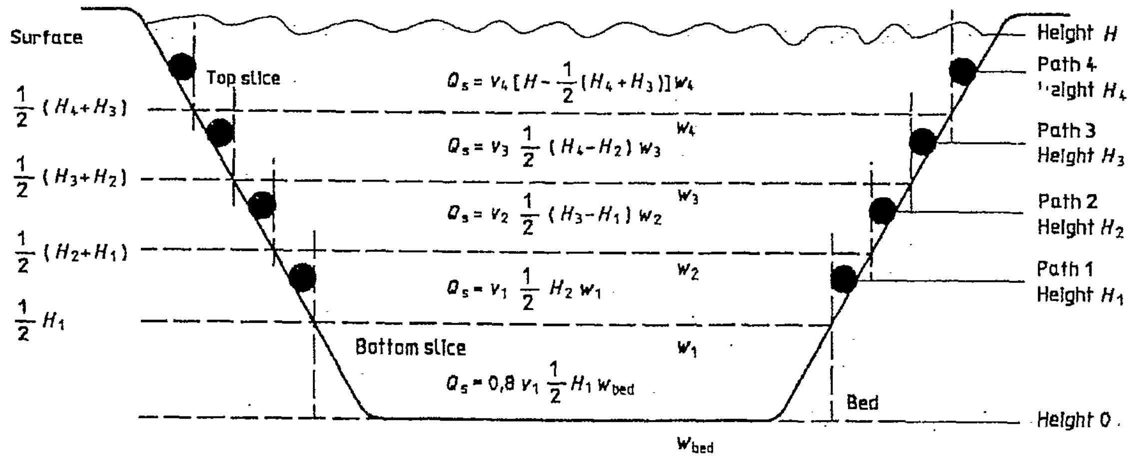


Figure 2.2 Example of the method used to calculate discharge by the mid-section method, from ISO 6416: 1992 (E).
H = elevation relative to stage datum, v is the velocity along each of the transducer paths, and w is the channel width at that point

2.1.5 Other factors

ISO 6416: 1992 (E) describes a number of additional factors which should be considered when deciding whether or not to deploy an ultrasonic gauge at a site. The following are especially useful:

- Characteristics of sound propagation *(2.2)*
- Site selection criteria *(2.5)*
- Site survey requirements *(2.6)*
- Measurement uncertainties *(2.11)*
- Installation and commissioning *(3.4 and 3.5)*

2.2 Development of the method; a literature review

One of the project objectives was to undertake a review of the literature relating to ultrasonic gauges. The literature search was completed using a wide range of methods which included the internet, conventional library catalogue searches, research institute libraries, equipment manufacturers, direct contact and personal interview with those involved in the development of the method. Once this material had been collated it was decided to complete the review in the following manner:

1. Review the early development of the technique in detail, including studies from both the UK and further afield.
2. Once the early research and development had been reviewed on a global context, concentrate on the evolution of the ultrasonic gauge network in the UK.

It was decided not to include detailed reference to recent papers (ie post 1980) describing foreign studies as the majority of this is concerned with very large rivers. However, an extended bibliography of papers published by the USGS is included in the Project Record. Most of these papers are accessible over the internet if required.

The earliest UK reference to flow measurement using the ultrasonic time of flight approach was found in a Patent Specification for an ultrasonic flowmeter submitted by Technical Ceramics Ltd of Ilford in 1957. The complete specification was published in 1960 (Patent No 856,415, published by The Patent Office) , and described how three transducers could be coupled to a computer to measure the flow rate in an enclosed pipe. One of the three transducers was mounted at 90^0 to the long axis of the pipe, and served as the 'control' for the other two which were mounted at an angle to the pipe wall, some distance apart. Acoustic pulses were then reflected in a zig-zag pattern off the pipe wall from one transducer to the other. The system operated on the 'sing-around' system whereby the acoustic pulse arriving at the second transducer triggered off the release of the second acoustic pulse. Even at this very early stage of development the company claimed an accuracy of 5% with the approach. The use of ultrasonics to measure flows in pipes has developed in tandem with open channel measurement, with Schuster (1975) reporting on advances made in Colorado, United States. One of the main uses of this technology has been for the measurement of flows in penstocks leading to hydro-electric stations, many of which were reported at a conference held on this issue in Montreal in 1996 (Biela and Marquez Santos (1996), Grego (1996), Levesque and Neron, (1996)).

The first identified paper to introduce the concept of using ultrasonics in open channels was published by Hess, Swengel and Waldorf in 1950. A number of papers were presented at the Sixth Hydraulic Conference at the University of Iowa in 1955 (for example, Swengel and Hess (1955)), and were followed by Fischbacher (1959 a, 1959b), Carter (1965) and Loosemoore and Muston (1969). The first published paper to appear in the UK was presented to the Annual General Meeting of the Institution of Civil Engineers in 1972 (Collinge and Herschy, 1972). It describes research and development work carried out by the Atomic Energy Research Establishment at Harwell (UKAERE Harwell) who were under contract to the Water Resources Board. This, and the work that followed, is also described in Green and Ellis (1974), Green and Herschy (1976), Herschy (1974, 1976a (a useful summary), 1976b), Herschy and Loosemoore (1974) and Loosemoore (1973). The research had been commissioned following the Symposium on river flow measurement held by the ICE at Loughborough University in 1969.

The Collinge and Herschy paper, which also includes an early description of the electromagnetic technique, introduces the underlying theory and principles associated with the ultrasonic time of travel method. Even at this very early stage it was recognised that '*for rivers having a large variation in stage a single pair of transducers will not be adequate and several pairs will be required*'. The early part of the investigations consisted of the installation of a single path gauge on the River Pang at Pangbourne, near Reading. It was installed upstream of a horizontal Crump weir in a 4.35 m wide channel. The transducers were installed at a height of 0.6 of the estimated modal depth; the velocity path was at 44^0 to the direction of flow, giving a path length of 5.97 metres. The use of a multiplexer enabled each transducer to serve as both a transmitter and receiver. At this early stage the flows were calculated on a daily basis, and no correction was made for the varying cross-sectional area of the channel, leading to the introduction of consistent (and acknowledged) errors in the derived flows. Despite these limitations, the resulting daily flows recorded between April and June 1971 were all within 11% of those measured over the Crump weir.

The success of the early studies at Pangbourne led to the programme being extended to include larger rivers. A single pair transducer system was installed in the River Thames at

Sutton Courtenay near Abingdon in January 1973. The channel section was 37 metres wide, and had an average depth of 2.25 metres. Fluctuations in stage were known to be small for more than 95% of the year, and it was thought that 'normal' fluctuations in stage would not measurably affect the channel velocity across the path length. The transducers were installed at 60^0 to the direction of flow, and were mounted on moveable carriages which enabled a vertical adjustment of up to 2 metres to be made. (It is perhaps worth noting that, even at this very early stage, the potential commercial benefits of the equipment were being identified: an estimated cost of £10,000 for a single path gauge was compared to capital costs of £60,000 for a Crump weir, and UKAERE Harwell were beginning to market their 3095 gauge).

The Sutton Courtenay gauge initially calculated flows over a 15-second interval every 15 minutes. However, close examination of the recorded data showed an unacceptable degree of scatter which was attributed to pulsations in the river flow. Increasing the measurement interval from 15-seconds to three minutes reduced the scatter to within acceptable limits. The ultrasonic gauge flows were compared to eight gaugings derived by boat gauging using a bank of five Braystoke current meters over a three month period; a pair of current meter arrays were also deployed permanently in the river, and their readings recorded every minute by a camera. Each complete gauging took between 2 ½ and 3 ½ hours to complete.

The ultrasonic gauge was used in a similar manner to the current meter, with three sets of 3-minute readings being taken at 0.2 metre vertical intervals up the water column. In general, a total of seven different sets of ultrasonic velocity readings were taken through the channel cross section. Comparison of the ultrasonic 'gaugings' to those obtained with the Braystoke showed that there was good agreement between the two methods. The maximum deviation was 7.6%, within the uncertainty associated with the current meter gauging, and the mean deviation from nine 'matched pair' gaugings was 2%. One additional feature noted from the comparison between the conventional current meter and the ultrasonic method was that, due to the very low discharges that occurred at the time of the evaluation, the ultrasonic method was able to measure river flow at times when it was not possible to deploy current meters as the velocities were below the minimum speed of response of the current meters.

Having demonstrated that the ultrasonic gauge was able to accurately measure both river velocity and flow at Sutton Courtenay by altering the height of the transducer path, Herschy and Loosemore (1974) extended the analysis of the recorded data to try and determine the most appropriate position in the vertical plane to deploy the transducers. This was done in the following way:

- d/D was calculated for each ultrasonic gauging, where
  d = depth of transducer from water surface
  D = total depth of flow at any stage

- C_l was calculated for each ultrasonic gauging from Q/Q_l, where

    Q = average discharge for each gauging

    Q_l= discharge calculated from the data collected along the velocity path at d/D
- For each gauging values of d/D were plotted against the resulting C_l values, as shown in Figure 2.3 below.

This figure was then used to determine the optimum level of d/D by reading across from the C_l value of 1.0. It was found that the most appropriate position appeared to be at a value of d/D of 0.641.

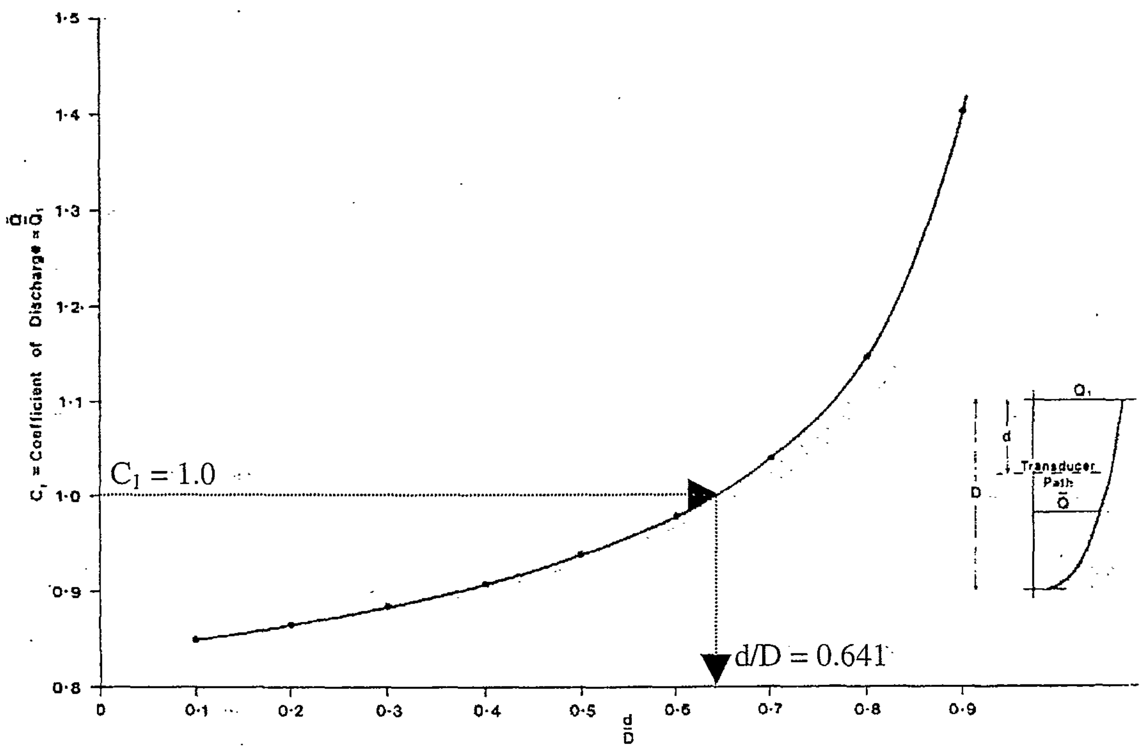


Figure 2.3 Curve of d/D values plotted against corresponding values of C_l where C_l = the average discharge for the ultrasonic gauging (Q) divided by the discharge calculated from the respective d/D value (Q_l). (After Herschy & Loosemoore, 1974). (Note: this figure was derived from the average of 15 different ultrasonic gaugings - the original paper demonstrated that the curve was representative of all but one of the gaugings)

The analysis was then extended even further to examine the variation of C with stage, where

C = actual discharge/measured discharge

Values of d/D were obtained for different values of D; these were then entered into Figure 2.3 to obtain corresponding values of C. The resultant values of D and C were then plotted, with the mean stage over the recorded period having a C value of 1.0. The analysis showed that for 95% of all recorded river levels the C value was within ±2.5%. This tolerance increased to a maximum of 11% at a stage equivalent to when the river spilled out of bank, approximately at the level of the mean annual flood.

The conclusion taken forward from this analysis was that if vertical velocity (or discharge) curves were established at similar single path ultrasonic sites this approach could be used to determine the most suitable level at which to deploy the transducers. However, it must also be remembered that this was based on the assumption that the aim was to accurately measure the modal flows, and was based on analysis from a site where there was a limited range in stage variation. These conclusions were then tested at two further UK sites, both of which had a single path system installed (Green and Herschy, 1976). The sites were at Knapp Mill on the River Avon and Kingston on the River Thames. At both sites the transducers were mounted on a vertical carriage, and it was found that, as with the Sutton Courtenay studies, the ultrasonic flows were in close agreement with those derived by more conventional means.

Further afield, Smith (1969, 1971, 1974) has also reported on the deployment of single path systems in **very** large rivers, most notably the Columbia River which, in terms of discharge, is the third largest river in the United States (mean annual flow in excess of 5,000 cumecs, maximum recorded flow thought to be 35,000 cumecs). The catchment is highly regulated and effectively consists of a cascade of lakes and dams, with the backwater from each dam extending upstream to the toe of the next structure. Consequently, due to the very deep and slow moving water current meter gauging was found to be unsuitable, and an ultrasonic gauge was installed at The Dalles in 1969. At this point the river has a maximum width of 450 m, and a depth of 37 m. With such a large channel it was difficult to find a viable reference to which the ultrasonic data could be compared. Consequently, an analysis of the theoretical uncertainties associated with the approach was undertaken, which produced a combined uncertainty of ±5.5%. A rating curve was established after only one year of operation, and subsequent data have confirmed that gauged flows are within ±5% of this, confirming the dependability and stability of the system in large rivers.

Both the Sutton Courtenay and Dalles studies were carried out in channels which had a similar depth:width ratio (0.06 and 0.08 respectively). Botma and Klein (1974) describe studies undertaken by the Delft Institute in Holland in rivers with a much lower ratio, typically less than 0.02. This work was started as early as 1958, but initial studies came across a number of problems associated with the technology behind the transducers. These problems were overcome in the early 1970s, and a new gauge was installed on the River

Nord near Ablasserdam. This had two diagonal velocity paths, both deployed at the same level. The first was at a wide angle to the direction of flow to give a coarse velocity reading, whilst the second was at a narrow angle to the flow to give a fine reading. The Netherlands research studied several known problems associated with the ultrasonic approach, including vertical salinity or thermal gradients bending the acoustic signal, and water velocity gradients causing divergence of the path. Botma and Klein concluded that the velocity path should be kept as short as possible, preferably mid-depth in the vertical section to avoid interference from the surface or river bed, and that non-homogeneous water bodies should be avoided.

Much of the work described thus far formed the main focus of a symposium on river gauging by the ultrasonic and electromagnetic methods held at the University of Reading in 1974. The symposium was hosted by the Water Research Centre and Department of the Environment, Water Data Unit. Single path systems had formed the main focus of early research and development throughout the world, and as a result the majority of the presentations were concerned with this. However, the formal discussion that closed the symposium contained many useful points, particularly with reference to how the technique could be taken forward in a pragmatic way for day to day use at 'typical' gauging stations. A significant amount of the discussion was concerned with site selection and the method of mounting the transducers, the general consensus being that it was not always necessary to spend large amounts of time and money on engineering works associated with the gauge installation, and that acceptable results could be obtained with less costly installations provided a suitable channel reach was chosen.

Discussion also focused on different methods of conveying electrical signals to the far bank, with one speaker suggesting that for large river installations this was the biggest single factor in determining the cost of gauge installation (up to $25,000 at 1974 prices). There was general agreement that either cableway or in channel approaches were most common, although Plessey were undertaking some trials using radio systems (these would require a separate power supply to each side of the river).

A number of limitations to using the equipment were also discussed, the main ones being signal attenuation due to aeration and/or sediment load. USGS data suggested that for each 20 mgl^{-1} in sediment load there was an increase of 20dB in the attenuation of the sound signal, although it is not known over what path length these data were collected. Further problems were also described with reference to the detection of the direction of flow, particularly in tidally influenced channels, and with the depth of water required for wide channels.

Whilst the majority of these discussion points all related to the studies already completed with single path gauges, it is apparent that multi-path gauges were beginning to emerge as the next stage in the development of the ultrasonic method. Whilst it was accepted that multi-path instruments should not be regarded as a panacea for all situations, particularly when intelligent use is made of current meter surveys or occasional scans of the vertical velocity distribution by moving the transducer paths, a number of speakers at the symposium outlined their plans for future work using multi-path systems in rivers of differing sizes. For example, Herschy and Loosemoore (1974) listed 23 possible sites for study in the UK, including several that have subsequently had multi-path gauges installed and one (Walcot on the River Tern) that was used for this R&D Project.

The next five years saw a rapid expansion in the ultrasonic gauge network and by the end of 1978 a total of 19 ultrasonic gauges had been installed in the UK, of which two were multi-path installations (Ashleworth on the River Severn and Blackwell Bridge on the River Rother). The location of all 19 sites is shown in Figure 2.4.

This dramatic increase in gauges was the main focus of a seminar hosted by WRc and the DoE Water Data Unit at Reading in March 1979. A total of 18 papers were given by authors from Britain and abroad. The papers covered a wide range of topics, including presentations by alternative manufacturers to Harwell (Mackenthun, 1979) and a comparison of this equipment to the Harwell gauge (Critchley, 1979), together with a paper describing how Plessey planned to manufacture and distribute the Harwell gauge under licence (Cunningham, 1979). Other papers described the results of the ongoing research using single path gauges, with Herschy (1979a) outlining site selection criteria, and Mander and Child (1979) describing how single path gauges could be calibrated. However, whilst it might be argued that these papers were along similar lines to those which had previously been published, the majority of the publications arising from the seminar reflected two general themes:

1. Recent advances in the ultrasonic gauges;
2. Observations and lessons to be learnt from the recent expansion in the number of gauges.

In the first of these categories, Davis (1979) and Henderson (1979) reported on the calibration and evaluation of the two multi-path gauges installed at Ashleworth and Blackwall Bridge. Dutang and Cheze (1979) described how multi-path gauges were being used as part of the water resource management system in France, whilst Schmidt (1979) presented a paper on gauges that used a combined multi-path and crossed path configuration in the Netherlands.

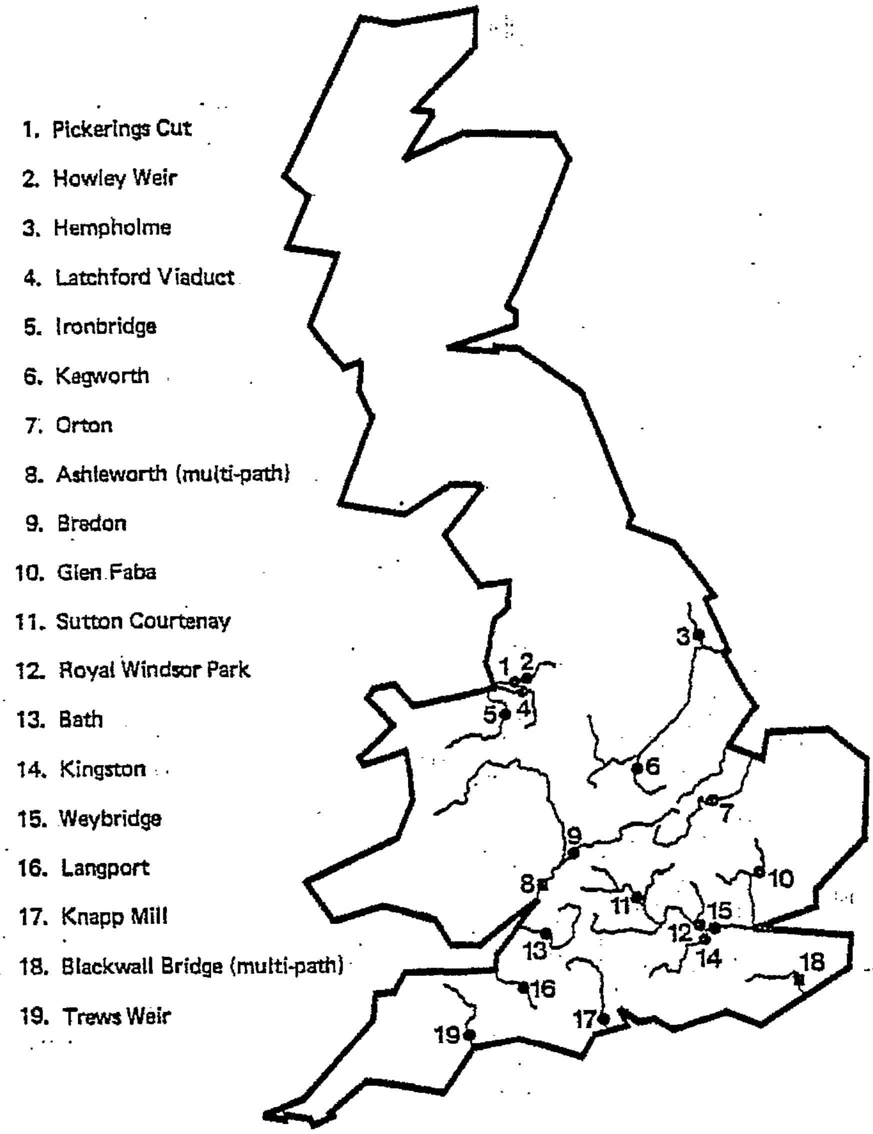


Figure 2.4 Location of the 19 ultrasonic gauge sites that had been commissioned in the UK by December 1978. Source WRc/DoE WDU ultrasonic river gauging seminar December 1979.

Many of the papers which concerned the more practical aspects of ultrasonic gauge use were presented as support papers to the seminar. Herschy (1979b) described the theoretical uncertainties associated with the use of ultrasonic gauges, and argued that whilst care should be taken in their commissioning, multi-path gauges should not require the same degree of calibration as single path units. Two authors (Green, 1979 and Weston, 1979) presented papers that described the difficulties associated with the measurement of the path angle, and the uncertainties that this introduced. Cole (1979) described the effects of temperature and salinity gradients, whilst Headey (1979) addressed the issue of tidal backwaters.

Perhaps the most interesting papers to emerge from the seminar, certainly in influencing future developments and adoption of the ultrasonic gauges into the UK hydrometric network, were concerned with the operation and maintenance of the gauges, and the processing of the data produced by the gauges. Lees (1979) described a system for processing the ultrasonic gauge data, and during the discussion session that followed the symposium it emerged that one of the weak links appeared to be the dependency on punched tape recorders. Many delegates argued that the priority should be to collect as much data as possible from the gauges, not least so that as analytical methods improved the data could be retrospectively processed if necessary.

Walsh (1979) described in some detail the numerous problems that had been encountered with the use of three Harwell gauges on the Rivers Weaver and Mersey and on the Manchester Ship Canal. Faults experienced with the equipment were "numerous and varied", the most serious of which involved the failure of the temperature controller for the electronic cabinet. Site location had also caused some problems, including weed growth, silting up and surges caused by canal traffic. Walsh also voiced concern about the future maintenance of the equipment, particularly as the gauges were already being superseded with newer, commercially produced instruments.

The issue of gauge maintenance was the subject of the paper presented by Rowse (1979) of the Water Data Unit. He listed the various tests that should be carried out during routine visits by hydrometric technicians, and described in detail the qualifications that a suitable maintenance engineer should have (including a degree in physics with a specialisation in electronics, or similar). There is little doubt that this paper reflected the nature of the work that had been completed thus far, particularly on the Harwell gauges. However, and in contrast to this, Stuart Walker of the Severn Trent Water Authority expressed several opinions in conflict to this in a post-seminar contribution that was also published in the proceedings. His views can be summarised as follows:

1. There is no such thing as a 'standard' gauging station because there is no such thing as a standard river. Consequently, whilst there was a need for the standardisation of the equipment, this should not affect its versatility, both in terms of price and configuration.
2. His preferred system would be multi-path, with the option of crossed paths if necessary.
3. Gauges could be made more reliable by the adoption of duplicate level sensors and data loggers, with the secondary system having a battery back-up if practicable.
4. Instruments should display a small quantity of past data on site. In addition to enabling system monitoring on site, this would also enable the 'single shot' transfer of a whole day's data by telemetry.
5. Finally, and in contrast to the views expressed in Mr Rowse's paper, Walker stated that a system that was dependent on 'the availability of a high grade electronics technician for its

security will not be widely attractive'. Instead, effort should be made to find a middle ground solution that enabled the hydrometric field technician to undertake preliminary analysis and assessment on site.

Whilst the benefit of hindsight might suggest that these views were rather obvious, it would appear that developments over the next two decades did follow the route suggested in these five points. The 1979 symposium perhaps represented the turning point in the development of the ultrasonic approach - prior to this date the majority of the work had been completed by research institutes. The presence of a large number of representatives from the various water authorities and river purification boards at the seminar indicated that the approach was of widespread interest to the hydrometric community, and signalled what might be considered to be a period of 'market led' development. Unfortunately, this shift towards practical implementation of the gauges appears to have been accompanied by a reduction in the number of published papers on the issue. In order to redress this, Jim Waters has provided an account of how the network of ultrasonic gauges has evolved in what is now the Midlands Region of the Environment Agency. This starts at the point where the 1979 conference left off, namely the multi-path gauge at Ashleworth.

From a users perspective the Ashleworth gauge provided a useful insight into the things to avoid when selecting a site for an ultrasonic gauge. Although multi-path, it was single direction and was positioned just downstream of a bend which introduced skew flow. The skew flow was itself a function of velocity, and no constant correction factor could be determined to correct for this. The site also had a highly mobile bed which therefore led to a very unstable cross-section. The site was tidally influenced and, with virtually every flood tide, all the transducer paths failed due to the high sediment load.

By this time the Region had also attempted to evaluate the Krupp-Atlas gauge which had been reported on at Reading (Critchley, 1979, Mackenthun, 1979). The equipment was installed at three sites between 1975 and 1978 but, due to a variety of reasons which included vandalism and damage from pleasure boat traffic, the tests foundered. As Waters describes it "*little had been learned about the equipment, but a great deal learned about the hazards of evaluation exercises*" (Waters, *pers. comm.*). At the same time this work was in progress, two further Harwell single path gauges were installed on the River Soar at Kegworth and the River Avon at Bredon. Whilst the gauges performed well, and continued to operate into the 1980's, it was acknowledged that the positioning of the transducer path at 0.6 of the depth was the key problem, particularly at sites where there were significant fluctuations in level.

By this time Harwell had effectively passed over the manufacture, supply and maintenance of their single path gauges to Plessey, for whom the market was perhaps too small and static. This led to the emergence of Sarasota Engineering Co, (Sarasota) acquiring the rights to develop an inproved multi-path gauge and, between 1982 and 1984, three new multi-path gauges were built at Bewdley and Buildwas on the River Severn and Derby on the River Derwent. Each of these sites will be dealt with in turn.

Bewdley was installed with a reflector system to prevent potential vandalism on the far bank. The reflector system itself worked well, and initially the system appeared to be perfect, with flows derived by current meter and ultrasonic gauge being in close agreement. However, as flows fell below 1200 Ml/d the gauge output began to differ from the current meter gaugings. This difference increased as river flows reduced. Extensive tests were carried out on the equipment, and numerous velocity profiles were recorded by current meter over the next few years to try and resolve this problem. Eventually it was found that the presence of a diagonal gravel shoal upstream of the site was the cause which, under low flow conditions, caused the river to flow in a sinusoidal path through the measurement reach - at higher flows the effects of the shoal were drowned out. The problem was resolved by rebuilding the gauge on a conventional cross-path system.

Both Buildwas and Derby were built with a cross-path configuration but, rather than having two paths crossing at the same level, the paths were interleaved. This resulted in an odd number of operational paths for 50% of the time which, if skewed flow is present, will introduce a bias into the measured velocities. Other lessons learned at these sites were associated with the degree of engineering associated with the transducer mountings. The gauges were originally most strongly engineered which meant that when transducers failed, which was then a more frequent occurrence than it is now, it was a major task to replace them. To overcome these problems both gauges were reconstructed using more lightweight materials and in a conventional cross path configuration.

Additional gauges have since been built at a large number of sites, including Darlaston, Saxons Lode, Shardlow, Pillings Lock, Deerhurst, North Muskham and Montford, together with the replacement of the single path gauges at Bredon and Kegworth. An electromagnetic gauge was also replaced with an ultrasonic gauge at Bescot in 1988. The majority of these gauges were of conventional crossed multi-path configuration. One the whole the gauges have proven to be most successful, the most notable exception being Darlaston where one set of transducers were mounted into a set of concrete steps. Unfortunately the steps had no foundations, and were washed into the river, leading to their replacement with a more conventional sloping array. At Pillings Lock the technology was once again stretched further with the ultrasonic river gauge being accompanied by two velocity measurement points in the flood plain. Little useful data has been collected thus far from these velocity meters.

Whilst the majority of the ultrasonic gauges in the Midlands Region have been installed in fairly large, deep and often navigable rivers, the technology has also been used at other sites.

In 1991 two gauges were deployed in culverted sections of the Rivers Leen and Erewash. Attempts were made to bounce the signal off timber and then steel reflectors mounted on the culvert walls but proved to be unsuccessful and the gauges were re-commissioned to the tried and tested line of sight configuration.

Finally, the Region have also installed a Peek/Sarasota 1408 twin path gauge on the River Poulter at Twyford Bridge. The site had previously had a Crump weir but subsidence due to coal mining had ensured that this was non-modular even during low flows. The gauge was installed on the existing wing walls, initially on a trial basis, but performance was such that it has since become a permanent installation.

2.3 Technical specification of the Project equipment

The original tender documentation for the Project stated the expected capabilities of the portable ultrasonic gauges that were to be used for the field studies. These were as follows:

1) The equipment should be portable, capable of being installed at a number of sites over a period of time; installation should be simple.
2) It should be capable of running from 12v battery power alone.
3) Under battery power it should be capable of recording level, velocity and calculated flow at a minimum of every 15 minutes over a period of not less than 1 week.
4) Measure at least two velocity paths and one water level.
5) Record actual velocity and water level/depth measured.
6) Ability to calculate and record estimated flow.
7) Resolution and accuracy of data stored on logger shall be within +/- 0.05% of the measured range.
8) The system was to be able to smooth/integrate spot readings over time.
9) Output format of data retrieved from logger was to be compatible with analysis software currently in use by the Agency (ie Hydrolog and spreadsheets).
10) The gauge should be capable of operating completely independently of any other equipment at a site.
11) Equipment and housings were to be robust, suitable for re-use, and suitable for UK climate conditions (temperature -20 to +50 ^{0}C, and relative humidity 70-90%).
12) Equipment to be suitable for a range of site conditions, including operation without a stilling well and remaining accurate over a wide range in water levels.

This specification was sent to the suppliers, following which it was decided to use two Sarasota/Peek Ultrasonic 1408 Open Channel Flow Meters. The SWS tender proposal was made on this basis. The full technical specification of this equipment is contained in Appendix C. Chapter 3 provides a full description of the equipment that was purchased, and the mounting systems that were designed for the Project.

One notable 'unusual' component of the equipment used for the Project relates to the logging of the data from the gauge. Rather than use propriety dataloggers and software, Psion IIs were used together with software developed by the Thames Region of the Agency. Together with a modified set of EPROMS for the 1408 gauges, this allowed the logging of 1-minute values of depth, path velocity and computed flow at 15-minute intervals.

2.4 Potential limitation - fisheries acoustics

As section 2.2 has described, the majority of ultrasonic gauge installations have been undertaken in large, deep rivers, many of which are navigable. The advantage of the ultrasonic approach to more conventional methods such as weirs and flumes is that it is non intrusive. However, whilst this may be the case for the physical movement of a body *through* the water, some concern has been expressed that it may actually affect bodies *within* the river, namely fish. The majority of research work that has been completed on fisheries acoustics related to the marine environment, and includes studies on fish as different as cod, dolphins and killer whales. Studies that have been completed on freshwater fish indicate that, in general, fish are not affected at frequencies above 1 to 1.5 Khz. As the majority of ultrasonic gauges use transducers ranging from 200 to 1000 Khz they clearly present no barrier to the movement of these fish. However, Peter Gough of Welsh Region has reported that there is one exception to this, the Twaite Shad. This has been found to actively avoid frequencies up to 200 Khz, although it is not affected by frequencies as high as 420 kHz. Although this fish is thought to occur in only four rivers in the UK, all within Wales, (Severn, Wye, Usk and Towy), it does highlight a potential limitation to using the equipment. The transducers used for this project were, with one exception, all of a frequency of 500 Khz or more.

3 GAUGE INSTALLATION AND COMMISSIONING

3.1 Introduction - the field sites

A total of six Environment Agency gauging stations were used as field sites for the Project, located in the Midlands, Welsh, North West and North East Regions (Figure 3.1). Full details of the work undertaken at each site, together with the individual results, are contained in the Site Reports contained in the Project Record. Appendix B to this Technical Report contains summary site data sheets, and Figure 3.2 shows a photograph of each site.

The sites were chosen for a variety of reasons; some were to enable specific Project objectives to be assessed whilst others provided a more general evaluation of the equipment and methodology at 'typical' sites. This chapter focuses on the practical aspects of using the equipment, particularly the installation; later chapters will incorporate the results of the field studies in assessing the different methodologies. Table 3.1 provides an overview of the different sites and summarises the work that was completed at each station.

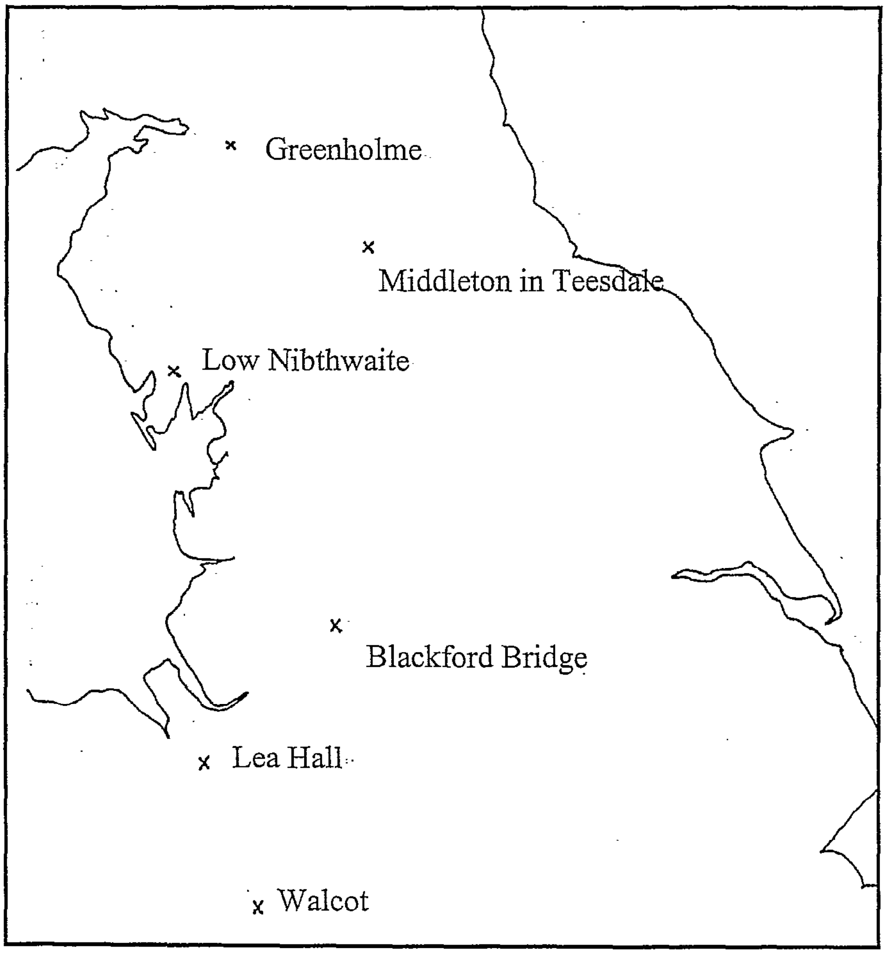


Figure 3.1 Location of the six gauging stations used as field sites for the Project.

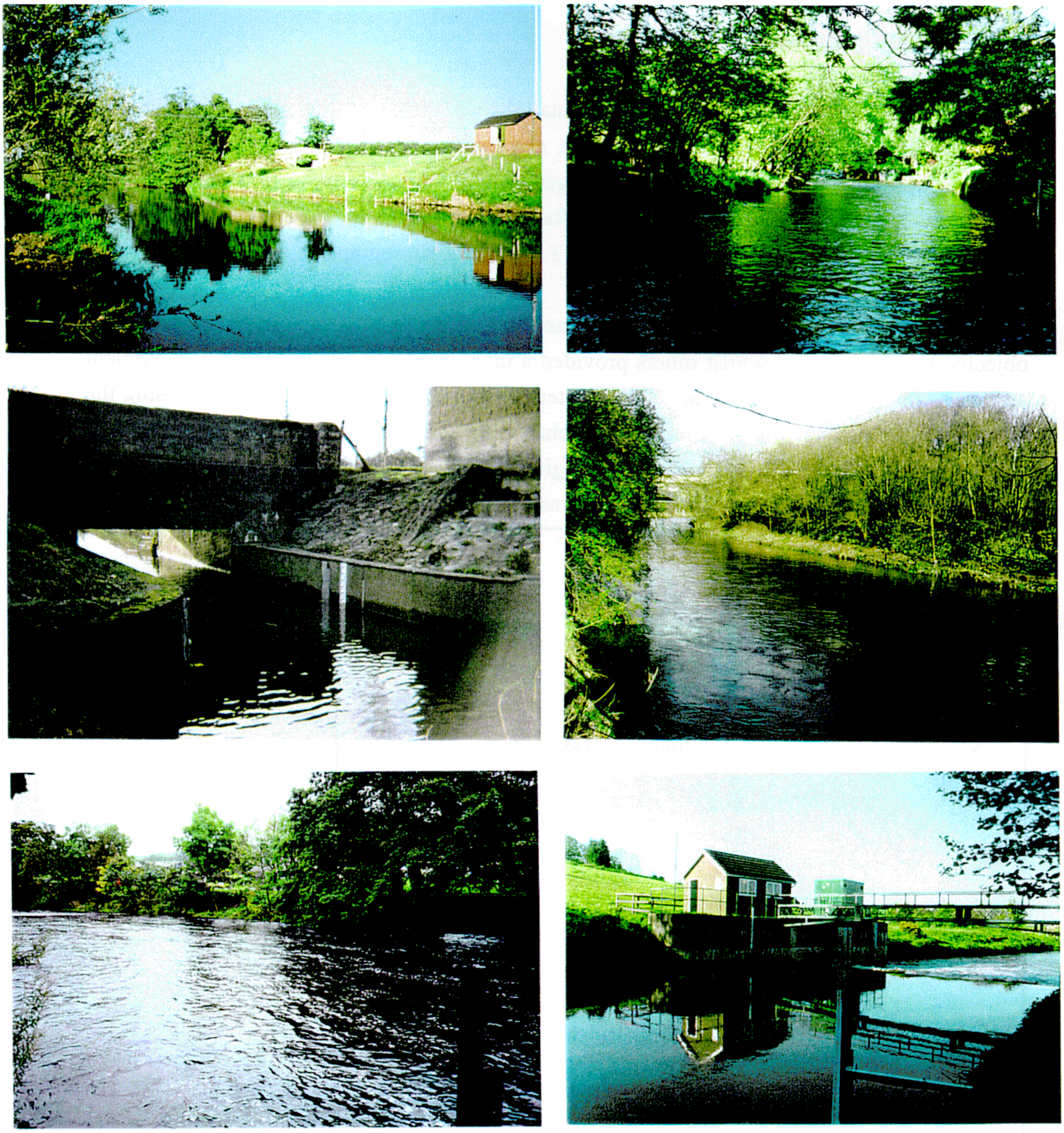


Figure 3.2 Photographs of the six sites used during the Project. Clockwise, from top left, the sites are Greenholme (under low flow conditions), Low Nibthwaite (typical flow), Blackford Bridge (high flow), Walcot (typical flow), Middleton in Teesdale (high flow) and Lea Hall (totally backed up).

Table 3.1 Summary of work completed at each of the six field sites.

Station & location	Site description and characteristics	Summary of work
Greenholme River Irthing, North West	Open channel site with informal flat V weir downstream of station. Wide range in levels and flows, well gauged by Agency. Non-modular flows occur. Channel c. 22 m wide	Transducer paths operated at 6 different levels over 5 significant events. Depth transducer in river channel. Battery power installation.
Low Nibthwaite River Crake, North West	Open channel site downstream of Lake Coniston. Artificial channel with vertical side walls. Channel c. 9 m wide	Very limited range in levels during study. Two sets of transducer paths operated in cross-path configuration with two types of transducer. Battery and mains power installation.
Lea Hall Allcot Brook, Welsh	Fibre glass Crump weir in narrow channel, vertical wing walls and level river bed. Limited gauging, with good theoretical rating but very badly affected by backing up from the River Dee. Channel c. 3 metres wide	Unsuitable for deriving a single stage-discharge rating due to backing up. Transducers operated at eight different levels during one event. Reflector trials undertaken. Mains power installation.
Walcot River Tern, Midlands	Concrete flat V weir with high (3 metre) vertical wing walls. Operational crest tapping with flushing system to correct for non-modular conditions, which arise due to both high and low flows. Agency also rates site by current metering upstream of section.	Transducers operated at 10 different levels over a wide range in flows. Modular and non-modular flows derived. Reflector trials undertaken. Mains power installation.
Blackford Bridge River Roch, North West	Open channel site with poor rating, located on slight bend in river upstream of large crescent shaped mill weir. Catchment is highly urbanised, hence dirty river. Flows can rise rapidly during spates Channel 25 m wide.	Transducers operated at five different levels during a number of significant flood events. Different means of routeing cables across river evaluated.
Middleton in Teesdale River Tees, North East	Wide, open channel site with non-Standard flat V weir control. Good rating by current metering throughout majority of range. River is very quick to rise, and range in levels is high (>3 metres). Channel 23 m wide.	Transducers operated at three different levels over many flood events. Different frequency transducers (two types) tried due to site conditions.

It is recognised that in using only one type of gauge for the Project there is an inherent risk that any results will only relate to that equipment. The terms of reference for the Project stated that, where possible, the findings should be suitable for general application and should not be related to a specific gauge. Any results which apply only to the Peek equipment have therefore been summarised in Appendix D.

3.2 Gauge installation

3.2.1 Site survey

ISO 6416: 1992 (E) provides specific guidance on site selection (in section 2.5) and the site survey (section 2.6). Factors to be considered include channel geometry and stability, weed growth, water temperature gradient, sediment load, water density/salinity, air entrainment and background electrical noise. It is assumed that the reader will familiarise themselves with this section of the Standard before deciding whether or not to install a gauge at a particular site. In cases where background electrical interference is suspected it may be necessary to seek advice from the gauge manufacturer before making a final decision (note that a site visit from the manufacturer is likely to be at a cost to the user).

For the purposes of the Project all sites received at least one initial survey before deciding to install the equipment; more than twenty potential sites were surveyed in this way before the final selection was made. During the initial survey the river channel was inspected up and downstream of the section to be gauged, usually by walking up and down the channel itself with a surveying staff to obtain a 'feel' for the depth and uniformity of the river bed. ISO 6416: 1992 (E) advises that this survey should extend for as much as ten river widths upstream, and two downstream, of the section to be gauged.

As the Project was to evaluate the equipment over as wide a range of flows as possible, particular emphasis was placed on the channel depths, especially close to the river bank. Under ideal circumstances the banks would be vertical, with a uniform bed level; in reality this was only the case at one site (Lea Hall), with other sites having more typical conditions of shallow depths adjacent to the bank and deeper conditions in the centre of the channel.

Once the sites had been selected each one was then surveyed more accurately using levelling equipment. At the first of the field sites (Greenholme) this survey was limited to three cross-sections; one along the line of the transducer path, and two opposite the two transducer racks. As analysis of the Greenholme data showed that the performance of the gauge in determining flows was sensitive to bed levels. Following this the channel survey was extended to include an additional cross-section mid-way between the two transducer racks, as shown in Figure 3.3.

There is a need to differentiate between the resolution needed for the two different types of survey. The initial survey provides an indication of bed conditions, and helps in selecting the optimum channel reach for installing the equipment. Once this has been identified, the detailed survey is then used to determine the parameters needed to calculate the flow.

The ISO Standard specifies that studies of velocity profile distributions should also be made prior to installing the equipment, particularly if a single path configuration is to be used. Prior to the start of the Project it was agreed that this would not be undertaken at any of the study sites as the gauges were being used to collect velocity data from as many different levels as possible. One of the reasons the Standard gives for recommending that velocity profile studies are undertaken is because of their importance in enabling the gauge to work effectively under low flow conditions. However, at higher flows (the main focus of this Project), the effects of boundary conditions diminish and the velocity profiles begin to 'standardise'.

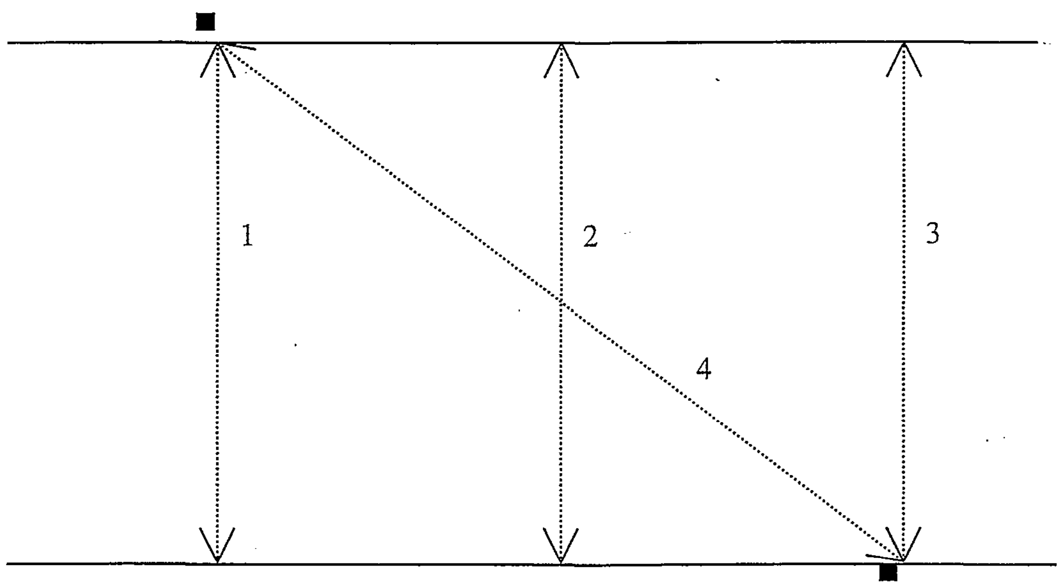


Figure 3.3 The four **recommended** cross sections that should be surveyed to establish the mean bed level for an installation where the transducer paths are along a single diagonal. Where a cross-path configuration is used **it is recommended** that a fifth section is surveyed along the line of the path of the second diagonal. Similar adjustments should be made for a reflector system.

Whilst velocity profiles were not undertaken, surveys of surface flows were made, both by current meter and through the use of floating polypropylene lines. The latter approach was particularly useful in determining the true direction of flow, and in confirming the uniformity of this. The technique was also used for determining some of the gauge parameters needed to calculate flow (see 3.3).

3.2.2 Mounting system

There are a number of different mounting systems available from the manufacturers of ultrasonic gauges; these include ramps, tubes and vertical towers. For the purposes of this Project it was decided to design and manufacture portable racks that would have the following properties:

- Straightforward to construct from readily available materials.
- Be light and portable to facilitate both transportation and installation.
- Be made of materials that were suitable for use in an aquatic environment whilst still being possible to work with when on site.
- Preferably be of a modular construction to ensure adaptability.
- Enable transducer paths to be operated at a number of different heights without having to realign the transducers.
- Where possible, enable transducer heights to be safely altered during flood events.

The final design of the transducer racks that were used for the Project at all field sites is shown in Figure 3.4, with Figure 3.5 showing one installed at Greenholme. They were made from standard profile aluminium sections, and assembled with grade 316 stainless steel bolts. Aluminium was chosen in preference to both stainless and galvanised steel due to the ease with which it could be worked and the lightness of the completed racks. It was possible to adapt the racks on site with nothing more sophisticated than a hacksaw and 12v cordless drill. For the quantities involved the aluminium was also surprisingly cost effective; a standard 1.2 metre rack assembly had a materials cost of approximately £70.

River bank installations

When installing the racks alongside a 'natural' river bank the first step was to push/drive the lower extension of the backing rack into the river bed using a sledge hammer, ensuring that the whole assembly was kept vertical. The rack was then braced by running lengths of aluminium (usually angle) back to the river bank and bolting these to stakes driven into the bank. By orientating the face of the backing rack at approximately 45^0 to the river bank it was possible to bolt these bracing sections directly onto the rack itself, as shown in Figure 3.4.

Only one 'natural' channel field site (Middleton) required more than this because of the nature of the bed and the high range in flows that were expected. At this site it was decided to install a mild steel pile, to which the backing rack could then be bolted. This, and two bracing stays, were concreted into the river bed as it was only possible to excavate a shallow hole due to the stony nature of the bed.

Despite prolonged exposure to high flows over a number of months all rack systems installed in this way survived intact for the whole of the study period, including those at Blackford Bridge where other aspects of the installation were subject to vandalism.

Artificial channel installation

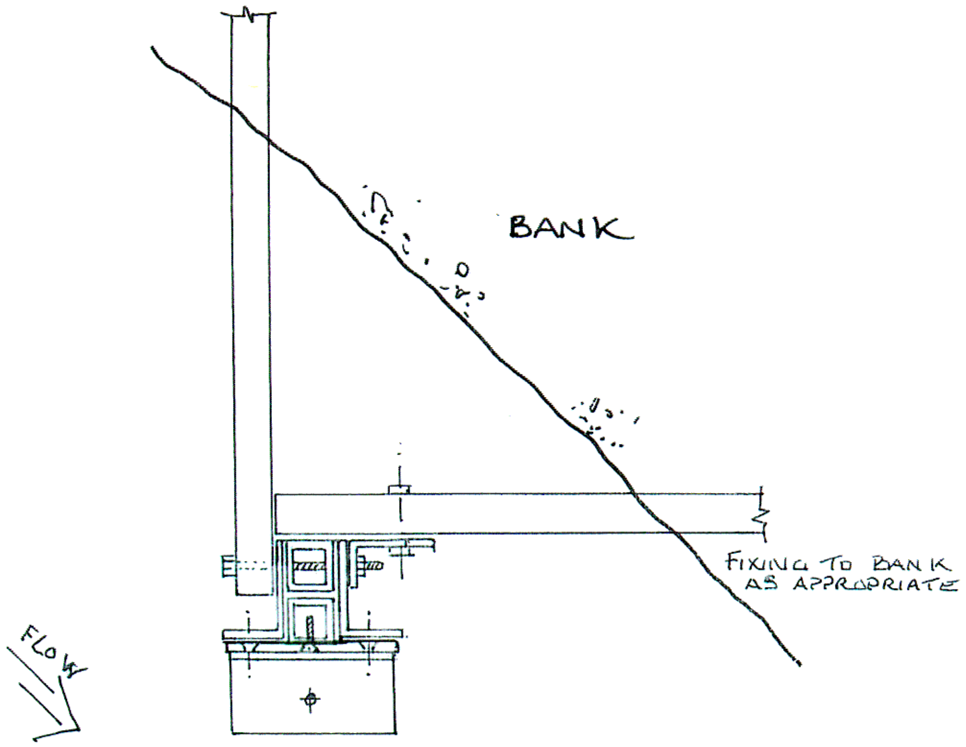
At two of the study sites (Lea Hall and Walcot) the transducer racks were mounted on to the wing walls of the weir structure. The same backing racks were used as in 'natural' channels, but these were adapted by having further sections of aluminium angle bolted on to enable direct fixing to the concrete structure (Figure 3.4). In such situations the back of the racks were parallel to the channel sides. At Low Nibthwaite the racks were mounted onto a stone wall which formed the sides of the artificial channel. Brackets were fabricated on site to which the backing racks were then mounted.

Only one of these installations was damaged during the study period, and that was when a canoeist used one of the brackets at Low Nibthwaite as a ladder to climb out of the river.

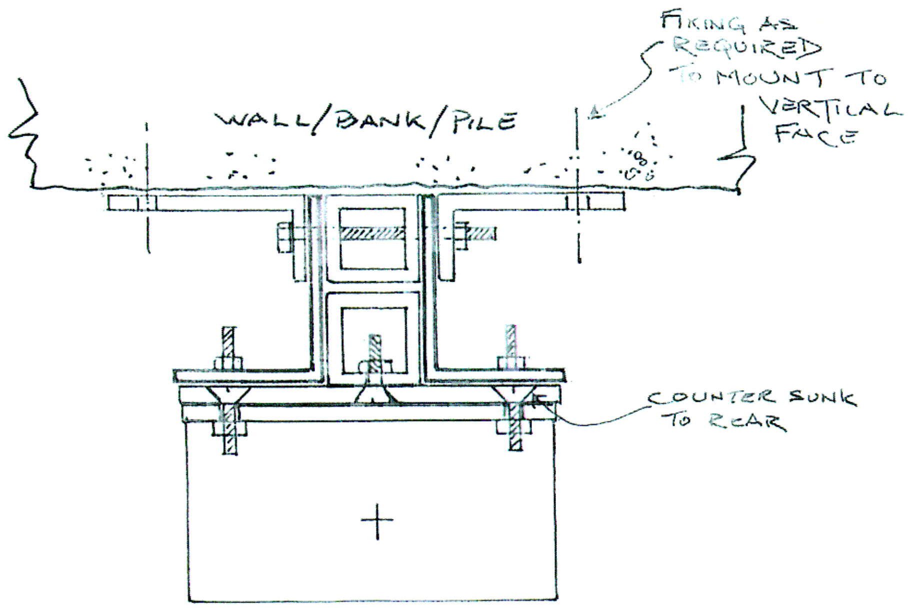
3.2.3 Transducers, alignment and cables

Three different transducers were used during the field studies, 250 and 500 kHz and 1 MHz, shown together in Figure 3.6. The 1 MHz units were used at Low Nibthwaite and Lea Hall, whilst the 500 kHz units were used successfully at all field sites. The 250 kHz transducers were only used at Middleton in Teesdale in an attempt to overcome repeated poor performance of the equipment at high flows, but with no success. (Table 2.1 gives guidance on the appropriate transducer frequency for differing channel widths)

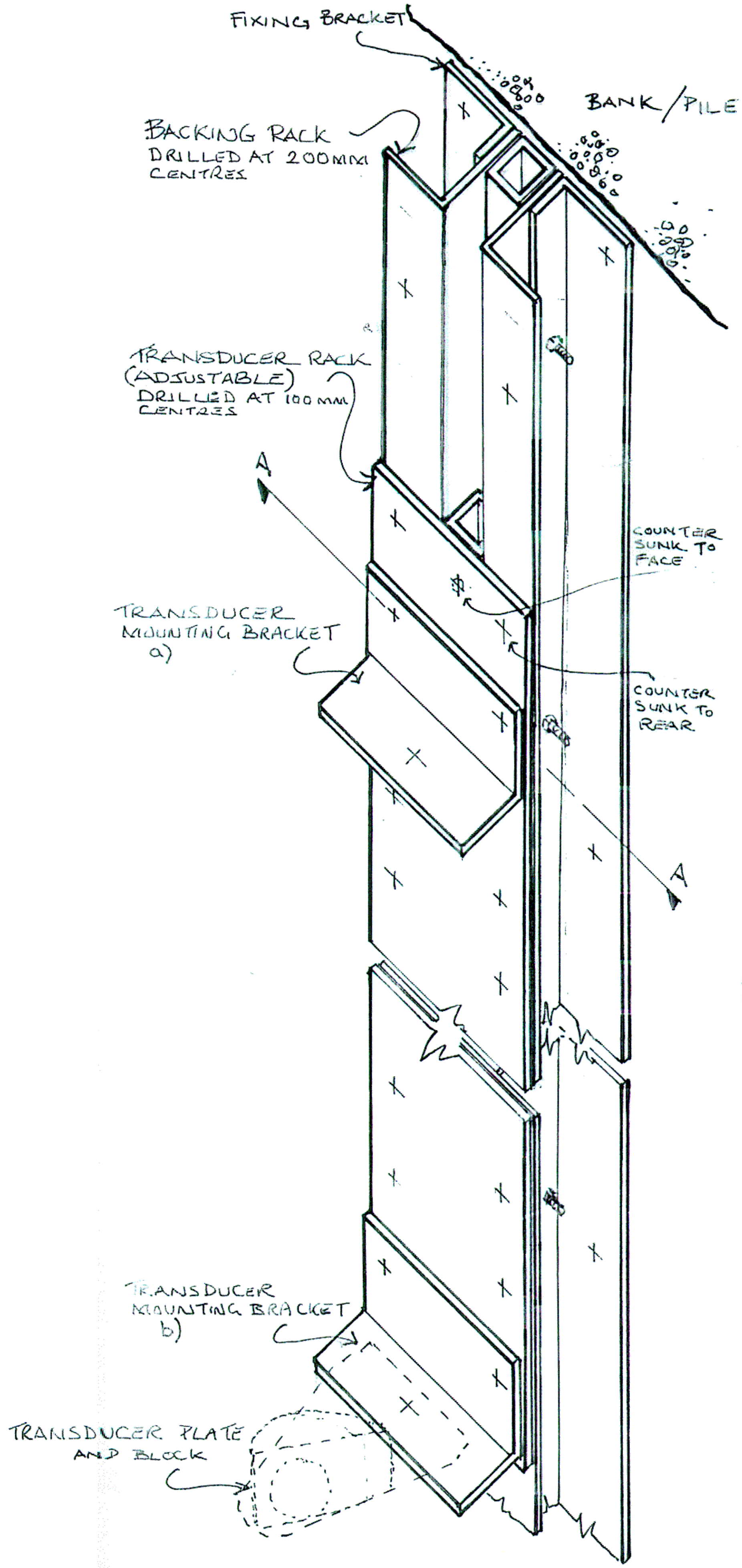
It is recommended that for general application purposes the 500 kHz transducers are used as the first choice with the Sarasota/Peek equipment at a new field site. The transducers worked in channels ranging from 3 to 30+ metres wide, and are thus suitable for use at the majority of the Agency gauging sites.



INSTALLATION DETAILS FOR NATURAL CHANNEL OR RIVER BANK



PLAN SECTION A-A
SCALE 1:2



TRANSDUCER MOUNTING SYSTEM
NOT TO SCALE

MATERIALS:-
STANDARD SECTION ALUMINIUM GRADE 6063T6

GRADE 316 STAINLESS STEEL BOLTS AND FIXINGS.

SIZES/BRACKETS CAN BE ALTERED TO SUIT SITE REQUIREMENTS.

TITLE: TRANSDUCER MOUNTING SYSTEM © 1999	
SCOTIA WATER SERVICES BELTON HOUSE WANLOCKHEAD	
CLIENT:	
SCALE: VARIOUS	REF:
DWN BY: A. CADD	DATE: 25.02.99

FIG. 3.4

Figure 3.5 Photograph of the upstream transducer rack installed at Greenholme.

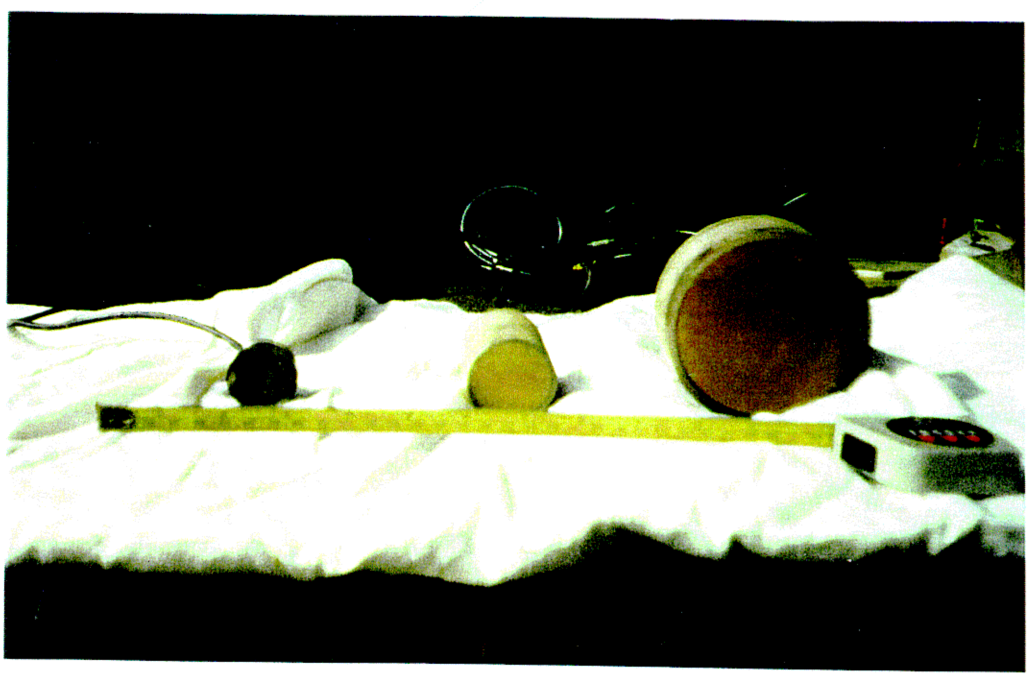


Figure 3.6 The different transducers that were used for the field studies. From right to left they are the 250 kHz, 500 kHz and 1 MHz units, measuring 100, 50 and 37 mm wide respectively.

Once both backing racks had been installed at a site the transducer mounting brackets were then mounted on to the transducer racks at the required spacing. These were then attached to the backing racks, with both brackets **above the water surface**. The transducer paths were then aligned by inserting a pipe of the same diameter as the transducers through the transducer mounting blocks, and rotating the block until the pipe pointed directly at the rack on the opposite bank. (Due to the large size of the 250 kHz transducers these were aligned by placing an engineering square across the face of the transducer itself, and lining this up with the opposite transducer.) **At every field site maximum alignment of the transducers was achieved by this method at the first attempt** (measured by the number of successful pulse counts on the gauge). Even when an oscilloscope was used to try and improve the alignment at both Greenholme and Low Nibthwaite it was found that the 'pipe approach' had achieved the optimum alignment.

Once the transducer blocks were aligned the transducers were installed and the racks lowered to the desired height. In the majority of cases the transducers had a short (typically 3 metre) length of co-axial cable terminating in a Fischer waterproof socket. These were then joined to the gauge transducer board, which had BNC plugs connected to short lengths of co-axial and Fischer waterproof plugs, by extension leads supplied by Peek which also had their ends terminating in Fischer connections. The connectors were subjected to relatively harsh conditions, being driven over, buried, dragged through conduit and brick walls, and dropped into rivers without their protective caps. They performed faultlessly over the three year field study period; not one connection failed, and all connections could be separated when the time came to remove the equipment. The connectors were certainly easier to work with than bare-ended cables that were then terminated with a BNC plug once the installation was complete; it was found that unprotected co-axial cables exposed to water were badly affected by water ingress, the damage affecting more than 30 metres of cable on one occasion. **It is thus recommended** that, where resources allow, the option of extension cables and waterproof plugs are used for portable installations. Current prices (1999) are £135 and £115 for 60 metre and 20 metre cables respectively.

One final point relating to the transducer cables regards the means of conveying the cable from the far bank transducer racks. Wherever possible this was done by means of a catenary cable, usually attached to an extension on a cableway tower where this was available. The cables were taped to a 4 mm galvanised wire rope which was secured to the far tower and then tightened by means of bottle-screws on the near bank, usually attached to the station wall. At both Lea Hall and Walcot it was possible to use bridges to support the cables across the river.

Due to the potential vandal risk the cables were all routed underwater at Blackford Bridge, both across and alongside the channel, which had an irregular bed. The cables were initially tied to galvanised steel cables which were in turn tied to or threaded through hollow concrete blocks. Following reports from hydrometric staff working at the site a number of visits were made to clear weed from the cables during the summer months of 1997 - it is estimated that almost 1 tonne of weed was removed on one of the visits. Despite these efforts the steel cables were eventually broken during a relatively minor event (believed to be in August 1997). All remaining cables and transducers etc were then removed for salvaging.

The coaxial cables were reinstalled in the river in October. Instead of using steel cables once more it was decided to use galvanised short link anchor chain to support the coaxial. 3/8" chain was used and was most successful, despite major events having occurred. The chain lay flat on the river bed and, despite the far end being cut by vandals some time between April and August 1998, was still intact and weed free when the gauge was removed in December 1998.

Whilst using the chain does present potential problems relating to manual handling legislation because of its weight, it was found that in practice it was much more straightforward to use than the steel wire and concrete block combination. By carrying the chain in a number of bins it was possible for two people to safely manhandle the chain from field vehicle to riverbank. Once on site, a catenary rope was then used to assist with pulling the chain across the river. A big advantage of the chain is that it lies flush to the river bed and can be pulled back upstream following major events which have caused it to 'creep' downstream a little. It should also be longer lasting than the steel cable should it be used for a permanent installation.

The depth transducers were mounted both in the open channel (Greenholme, Low Nibthwaite and Lea Hall) and in the station stilling well (Walcot, Blackford Bridge and Middleton in Teesdale). Both configurations worked well but had minor problems. Direct installation in the river (either at the base of one of the transducer racks, or on a separate post) provided the most consistent depth data, most likely due to having a homogenous water body above it rather than the potential thermal stratification and/or temperature lag that may arise with a stilling well installation. However, the transducer is more susceptible to vandalism and silting up, and does have to be installed as deep as possible to prevent multiple signals being returned during low flows. Whilst the stilling well installation is obviously more secure, and usually has a greater depth of water than that found close to the river bank, it was noted that consistent differences between measured and true stage were recorded. It is felt that these differences arose from two potential sources:

1. When the transducer velocity paths are not working the gauge assumes a velocity of sound, which is then used to compute the measured depth. Any differences due to

differing water temperature will cause an error in the measured depth; the magnitude of this difference will depend on the difference in temperature, so it is likely to be seasonal.

2. The same effect will occur when river levels rise, and the velocity path is submerged. Whilst the gauge may be able to calculate the true velocity of sound for the velocity paths, this may not apply to the water within the stilling well which is likely to take a considerable time to change temperature.

It is thus recommended that, where conditions allow, the depth transducer is mounted directly in the river channel. If this is not possible, or thought to be unwise, then the possibility of using an external source of depth measurement should be considered.

3.2.4 Power supply

Wherever possible the gauges were operated from a 240 volt mains supply in order to minimise any potential risk of gauge failure (the gauge is also able to operate from a 110v supply). The PSION II datalogger was also operated from a mains adapter, and no problems were encountered with this configuration.

At the start of the Project a number of options were suggested for further study, including solar power and alternative battery configurations to those recommended by the manufacturer. The Agency advised that their own 'in-house' technical staff already had sufficient knowledge in both of these areas, and it was thus decided not to include any assessment of additional options in the Project scope.

At Greenholme it was necessary to operate the gauge from an external 12-volt DC source as the station does not have a mains power supply. One of the objectives of the first season was to confirm that the gauges are able to operate for the specified period (seven days) from a 12-volt power supply. Peek recommended that 115 Amp Hour Gel Cells were used to power the gauges and confirmed that they would meet the specification. Consequently, four cells were purchased with the gauges for use on the Project.

The Greenholme studies confirmed that the gauges are able to operate for the specified period from a single 12-volt cell, but only just. The gauge was left for an eight day period during dry weather; when it was next visited the gauge had stopped and a significant part of the programmed data had been lost or, even worse, corrupted. This issue is discussed further in Appendix D. Because of this it became necessary to visit the sites on a six-daily cycle merely to change the batteries.

In addition to this, two other issues caused concern with the power supply. The first was one of portability - the cells weigh almost 45 kg and were very awkward to manhandle across rough terrain. The second is that whilst the single cells might satisfy the seven day requirement they only do this through deep discharging which will shorten their life-span. **It is thus recommended** that two 85 AH cells are used instead of the single 115 AH cell in the future; this will make handling much simpler and safer, lengthen the time between visits and prolong the life of the cells. For the purposes of the Project this problem was overcome by operating the gauge from two 115 AH batteries at a time, which allowed the maximum interval between visits to be extended to 12 days.

The Low Nibthwaite gauge was also operated from a 12-volt source, but in this case the battery was kept on a trickle charge via a Statpower Truecharge 10-Amp micro-processor controlled battery charger. Whilst this avoided the need to connect the gauge directly to the mains power, and ensured that the equipment would work for up to a week should the station have a power cut, it did introduce a major problem to the gauge operation at this site. When the equipment was installed considerable difficulty was encountered in getting the depth transducer to work accurately. More than three hours were spent with an oscilloscope trying to set the gain settings, but a satisfactory solution was not found throughout the entire monitoring period at the site. It was thought that the most likely source of the problem was an overhead cableway some 100 metres or so away from the site. It was only when this configuration was tried at another site that it was discovered that the problem was actually caused by the electrical interference arising from the battery charger which had been recommended and supplied by the gauge manufacturer.

It is thus recommended that this particular configuration is not repeated, but that the gauge is (preferably) operated direct from a mains power supply with the external 12-volt backup (in addition to the gauge's own internal battery) being installed on a 'use once only' basis before disconnecting prior to recharging.

3.3 Gauge Commissioning

3.3.1 Introduction

Clearly the main elements of commissioning any ultrasonic gauge will depend on the equipment itself. The 1408 was remarkably straightforward to set up, with the Peek manual providing guidance on most of the key issues. The majority of the parameters required by the gauge are determined by either physical survey or physical constraints relating to the study site. However, there were three parameters which merit further comment, and which are likely to affect equipment from other manufacturers: bed levels, minimum cover and the direction of flow. Each of these parameters, together with the other gauge information, is programmed into the gauge via a laptop computer on site.

3.3.2 Bed level and bed correction factor

Section 2.1.3 explained that in order to calculate the flow the gauge needs to know both the cross sectional area of the gauged section, and the ratio between the mean velocity of the lowest transducer path and the flow occurring in the lowest slice of the cross section. Two parameters are used to assist with this: the mean bed level and the bed correction factor.

It can be seen from Figure 2.2 that these two parameters are directly related; the same flow can be calculated by having a low river bed and low bed correction factor, or a high river bed and high bed correction factor. This issue was explored when analysing the Greenholme data, and this showed that one of two alternatives was required to produce accurate flow data:

1. If the bed correction factor set by Peek was used (0.8), the mean bed level had to be raised above the true datum.
2. Alternatively, if the bed level was set at the surveyed value, then the bed correction factor had to be reduced.

There is obviously a relationship between the bed correction factor, the true bed level and the level of the lowest transducer path. The closer the transducer path is to the river bed the more representative it will be of flow conditions, resulting in a higher bed correction factor. This explains the Peek value of 0.8, which was initially set as an arbitrary value by the manufacturer for another type of ultrasonic gauge. Whilst it may be reasonable to assume that multi-path gauges may be able to place the lower transducer path close enough to the bed to justify a value of 0.8, the studies at the Project field sites indicate that for portable installations with a vertical rack on each river bank, 0.65 is a more realistic value. **It is thus recommended** that the true bed level is set as a constant, and the bed correction factor is set to 0.65 in the first instance. Should calibration gaugings at low flows indicate that this value is too high or low it can then be altered accordingly, and any previous flow data can be adjusted as required.

3.3.3 Minimum cover

Both ISO 6416: 1992 (E) and the Peek instrument manual provide guidance on the minimum cover required above the transducer path for the gauge to function. The field studies found that these values were, in every case, higher than those which were needed. **It is thus recommended** that the minimum cover above the transducer path is set to 25 mm above the top of the transducer. Spurious data can be edited out if required, but bringing the velocity path 'on line' as soon as possible may help to get the depth transducer working more accurately, as described in 3.2.3.

3.3.4 Direction of flow (Figure 3.7)

Finally, and perhaps most importantly, the direction of flow is a key component in determining both velocity and flow. As there is a cosine function involved in the calculation of the velocity, the error in calculated velocity is greater for transducer paths with a large angle to the flow. For example, the Standard advises that a 1^0 difference between true and assumed flow direction causes a 1% error in velocity for a path at 30^0, and a 3^0 error for a path at 60^0 to the flow. The importance of accurately determining the direction can thus be seen.

Whilst it is relatively straightforward to identify the direction of flow for a well defined, straight channel, particularly one flowing between artificial banks such as wing walls or a mill offtake, this is not the case for a site located on a gentle bend in the river. This was the case at Blackford Bridge and, to a lesser extent, Middleton in Teesdale. In both cases the problem was overcome by stretching a line across the river upstream of the gauged section, and tying a floating line to the midpoint of this. The line then floated downstream parallel to the direction of flow, enabling the angle of the transducer path and channel dimensions to be determined by measuring the channel width at right angles to the floating line, as shown in Figure 3.8.

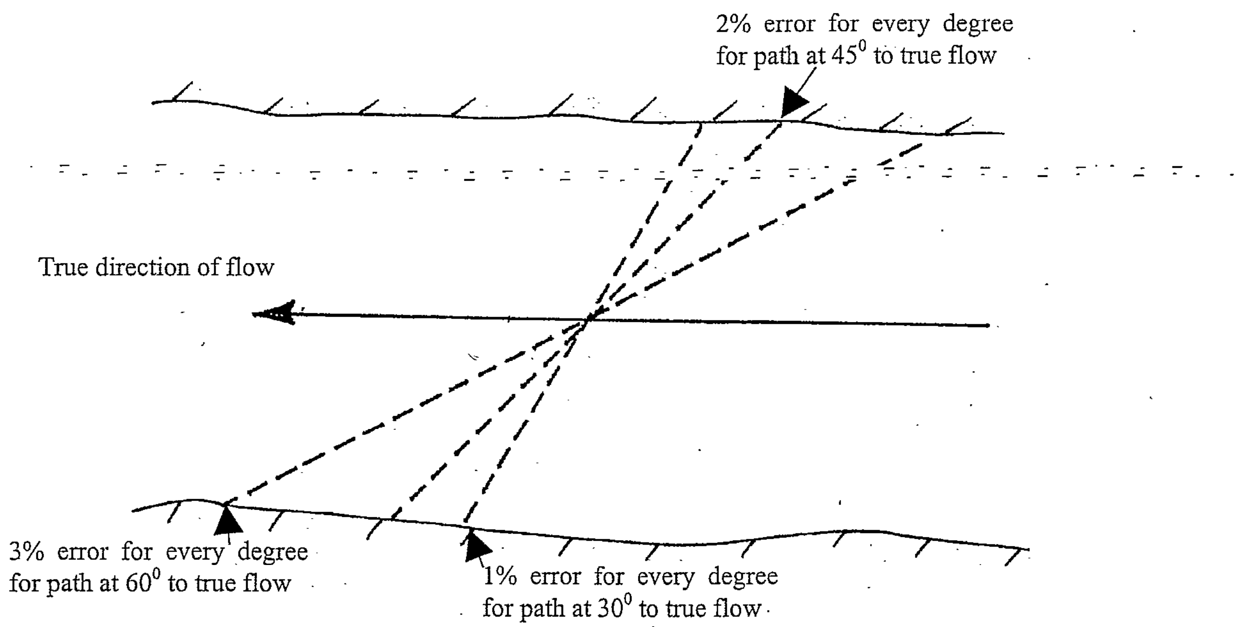


Figure 3.7 Diagram to illustrate the potential uncertainty arising from a 1^0 error in the determination of the true direction of flow for different transducer path angles.

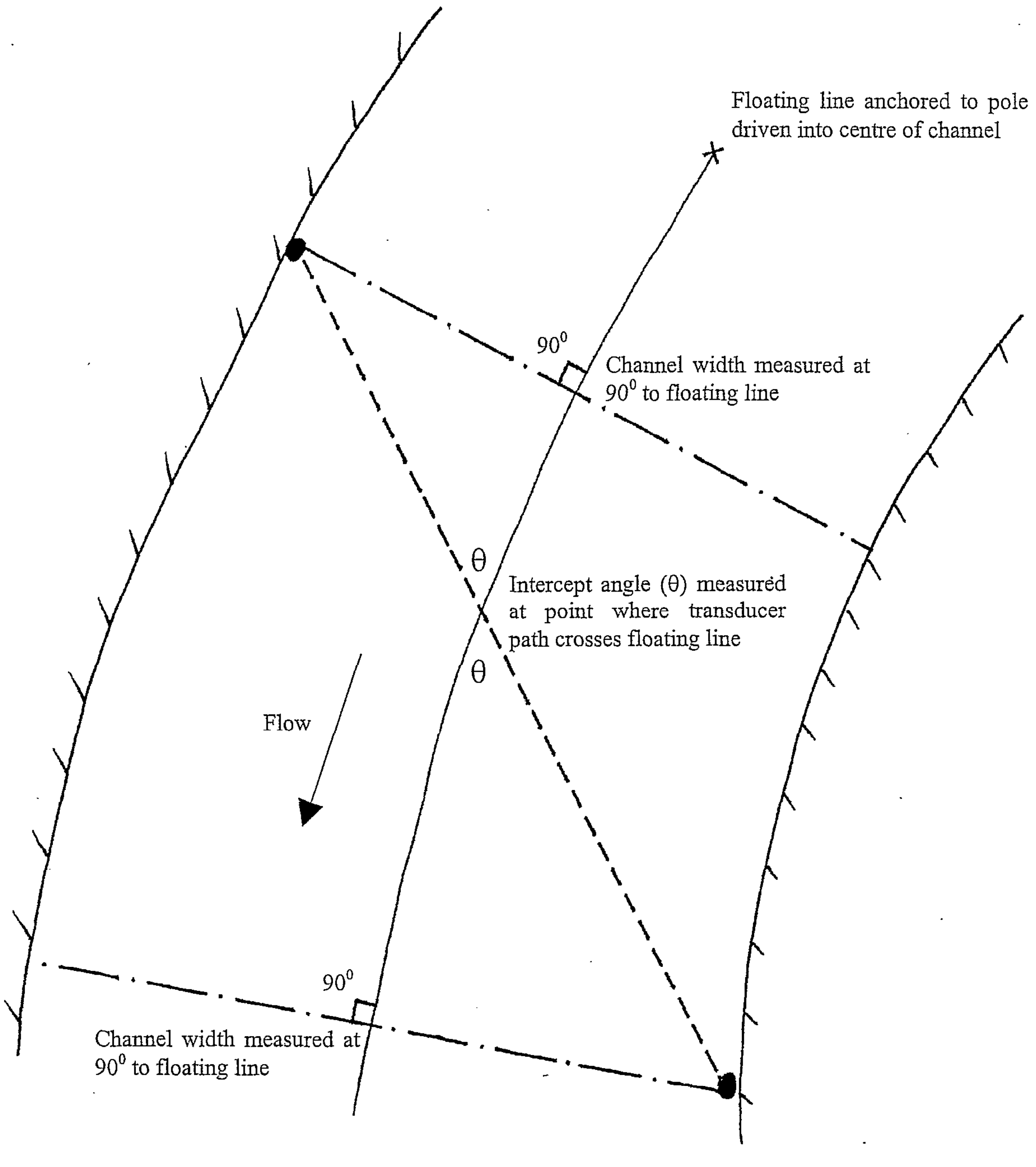


Figure 3.8 Diagram to show how a floating line was used to determine the direction of flow at a site located on a gentle bend in the river.

3.4 STAFFING IMPLICATIONS

One of the specific Project objectives was to identify typical costs of operating the equipment, both in terms of capital expenditure and manpower. A detailed note was made of the time taken to install and commission the gauges at the first four field sites; the results are contained in Table 3.2. From this it can be seen that a 'typical' installation such as that at Greenholme (the first installation to be completed) or Walcot will take approximately 30 staff hours to complete. More complex sites, such as Low Nibthwaite (a total of four racks were installed) might take up to 40 staff hours, whilst a relatively compact site such as Lea Hall could be completed in approximately 20 hours.

Table 3.2 Summary of staff hours taken to complete the first four ultrasonic gauge installations for the field studies.

Site	Greenholme	Walcot	Low Nibthwaite	Lea Hall
Initial Site Survey	6	6	6	4
Site Preparation	12	7	16	12
Installation/commissioning	14	18	16	6
Total	32	31	38	22
Comments	First installation	A total of four paths were installed between 2 racks	Four racks and sets of cables to be installed	Would have been 4 hours quicker if gauge had been functioning

It should be noted that these values only relate to the actual time taken on site to install the equipment. No allowance has been made for equipment procurement, travel time or decommissioning. These will be included in the 'typical operating costs' sections in the following chapters.

4 OPERATING THE GAUGE AS A TWIN PATH SYSTEM

4.1 Introduction

During the course of the Project the gauges were always deployed as a twin path system, with two sets of transducers deployed at any one time. In the majority of cases the paths were configured in parallel, ie one path was above the other. The only exception to this was at Low Nibthwaite where it was possible to use a cross-path configuration as four transducer racks had been deployed to enable the 500 kHz and 1Mhz transducers to be evaluated at the same site.

In all cases the equipment was operated for at least two ‘events’ without altering the height of the transducers. The data were then examined to determine whether or not there was a consistent relationship between path velocity and river level, before raising or lowering the transducer racks in preparation for collecting velocity data from different levels.

Once data had been collected from a number of levels they were processed in two ways:

1. The event data (as recorded) were compared to the Agency data for the same event. Minor changes were sometimes made to the gauge data, reflecting ‘new’ survey dimensions for example, and the resultant data sets were then compared.
2. Once field studies had been completed at each site, the data were combined to enable a ‘multi-path’ configuration to be modelled for each site.

Chapter 5 will address the multi-path gauge replication at sites where this was possible - ie, sites where there was a consistent relationship between velocity and water level, and where it was possible to collect data from a number of different levels. This Chapter (4) will focus on using the gauge only as a twin path system, and will present key data collected during this part of the study. Further examples are in the Site Reports that are contained in the Project Record, together with the data sets themselves, and Chapter 6 uses data collected from a twin-path configuration at Walcot.

The various Site Reports all present data collected during high flow events from the field sites, and describe the analysis that was undertaken on the various data sets. Rather than repeat all of this information in this Chapter, individual events will be selected from these Reports that reflect the range in gauge performance at the study sites. Table 4.1 summarises the events that are contained in the Site Reports, together with identifying those selected for use in this and subsequent Chapters.

Table 4.1 Summary details of the events used for the analysis presented in Chapters 4-7.

Start date of event	Transducer path levels (m)	Minimum stage (m)	Maximum stage (m)	Chapters
Greenholme				
10/12/1996	0.088, 0.388 metres	0.371	1.318	4,5
17/2/1996	0.088, 0.488 metres	0.405	1.202	4,5
23/4/1996	0.088, 0.588 metres	0.336	0.738	4,5
1/5/1996	0.088, 0.588 metres	0.325	0.901	4,5,7
29/5/1996	0.188, 0.588 metres	0.307	0.908	4,5
Low Nibthwaite				
11/2/1996	0.10, 0.30 metres	0.572	0.726	4
Blackford Bridge				
10/06/1997	-0.1 metres *	0.077	0.416	5
03/08/1998	-0.1 metres *	0.447	0.686	5
07/01/1998	0.0, 0.6 metres	0.271	1.228	4,5
01/03/1998	0.2 metres *	0.252	1.447	4,5
04/04/1998	0.4 metres *	0.445	0.688	5
Middleton in Teesdale				
19/11/1997	0.4 metres *	0.471	1.275	5
21/01/1998	0.5 metres *	0.582	1.374	5
22/04/1998	0.7 metres *	0.689	1.329	5
Walcot				
18/12/1996	-0.1, 0.2 metres	0.403	1.413	6
27/11/1997	0.1, 0.2 metres	0.464	1.185	6
1/1/1998	0.5, 0.8 metres	0.777	1.930	6
10/4/1998	Assessment of crest tapping blockage - various			6
16/9/1998	Various - reflector trials			7
Lea Hall				
15/2/1997	Various - reflector trials			7
1/3/1997	Various - reflector trials			7

* Twin path configuration was used, but data from only one path was collected or used.

4.2 Gauge performance - level measurement

The depth transducer was deployed in one of two ways - in the stilling well inside the gauging station, or directly in the river channel. The in-channel deployment was used at Greenholme, Low Nibthwaite and Lea Hall, and the agreement with the Agency data collected from the stilling well was generally good. Minor problems were encountered due to siltation at Greenholme but, with this one exception, and problems associated with the electrical supply at Low Nibthwaite that will be described fully in section 4.3, the equipment performed well under these conditions. For example, the depth transducer at Greenholme did not differ by more than 2 mm from the Agency TG 1150/shaft encoder values during high flow events at the site.

As the Agency level data are all collected from the stilling well it is not possible to compare the Agency data to the gauge data collected from in the channel itself for all sites as this may introduce potential uncertainties due to well lag. It is thus necessary to compare levels collected from within the well to data collected by the Agency to quantify how well the equipment performed. Well level data were collected at Walcot, Blackford Bridge and Middleton in Teesdale.

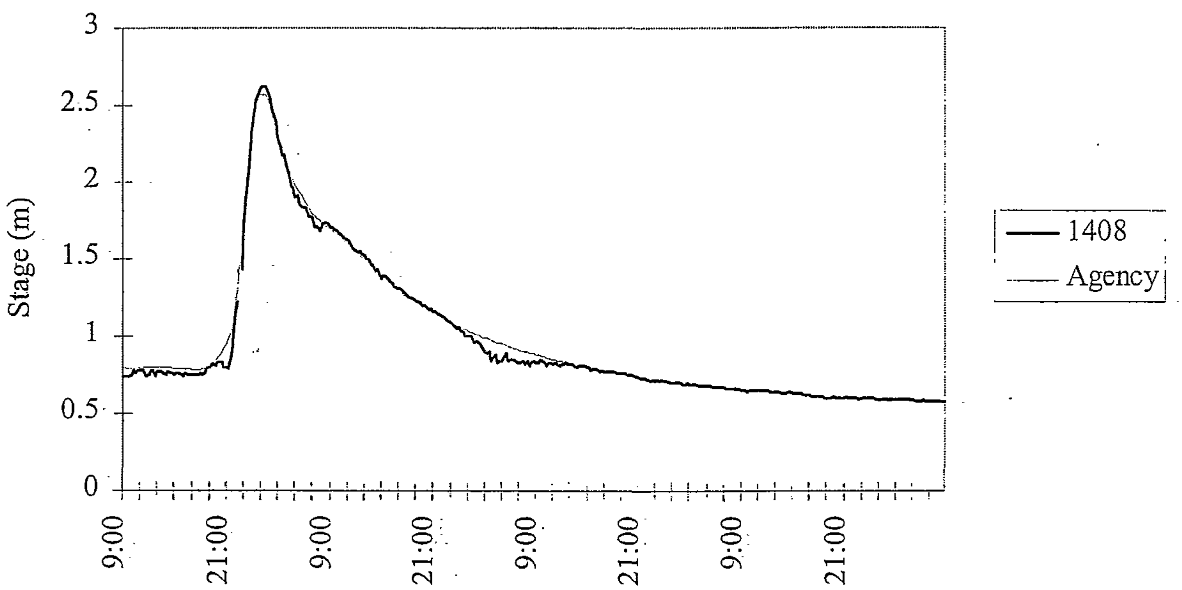


Figure 4.1 Stilling well water levels recorded by both the Agency instrumentation and the ultrasonic gauge between 0900 on the 8th and 0900 on the 12th January 1999 at Middleton in Teesdale. The tick marks on the time axis represent a two hour period.

The wide range in levels at Middleton in Teesdale theoretically enables a thorough assessment of the gauge performance at measuring water level to be undertaken. One of the largest events that occurred during the study period was in early January 1998; Figure 4.1 shows a time series plot of the water level recorded by both the Agency instrumentation and the ultrasonic gauge during this event.

A number of observations can be made from Figure 4.1:

- In general the instruments correlate well; particularly on the rising limb of the hydrograph.
- Initially, the ultrasonic gauge provided a lower measurement of water level than the shaft encoder used by the Agency. This discrepancy appears to disappear once water levels start to rise, although the two instruments show a different initial response.
- During the (very) steep rising limb of the event the levels recorded by both instruments are effectively the same; the only differences may be due to timing differences between the instruments rather than actual differences in measurement. This is particularly impressive given the rate of rise - almost 1.8 metres in less than three hours. (Note that the 'missing' gauge data represents a single data point; this was because SWS were on site during the event, and had taken the gauge 'off-line' to try and get the velocity paths working.)
- The peak levels recorded during the event are very similar for both instruments, differing by less than 30 mm (1.7%).
- The levels recorded during the recession limb appear to be virtually identical for the majority of the event. However, there are two exceptions to this, both of which show the ultrasonic gauge recording a lower level than the shaft encoder. The reason for this is not clear.

Other events were also analysed to assess the extent to which the ultrasonic gauge level data agreed with that of the Agency shaft encoder, and similar results were found. Unlike some of the other sites used for the Project there was no consistent relationship between the gauge's ability to measure depth and whether or not the velocity path(s) were working (see later). Instead, the relationship appeared to reflect a tendency for the gauge to record lower values than the shaft encoder at low river levels, with the two approaching equal values as the river rose. Figure 4.2 shows a plot of the ultrasonic recorded level plotted against the level recorded by the Agency during the November 1997 event, and this relationship can be clearly seen. Spot checks during site visits confirmed that neither instrument was consistently correct, with the staff reading in the river often varying from that shown by either instrument.

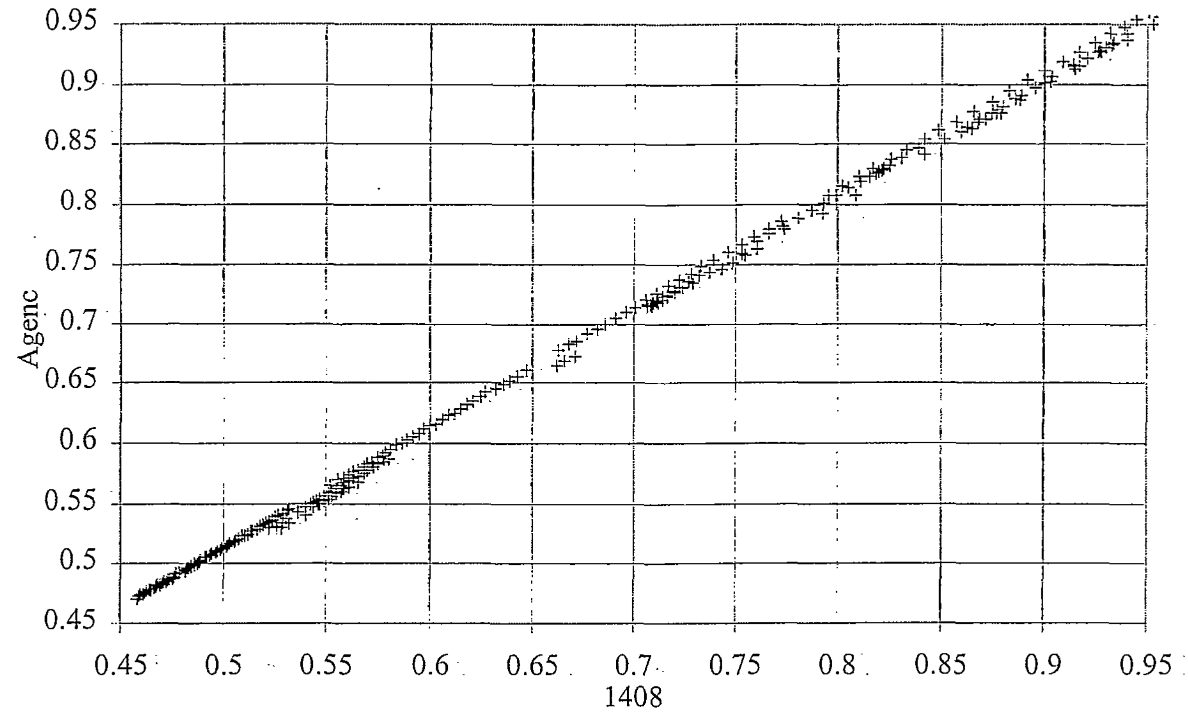


Figure 4.2 Water levels (between 0.45 and 0.95 metres above stage datum) recorded by the ultrasonic gauge plotted against those recorded by the Agency shaft encoder for the November 1997 event at Middleton in Teesdale. Note that at low levels the ultrasonic gauge tends to record lower values than the shaft encoder, whilst the data appear to match better at higher levels.

One further point that should be made about the gauge performance at measuring water level relates to when the velocity paths are not working, either because they are out of the water or because the paths have actually failed. Under these circumstances the velocity of sound value resets to the default gauge setting, rather than that calculated when the velocity paths are working. It was observed that when this is the case, the gauge depths differed from the Agency instrumentation (and true water level), typically by up to 10 mm. The degree of this discrepancy depends on both the water temperature and the depth of the transducer relative to the water surface in the stilling well.

Finally, it should also be noted that when the depth transducer failed, either due to being silted up or, in the case of some stilling well installations, disturbed when maintenance work was being carried out in the well, the gauge automatically switched on both of the velocity paths. Thus, even when it is not possible to collect depth data (and, consequently, derive flows), the equipment is able to collect velocity data that can then be processed with level data from another source.

4.3 Gauge performance - measuring flows

The primary objective of this Project was to evaluate the ability of a twin-path portable ultrasonic gauge to measure flows, and to use the derived data to produce a calibration curve for a site. This section of the Chapter will begin to address this objective, and will use examples from the studies at Greenholme, Low Nibthwaite and Blackford Bridge.

4.3.1 Greenholme

Greenholme was the first site to be used for the Project, and was one where the performance of the equipment can be quantified with a reasonable degree of certainty as the station has a known and stable stage-discharge relationship. The main weakness to the studies undertaken at the site is that they cover a relatively small range in flows (for the area) due to the very dry weather that coincided with the field trials during the first winter. Progress Reports W6/i646/3 and W6/i646/4 describe the results that were obtained at Greenholme in detail. For the purposes of this Report the data from the first two events will be used as they were the two highest events to occur at the site.

When the gauge was installed at Greenholme it was configured with the default settings. Specifically, the mean bed level was set at that which was surveyed along the velocity path, and the bed correction factor was set at 0.8. The depth data recorded by the equipment has been used to derive the flows rather than that collected by the Agency as there was very little difference between the two for this site.

When analysing the data from the events at Greenholme it quickly became apparent that, regardless of the levels at which the transducer paths were deployed, the gauge consistently produced higher flows for a given stage than the Agency rating. If it is assumed that the gauge is working properly, the flow is parallel to the banks and the path length and levels had been accurately surveyed, there were two possible explanations for this:

1. The mean bed level was too low, resulting in the cross-sectional area of the channel being overestimated, or
2. The bed correction factor was too high, and that in reality the velocities in the lowest 'slice' were less than 80% of those recorded by the lowest velocity path.

Chapter 3 has already described that, based on the study results from a number of sites, in order to overcome this issue the recommended approach is to survey more cross sections, as shown in Figure 3.2, and to set the bed correction factor to an initial estimate of 0.65. However, this was not known at the time the Greenholme studies were underway, so an alternative strategy had to be used.

The channel cross-section at Greenholme was far from uniform, with a sandstone ledge lying a short height under the water surface. Following advice from the gauge manufacturer, it was initially decided to adjust the mean bed levels to see how this would account for this. Whilst it was possible to retrospectively optimise this parameter by using data collected during the whole event, it was felt that a more realistic approach would be to try and adjust the level using data that might reasonably be available to the technician installing the equipment.

It was therefore assumed that, if no flow data were available for a site, it would be possible for a gauging to be undertaken at the same time as the gauge was being installed or commissioned. In order to represent this it was assumed that the first flow value from the Agency rating would reflect the derived flow from the gauging, and the mean bed level was thus adjusted to produce a flow that was as close to the first corresponding Agency flow value.

This meant that the mean bed level was adjusted from -0.47 metres to -0.32 metres, resulting in the first flow value from the gauge being reduced from 4.55 to 3.94 cumecs, compared to the Agency value of 3.924 cumecs. As the transducer path had been installed in the deepest possible channel section (to enable the transducer paths to be operated at as wide a range of levels as possible) this adjustment appears to be physically reasonable.

Figure 4.3 shows the Agency, gauge and adjusted gauge flows recorded at Greenholme between 0000 on the 10th February 1996 and 0000 on the 15th February. Figure 4.4 shows the percentage difference between the Agency flows and those calculated by the gauge with both default and adjusted bed level parameters.

From these data it can be seen that whilst the gauge performs reasonably well with the default settings, its performance is dramatically improved by adjusting the mean bed level solely on the basis of the first flow value. For the first event the mean difference in flows derived by the Agency rating and the gauge falls from 8.07% to 1.45 %, with the maximum difference being just 6% during the peak flows. If it is considered that, at this time, the highest transducer path was almost 1 metre below the water surface, and one of the transducer paths had failed (the lower one) during the higher flows, this 6% difference can be both understood and explained.

It can also be seen from Figure 4.3 that the gauge failed to function during part of the event. Close analysis of the data reveal that the lower of the two velocity paths failed for approximately 40% of the total duration, whilst the upper path failed for approximately 6 hours, or 5% of the event. This was the first event to occur in the catchment for almost twelve months, and neighbouring fields had been recently ploughed prior to planting. Given this it is likely that sediment loads, be they suspended or saltated, will have been high, and it is felt that this is the reason why the velocity paths failed.

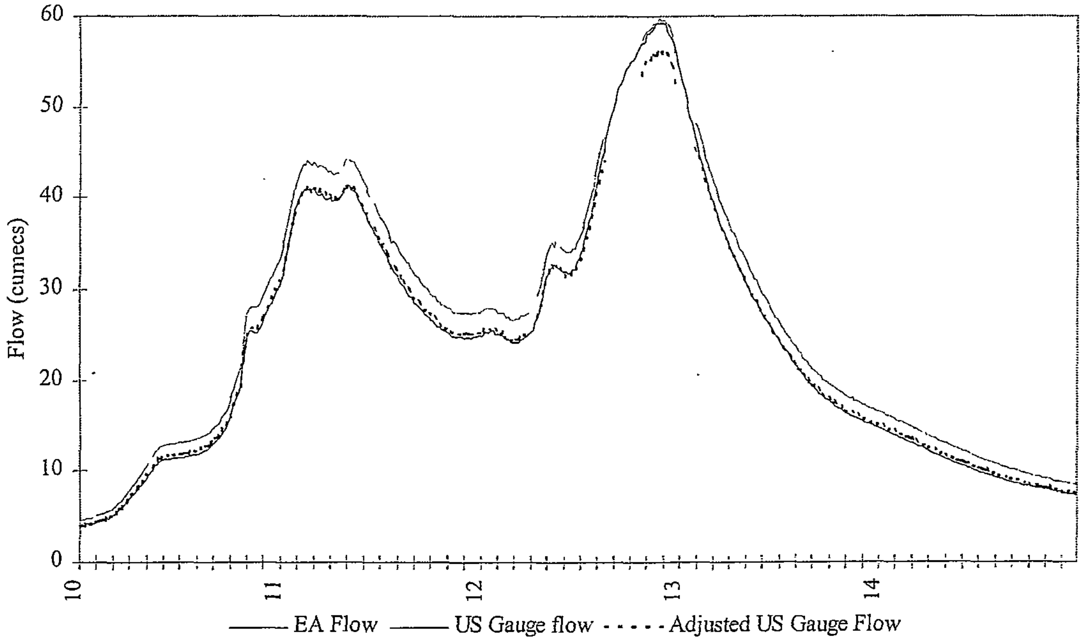


Figure 4.3 Agency, gauge and adjusted gauge flows at Greenholme between 0000 on the 10th and 0000 on the 15th February 1996. The transducers paths were deployed at 0.09 and 0.39 metres above stage datum, and the maximum stage during the event was 1.317 metres. Tick marks are at two hour intervals.

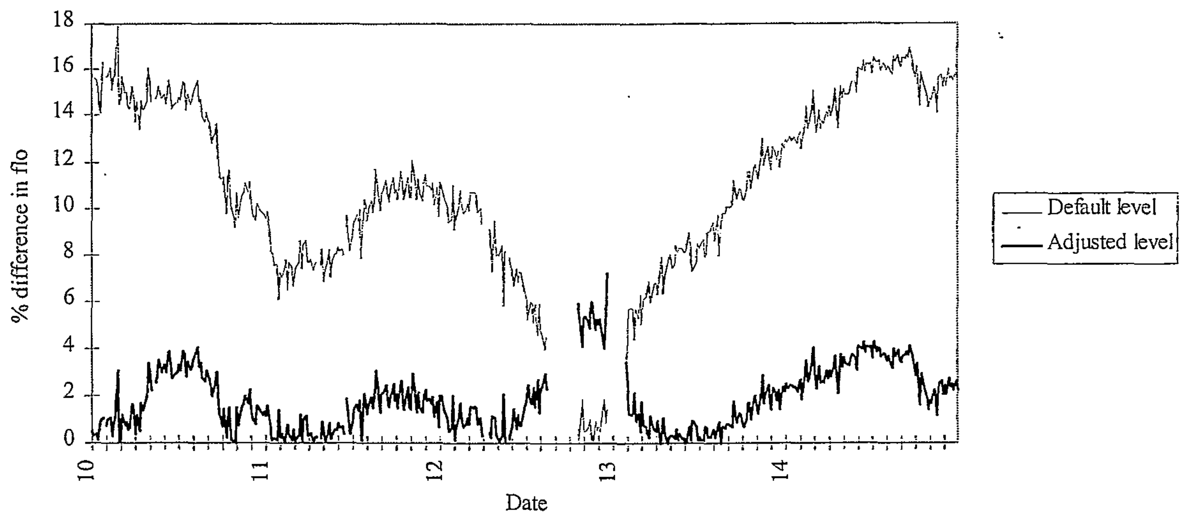


Figure 4.4 Percentage difference between flows calculated by the Environment Agency rating for Greenholme and those produced by the ultrasonic gauge using both the default and adjusted mean bed levels between February 10th and 15th 1996.

Figures 4.5 and 4.6 show the same information to that contained in Figures 4.3 and 4.4 but for the event that occurred between February 17th and 21st 1996. The data were processed in the same way as for the first event, and the mean bed level was set to the same value as that of the first event.

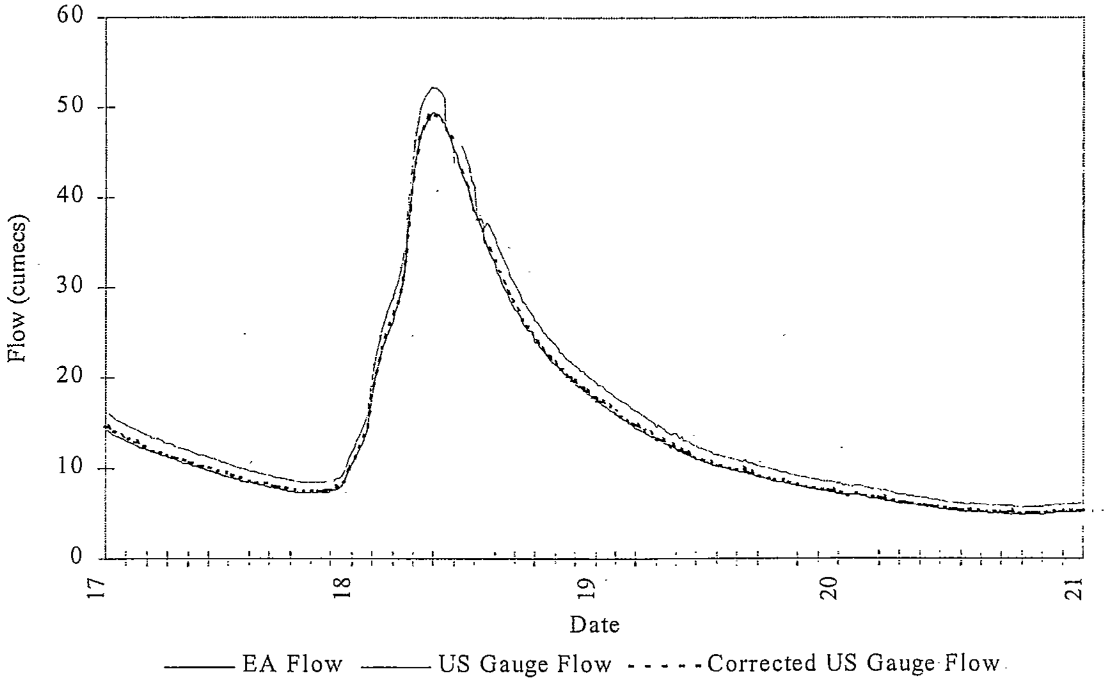


Figure 4.5 Agency, gauge and adjusted gauge flows at Greenholme between 0000 on the 17th and 0000 on the 21st February 1996. The transducers paths were deployed at 0.09 and 0.49 metres above stage datum, and the maximum stage during the event was 1.200 metres. Tick marks are at two hour intervals.

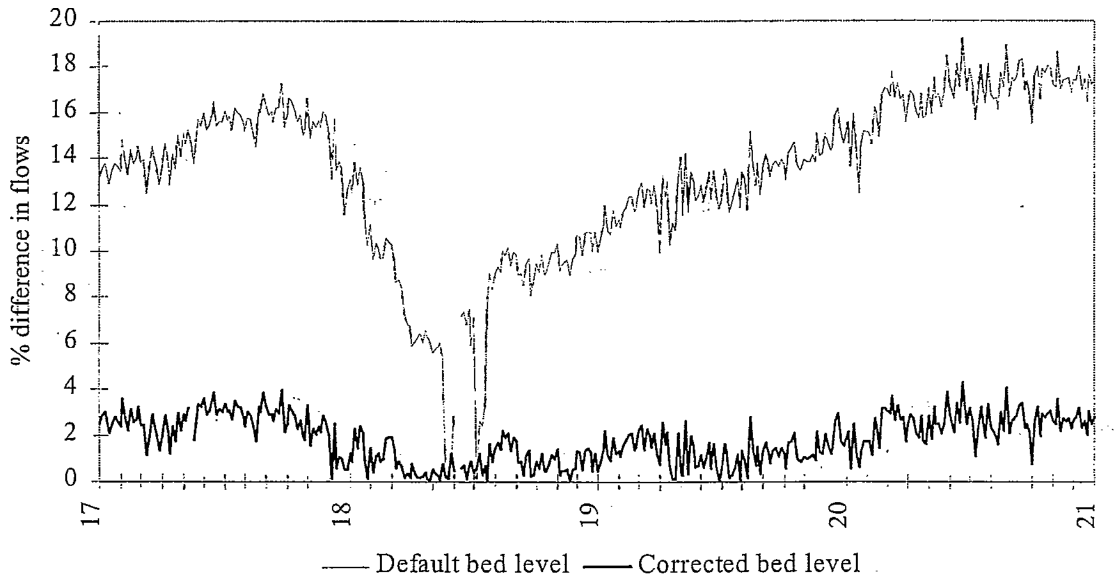


Figure 4.6 Percentage difference between flows calculated by the Environment Agency rating for Greenholme and those produced by the ultrasonic gauge using both the default and corrected mean bed levels between February 17th and 21st 1996.

It can be seen from Figure 4.5 that the hydrographs produced by the Agency rating and the corrected gauge data are virtually identical throughout the whole event; the mean difference between the Agency and corrected gauge flows is only 1.76%, compared to 13.31% for the gauge flows that had the default bed level setting. Although the second event was of similar magnitude to that which occurred earlier in the month the gauge managed to function throughout virtually all of the event, with only three missing datapoints throughout the entire four day period. This would appear to confirm the earlier hypothesis that the sediment loads were high during the first event, causing the velocity paths to fail.

This analysis was repeated for the remaining three events that occurred at Greenholme. Summary results are given in Table 4.2.

Table 4.2 Summary results of the analysis carried out on the data collected during the five high flow events at Greenholme over the period January - May 1996. The % data refer to the mean difference between the Agency and gauge flows for the event using the appropriate gauge settings.
Initial adjusted bed level - the value determined from the first flow value of the first event.
Event specific bed level - the value determined from the first flow value of the individual event to which the analysis relates.

	Event 1	Event 2	Event 3	Event 4	Event 5
Q Mean (cumecs)	24.64	14.14	11.44	8.07	9.54
Q Max (cumecs)	59.27	49.42	19.79	29.77	30.24
Height of low path (m)	.088	.088	.088	.088	.188
Height of high path (m)	.388	.488	.588	.588	.688
Default gauge bed level	8.07%	13.31%	5.05%	8.66%	5.75%
Initial adjusted bed level	1.45%	1.76%	6.04%	4.27%	4.23%
Event specific bed level		1.55%	1.05%	2.55%	1.09%

From these data it can be seen that over all events the gauge performed well, and after adjusting the mean bed level based on a single known flow value the performance was improved even further. For all events the gauge calculated flows to within 2.5% of those derived from the Environment Agency rating. The data from the two events presented in this section were combined and plotted as a stage discharge relationship, together with the Agency rating, in Figure 4.7. It can be seen from this that the agreement between the two datasets is very close. The gauge data tend to produce lower flows at higher stages, due to the relatively low level of the transducer paths. This is particularly noticeable for the highest cluster of data points, which relate to the peak of the first event when only one of the velocity paths was working.

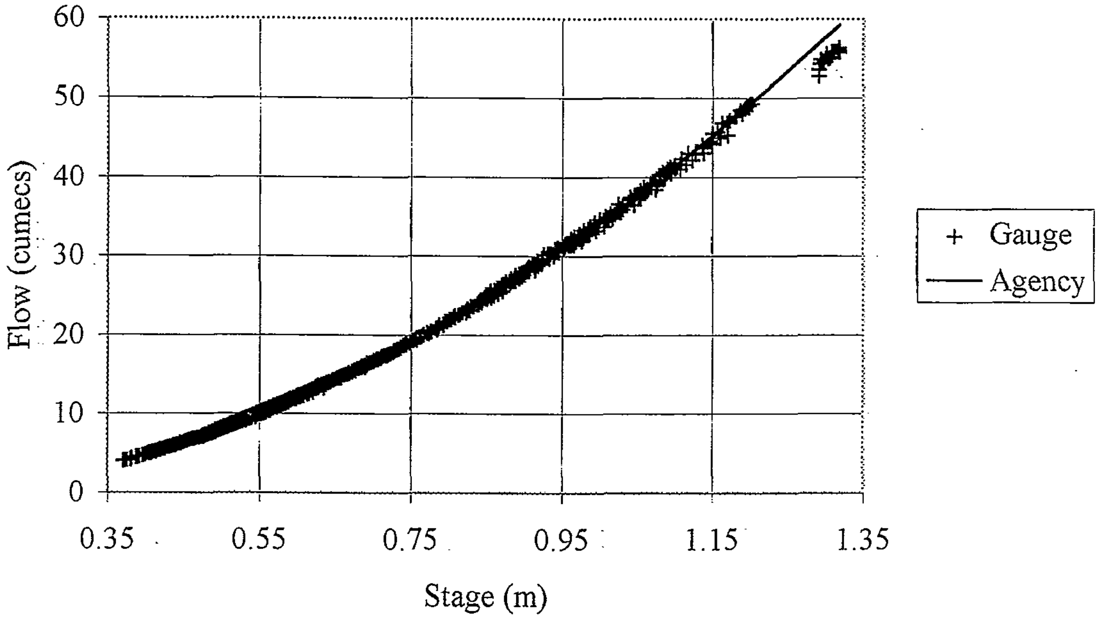


Figure 4.7 The Environment Agency rating curve (Agency) plotted against the flow data derived by the ultrasonic gauge (Gauge) for the two events that occurred in February 1996.

Analysis of bed level and bed correction factor values

As it has already been explained, the studies at Greenholme quickly raised the issue of whether or not the *mean bed level* or *bed correction factor* should be adjusted when commissioning the gauge to ensure that the data collected by the lowest velocity path were used in a way that reflects the site conditions. The Project Board spent a considerable amount of time discussing the merits of altering the bed level during low flow events to fine tune the gauge, as recommended by Peek, or adjusting the correction factor used to reduce the velocity in the lowest panel. It was decided to explore this further using the data collected at Greenholme. The same five events that were used for the work detailed in Progress Report W6/i643/3 were used for this analysis. A simple model was created and operated by four different methods as follows:

1. The optimum bed level was set using only the first four observations recorded by the gauge once the river had started to rise, representing data collected during the first hour of an event, with the reduction factor being set to the Peek default value of 0.8. This bed level was then used to calculate the flow for the whole event. The optimum level was identified by minimising the difference between observed and calculated flows;

2. The reduction factor used to apply the velocity recorded over the lowest path to the lowest panel was optimised using the same method, on the first four observations. The bed level was set to that measured during the initial channel survey;
3. The bed level was then optimised using data collected over the whole event, ie with the benefit of hindsight;
4. Similarly, the reduction factor was optimised using the complete data set.

The results of this analysis are summarised in Progress Report W6/i646/4, contained in the Project Record. The analysis demonstrated that there is little to choose from adjusting either parameter, and that all four methods appeared to give an acceptable performance. The mean average percentage difference between observed and calculated flows for the five events was no more than 3.05% by any method, and less than 5.1% for any individual event. It appears that adjusting the bed level gives marginally better results when the methods are compared over the five events as a whole, but it was also noted that this approach also produced the highest errors for single events. Additional observations were that the mean bed levels appeared to fall within a narrower range than the reduction factors, probably because it affects two of the three discharge 'slices' and thus has a greater effect on the flow derivation, and that all the reduction factors were significantly less than the 0.8 used in the Peek software.

Whilst these results demonstrated that the gauge can produce acceptable results when operated in a number of different ways, it is important to remember that if a general, simple approach can be established that does away with the need for calibration or optimisation of specific parameters, this will significantly help the Agency in using the equipment at a wide variety of sites with different personnel as it will allow a consistent procedure to be followed. With this in mind the model was re-run for the five different events, using the mean bed level or reduction factor as appropriate for each of the four methods. The results from this are given in Table 4.3, from which it can again be seen that adjusting the mean bed level would marginally appear to be the better of the two approaches.

Finally, it should be remembered that these results only apply to the Greenholme data sets. Following further discussion with the Project Board, and after further data had been collated from other study sites, it was decided that the first step to be taken when commissioning the gauge should be to reduce the bed correction factor to 0.65. This generally gave acceptable results for all of the field sites. Should it then be found that this still results in large differences between 'true' and gauge flows, the bed level can then be adjusted on the basis of the available information to improve the situation.

Table 4.3 Summary results obtained by using the average mean bed levels and reduction factors from the four different methods and applying them to the five individual events.

Set bed level from first 4 values, mean bed level -0.34	Event 1	Event 2	Event 3	Event 4	Event 5	Mean
Mean difference in flows	0.621	0.439	0.487	0.267	0.436	0.450
Mean % difference in flows	3.27	3.94	4.11	2.87	4.36	3.71
Set reduction factor from first 4 values, mean reduction factor 0.53						
Mean difference in flows	0.656	0.445	0.478	0.262	0.592	0.811
Mean % difference in flows	3.21	4.03	4.04	2.83	6.17	4.06
Set bed level over whole event, mean bed level -0.34						
Mean difference in flows	0.621	0.439	0.487	0.267	0.436	0.450
Mean % difference in flows	3.27	3.94	4.11	2.87	4.36	3.71
Set correction factor for whole event, mean reduction factor 0.49						
Mean difference in flows	0.613	0.587	0.352	0.201	0.462	0.440
Mean % difference in flows	3.51	5.25	2.99	2.41	4.66	3.76

4.3.2 Low Nibthwaite

Having demonstrated that the gauge worked well at Greenholme, further examples will be used to assess the performance at further sites when deployed as a twin-path system. The first of these is Low Nibthwaite, where there was only one event of any significance during the time that the gauge was deployed at the site. A number of additional lesser events were recorded, during which the gauge was able to replicate the flow data produced by the Agency rating.

As the equipment was installed at Low Nibthwaite on the day after the Greenholme gauge was installed the mean bed level and bed correction factors were also set to the default parameters. Figure 4.8 shows the Agency flow data between 1200 on the 11th and 1200 on the 15th February 1996, together with those calculated from the gauge data, and the % difference data between the Agency and corrected gauge flows. It can be seen that the 'Gauge flow' series is considerably more 'spiky' than that produced from the Agency data; this is because the depth transducer was providing erratic data due to problems with the power supply, as described in section 3.2.4. The 'Adjusted flow' data series was thus derived from the Agency stilling well level data and the data collected from the two velocity paths, with the bed correction factor/mean bed level parameters being determined by the method described in section 4.2.1.

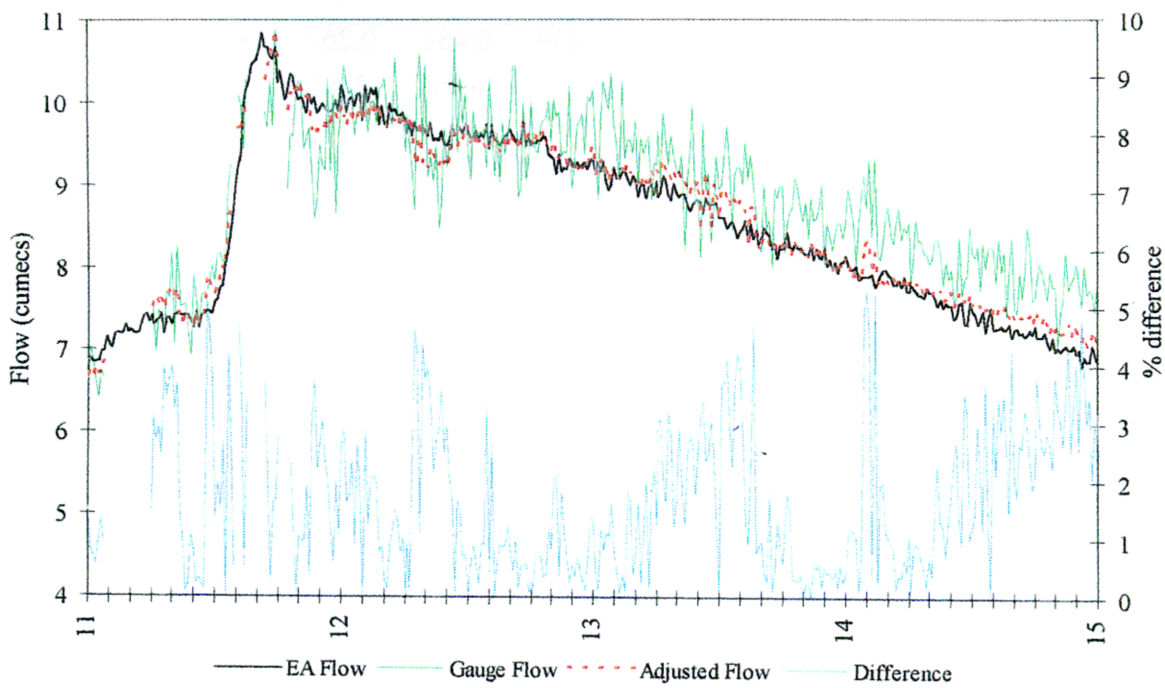


Figure 4.8 Agency, gauge and adjusted gauge flows at Low Nibthwaite between 1200 on the 11th and 1200 on the 15th February 1996. The transducers paths were deployed at 0.1 and 0.3 metres above stage datum, and the maximum stage during the event was 0.726 metres. Tick marks are at two hour intervals.

It can be seen from Figure 4.8 that the gauged flows at Low Nibthwaite agree closely with those derived from the Agency stage discharge calibration, The mean difference between the Agency and gauge flows (corrected) is only 1.7%, with very few 15-minute values exceeding the 4% threshold.

4.3.3 Blackford Bridge

An ultrasonic gauge was installed at Blackford Bridge for over twelve months, during which time a number of significant flow events occurred. The Blackford Bridge Site Report contained in the Project Record presents data from five of these events, many of which are used in Chapter 5 of this Report. As there is considerable uncertainty in the Agency rating for the site the case studies will not be discussed in detail in this Chapter. Instead, data from two events that occurred between January 8th and 10th and March 2nd and 10th 1998 will be presented to demonstrate the gauge performance at this site in a general context. The gauge performance will not be quantified as there is no known 'true flow' to which the data can be compared.

The first of these event was of similar magnitude to the Mean Annual Flood for the site, and had a maximum level of 1.212 metres above stage datum, at which point it was beginning to flow out of the main channel on the far bank. Only 28 events had been of a higher level during the entire 23 year record for the station. The flow data are presented in Figure 4.9.

Note that by the time this field site was being used the bed correction factor was being set to 0.65 when the gauge was commissioned, and the mean bed level was obtained from the more detailed site survey. There is thus no data series relating to 'Corrected gauge', as with Greenholme and Low Nibthwaite. Instead, there is an additional hydrograph, titled 'HR Flow', which is based on the theoretical rating for the site that was derived by HR Wallingford in a recent study for the Agency.

It can be seen that the gauge produces flows which lie between the HR and Agency data, and might thus be considered to be reasonable. The Site Report contains a detailed explanation of why it is considered that the Agency rating overestimates high flows at the site. This can be summarised by the fact that high flow ratings are undertaken by handline from a large road bridge upstream of the station. As the gauge recorded <u>mean</u> path velocities in excess of 1.8 ms^{-1}, and peak velocities in mid channel are likely to exceed this, if a current meter is deployed by handline it is unlikely that the suspension cable will be vertical; thus systematic positive errors will be introduced into the gaugings. The Agency are aware of this situation, and have recently installed a full cableway at the site.

The second event, shown in Figure 4.10, is based on velocity data from only one transducer path (the upper path had been vandalised), and was the sixth highest event to have been recorded at the site. Again, the gauge data lie mid-way between the Agency and HR values.

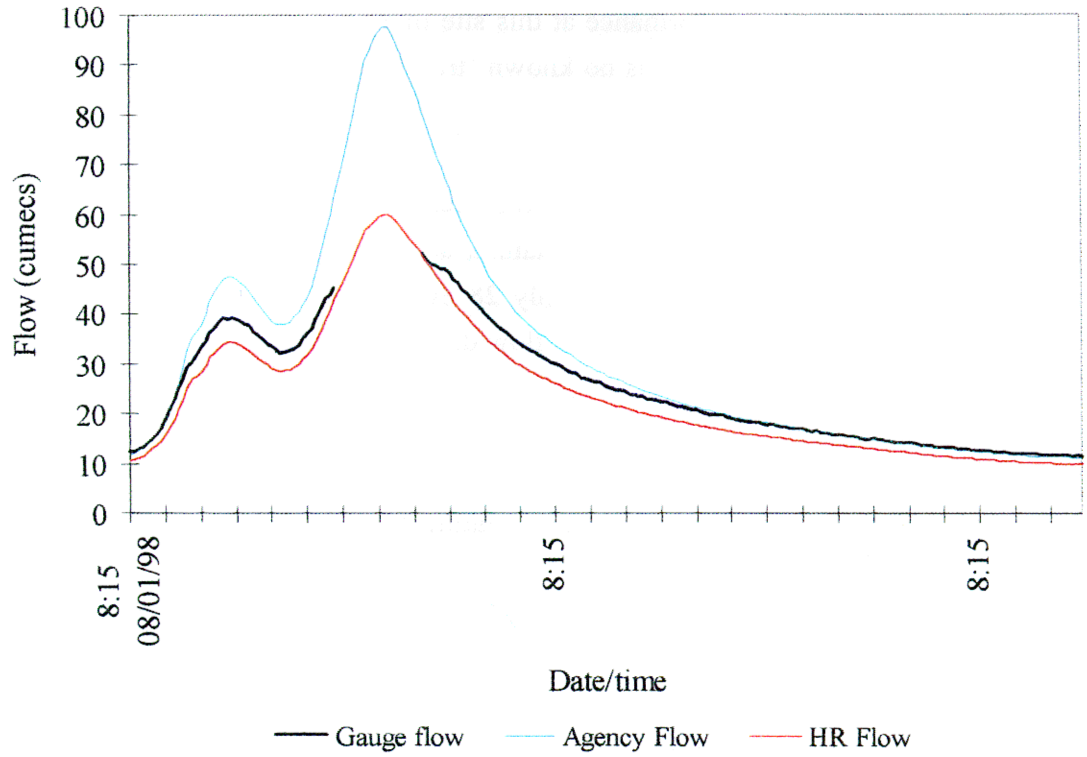


Figure 4.9 Flow data for Blackford Bridge gauging station between 0815 on the 8th and 1400 on the 10th January 1998. The transducers paths were deployed at 0.0 and 0.6 metres above stage datum, and the maximum stage during the event was 1.212 metres. Tick marks are at two hour intervals.

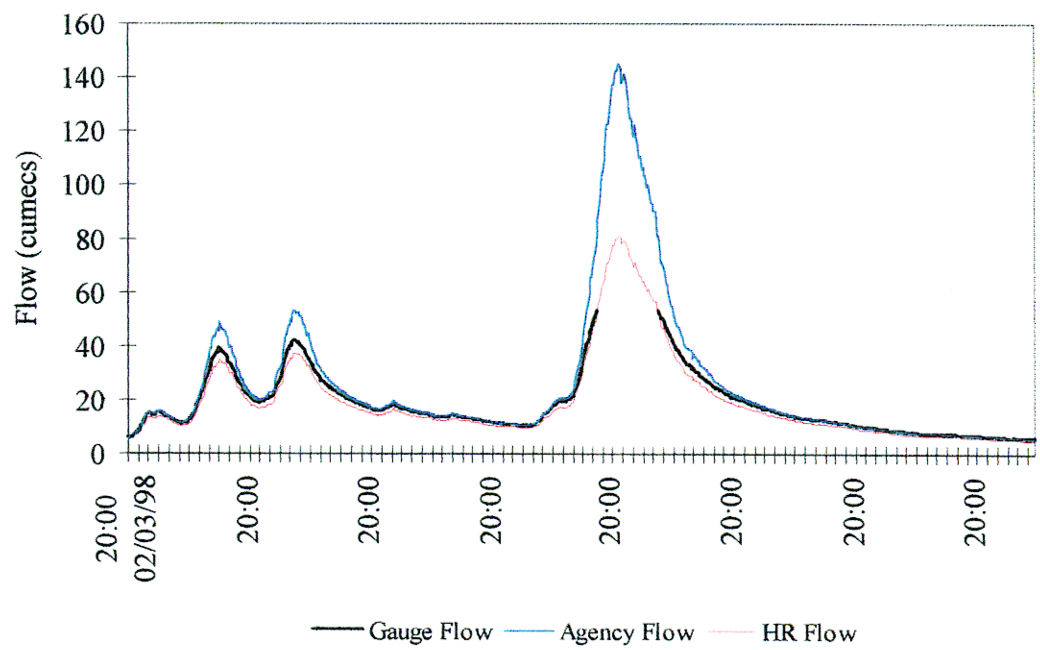


Figure 4.10 Flow data for Blackford Bridge gauging station between 2000 on the 2nd and 2000 on the 10th March 1998. Only one transducer path was operational during the event at 0.2 metres above stage datum, and the maximum stage during the event was 1.416 metres. Tick marks are at two hour intervals.

It can be seen from both Figures 4.9 and 4.10 that the gauge failed to work during both events as the river approached peak levels. Whilst the power-law nature of the rating curves makes it appear the gauge was not able to work for almost half the range in Agency derived flows, the reality is that the velocity paths failed at a stage of approximately 1.0 to 1.1 metres. This level equates to an event which would, on average, be expected to occur twice a year. It can thus be seen that the gauge performed well, and was able to cope with events from a heavily urbanised catchment which is likely to produce high sediment loads.

One difference between Figures 4.9 and 4.10 is that in the first event it can be seen that the gauge failed at a lower level on the rising limb of the hydrograph than when it resumed on the recession limb. During the second event the level at which the gauge failed and then resumed is the same; this was also the same level at which the gauge resumed measurements during the first event. This may be explained by the hypothesis that the first two 'lesser' events visible in Figure 4.10, which occurred three days earlier, may have 'flushed' much of the sediment through the system before the main event occurred.

4.4 Limitations of operating the gauge as a twin path system

Section 4.3 has presented the results obtained from using the gauge as a twin path system. Whilst the general performance of the equipment was good, with flows generally being determined to within 5% of the 'true' values, a number of limitations to the equipment also emerged. Some of these were common to all sites and/or approaches, and some have already been addressed in Chapter 3. Those which emerged as a result of the field studies presented in this Chapter are summarised below.

4.4.1 Systematic errors in the calculation

The principal limitation to using a twin-path configuration is the systematic errors that are introduced into the derived flows. These can be summarised by the following sequence of events, which may occur during the rising limb of an event:

1. Assuming that the event starts with the lower velocity path only just covered enough to be operational, the gauge is likely to overestimate the true flow as the velocity readings will be biased towards higher flows. Whilst this can be overcome by adjusting the bed correction factor and/or mean bed level, to do this would only make matters worse during higher flows.
2. As levels rise this overestimation will reduce until the gauge is calculating the true flow.
3. The gauge will then begin to underestimate the true flow as levels continue to rise as the single velocity path will increasingly undervalue the water velocity in the highest slice of the channel cross section.

4. Eventually the higher path may become operational. This will then start the overestimate-correct-underestimate cycle once again, with the underestimates continuing to rise as water levels rise.

This fundamental limitation arising from a small number of velocity paths is the reason why the majority of permanent ultrasonic gauge installations at strategically important gauging stations are multi-path configurations. Whilst the above cycle will still exist, the degree of error introduced into the derived flows reduces as the difference in height between successive transducer paths diminishes, and will depend on the uniformity and consistency of the velocity profile. This issue will be explored further later in section 4.5.

4.4.2 Gauge failure during high flows

It was repeatedly found, at almost all sites, that the velocity paths failed during high flows. Chapter5 will present further information to support this finding from Middleton in Teesdale, where the gauge consistently failed at 'medium' levels during every event. The results from both Greenholme and Blackford Bridge presented in this Chapter all suggest that the gauge failed due to high sediment loads. The evidence to support this comes from the differing levels at which the paths fail and resume during individual events, and from event to event.

This issue was identified at the start of the Project, and the Agency was offered an option to include studies to attempt to quantify the sediment load. This option was not taken up. Consequently, there were no sediment concentration or loading data collected during the study that enable any analysis to be undertaken. Despite this, the research team are of the opinion that it is not merely a matter of the sediment concentration that causes the gauge to fail, but a function of this together with path length and velocity. High sediment concentrations may not prevent the gauge from working in a relatively narrow or slow moving channel, such as Walcot (see Chapter 6), but if these are combined with longer velocity paths and higher velocities then the total sediment load is high, resulting in attenuation losses in the acoustic signal, as described in ISO 6416 (2.2.3.3).

Whilst this Project did not include the collection of suspended sediment data, there is a limited amount of data available for Catterick Bridge from the LOIS (Land Ocean Interaction Study) which was supported by NERC, SEPA and the Environment Agency. Data are available for a 'twin peak' event in January 1995, and are plotted in Figure 4.11. This shows that the 1408 gauge failed as the turbidity increased during the rising limb of the first peak, the gauge failing at a flow of almost 50 cumecs, when the turbidity levels were approximately 230 NTU units (similar to mgl^{-1}). The gauge started working again at much higher flows during the recession limb (c. 90 cumecs), by which time the turbidity levels had fallen from a peak of 500 NTU to 200 NTU. (It is not known why the gauge subsequently failed during the latter part of Julian day 34743, when both flows and sediment concentrations were much lower.)

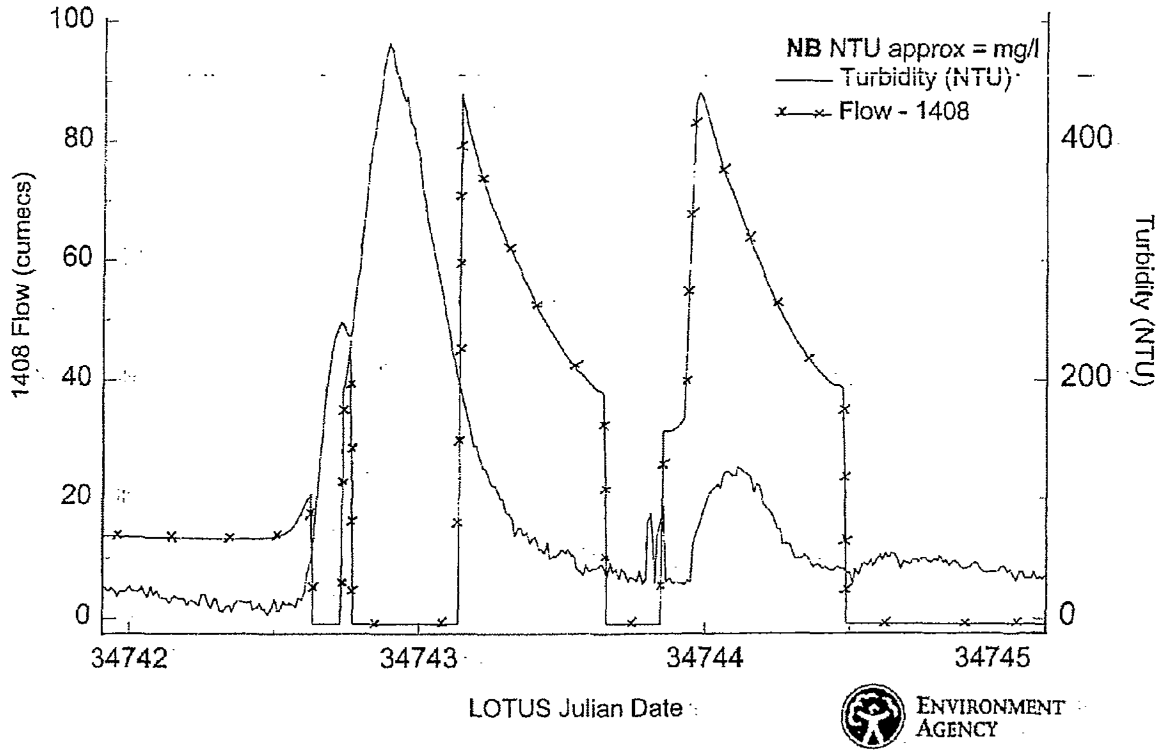


Figure 4.11 Turbidity and flow data recorded at Catterick Bridge in February 1995. The data were collected as part of the LOIS project.

It can also be seen from Figure 4.11 that the gauge was able to function throughout the whole of a similar sized event 24 hours later, when peak flows again exceeded 85 cumecs. Sediment loads were much lower on this occasion, peaking at only 120 NTU, suggesting that the majority of the sediment supply to the river had been utilised by the first event. This phenomenon was also observed at Blackford Bridge where the gauge was able to operate at higher flows during events which followed immediately after other, lesser events.

4.5 Determining the optimum level for deploying the two transducer paths

Section 4.4.1 has described the systematic errors associated with the use of a limited number of velocity paths, these limitations were known before the Project started, and as a result the specific objectives listed in section 1.3 included the following:

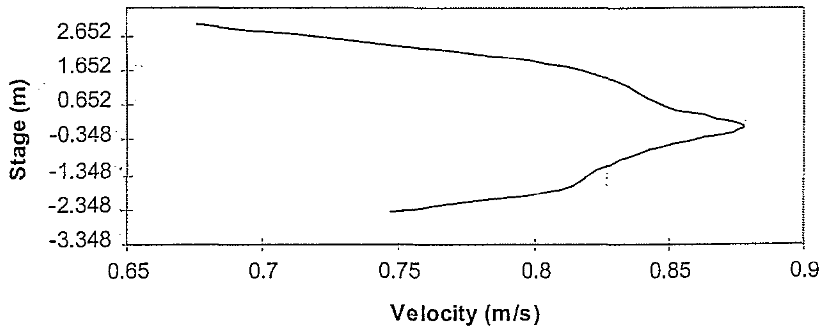
a) To determine the optimum configuration.
b) To use any existing suitable ultrasonic gauging stations in a manner which replicates the portable equipment.

This section of the Report will combine these two objectives, and attempt to use path velocity data from existing multi-path gauging stations to determine the optimum configuration for the two paths used in a twin-path system.

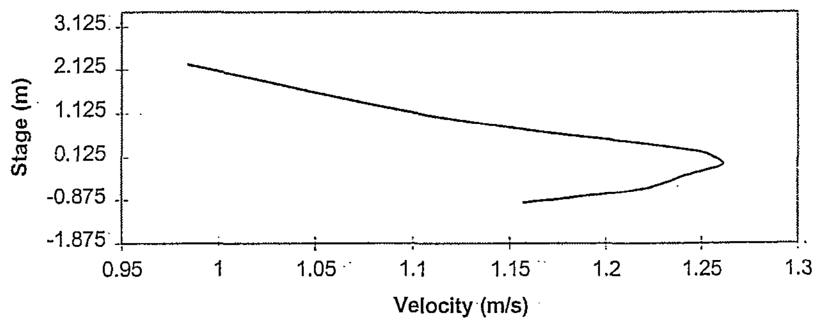
At the start of the Project all Agency Regions were contacted to ask whether or not they would be able to provide suitable data for use in the Project. The most encouraging response came from the Midlands Region, who proceeded to supply data from four sites (Buildwas, Saxons Lode, Montford and Deerhurst) over the 1996/97 winter. The data typically included ten sets of readings recorded at one-minute intervals of level, flow and path velocity (for up to 16 different path levels in some cases), for each event. These data are contained in the Project Record. All four gauges have a cross-path configuration, with each path of the X having a transducer path installed at each level (to within 50 mm). Thus, a sixteen-path gauge would produce twenty velocity values from eight different levels during a ten minute period..

In order to establish velocity profiles for each site and event, the one-minute velocity values for each event were averaged and then plotted against stage. The complete set of profiles are contained in Appendix E to this Report. Figure 4.12 shows one example velocity profile for each of the four sites. It can be seen from this that (with the exception of Deerhurst) whilst the profiles show a consistent pattern, they do not follow the expected pattern in that they tend to have their peak velocities approximately mid-way up the water column. This may be partly accounted for by remembering that the vertical section represented in all the plots in Figure 4.12 is not the same as the water column at a specific point in the channel cross section. The section shown in the plots is drawn between the mean river bed level and the water surface for the section of channel covered by the gauge. This is only directly comparable to the true vertical section at a limited number of points - elsewhere, the channel will be either deeper or shallower, and the relative positions of the transducer paths in the profile will alter accordingly.

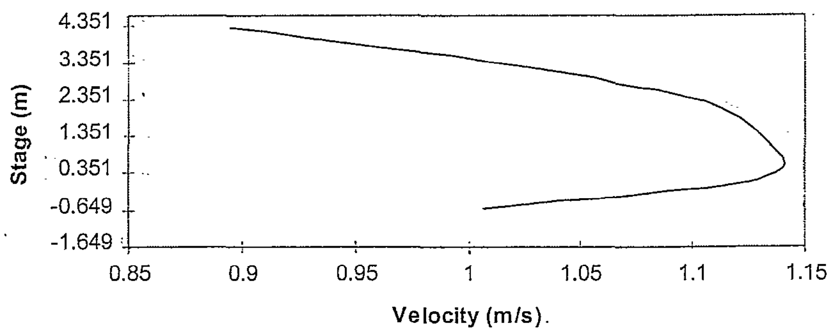
A further factor may be due to the fact that the data were all collected during high flow events. Under such conditions the mean velocity in the upper sections of the water column may be reduced due to greater frictional losses along the vegetated river banks, and the channel flow becoming less efficient as the cross section begins to widen due to the increased boundary layer. If these two factors are taken into account, it might help to explain the profiles observed at Saxons Lode and Montford.



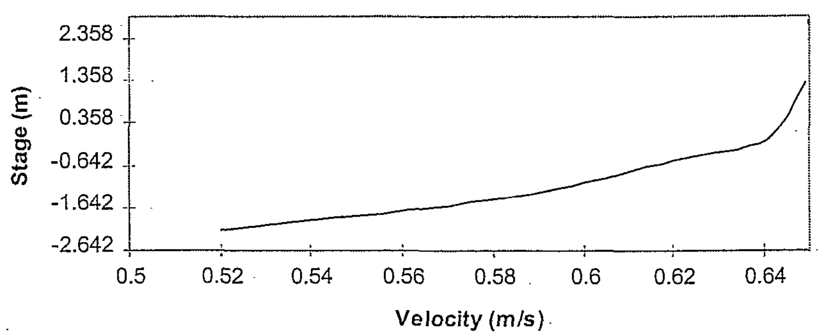
Saxons Lode, 26/2/1997



Buildwas, 19/2/1997



Montford, 19/2/1997



Deerhurst, 5/12/1996

Figure 4.12 Examples of the velocity profiles derived from the four multi-path gauges for which data were available. In all cases the y-axis boundaries reflect the river bed and water surface at the time the data were recorded.

However, the profile at Buildwas is still not fully explained by these two potential factors. If the profile is studied carefully it can be seen that the peak velocity is at approximately 40% of the total water column depth, ie the point at which one would normally expect to find the mean velocity. This has been discussed with the Hydrometric staff from the Region, who have confirmed that the site is known to be a 'problem site', and many hours have been spent analysing the data from the gauge.

In order to assess the ability of a twin path gauge to replicate the performance of a multi-path unit a model was constructed that enabled all combinations of the velocity data collected from each of the transducer paths to be used to replicate a twin path system. This was run for each event at the four sites for which data were available. In order to simplify matters the data were not used to calculate the flow, as this would require the inclusion of variable path lengths which had not been used for any of the portable gauge installations. Instead, an index of flow was derived by multiplying the velocity data by the height of each slice that it represented. In this way the area 'through' each three-dimensional velocity profile was calculated looking across the channel.

For a given event at a specific site the following sequence of calculations was made:

1. The full set of velocity data were used to derive the 'optimum' flow index by summing the products of the recorded velocities and the 'slices' through the channel cross-section which they represented.
2. The velocity reading from the lowest transducer path was then set as the lowest path, and used to derive the flow index along with the transducer path immediately above it. This flow index was compared to the 'optimum'.
3. Keeping the lowest transducer path as the lowest path, step 2 was repeated for all of the other transducer paths.
4. Once all possible combinations using the lowest transducer path had been assessed, steps 2 and 3 were repeated using the next lowest transducer path as the gauge's lowest path.
5. This was repeated until all potential combinations of transducer paths had been used.

A total of 242 different combinations of path configurations were used, and the resultant flow indices expressed as a fraction of that produced by the full set of data obtained from the multi-path gauge. These results are contained in Appendix F, and summarised in Table 4.4.

Table 4.5 contains examples of these results for the four velocity profiles plotted in Figure 4.12. Note that whilst the flow indices were calculated by using absolute values to determine the height of each slice represented by the velocity paths, the transducer path levels are expressed as a fraction of the total water column height in Appendix F and Table 4.5 to enable comparisons to be made between different events at different sites. For example, using the

Saxons Lode table as an example, it can be seen that a combination of the velocity path located at 0.32 of the water column depth (read from the top axis of the table) and the path at 0.40 of the water column depth (read from the vertical axis of the table) produces a flow index that is 0.99 that produced by the full data set, ie it is to within 99% of the 'optimum'.

Table 4.4 Summary results from using the four Agency multi-path gauges to represent twin-path configurations.

Site	Number of combinations	Combinations falling within 2%	Combinations falling within 3 %	Combinations falling within 5 %
Saxons Lode	79	59	76	63
Buildwas	78	33	40	55
Montford	64	42	55	66
Deerhurst	21	43	67	95
Total	242	45%	58%	73%

From Tables 4.4 and 4.5 and Appendix F, it can be seen that reducing the number of velocity paths does not appear to have as much effect as might be anticipated. Almost 75% of the different twin-path configurations produce flows that are to within 5% of the 'absolute' value derived from the full range of velocity paths available to the multi-path gauge, and 45% are within 2%. Indeed, the Deerhurt data show that 95% of the different twin-path configurations produce flows that are within 5% of those derived from the full multi-path gauge, further confirming the earlier observation that the velocity profile data from this site appear to follow the expected pattern more closely than the other three sites. Only 11 of the 242 different twin-path configurations produced flows that differed from the multi-path values by more than 10%. The majority of these were associated with the upper velocity path being deployed at its highest level and the lowest velocity path at the lowest level; again, the main exception to this was Buildwas, where the deployment of both velocity paths close to the mid-range of levels overestimated the flow, as suggested by the velocity profiles.

It is thus concluded that, in the majority of cases, the use of a twin-path configuration appears to produce results that are not significantly inferior to those from the more costly multi-path gauges. Almost 75% of the modelled combinations performed to within 5% of the multi-path gauge, and less than 5% of differed by more than 10%.

Table 4.5 Examples of the results obtained when using the multi-path velocity data to replicate a twin-path gauge for the four Agency gauging stations and the respective events used for Figure 4.11. In all cases the x-axis represents the lower of the two velocity paths. All levels are expressed as a fraction of the total water column. Cell values indicate the degree to which the twin-path model was able to replicate the multi-path data. Shaded cells indicate configurations that produce a flow to within 2% of that derived using the full dataset

	Relative height of lowest transducer path							
	Level	0.14	0.23	0.32	0.4	0.49	0.58	0.76
	0.23	0.98						
Relative	0.32	0.99	0.99					
height	0.40	1	1.01	0.99				
of upper	0.49	1.03	1.03	1.02	1.01			
transducer	0.58	1	1.01	0.99	0.99	0.99		
path	0.76	0.96	1.01	0.97	0.97	0.98	0.94	
	0.93	0.87	0.91	0.91	0.92	0.94	0.91	0.86

Saxons Lode 26/2/1997

	Relative height of lowest transducer path						
	Level	0.17	0.23	0.28	0.33	0.39	0.53
	0.23	1.09					
Relative	0.28	1.1	1.1				
height	0.33	1.1	1.11	1.11			
of upper	0.39	1.1	1.1	1.1	1.09		
transducer	0.53	1.01	1.02	1.02	1.02	1.01	
path	0.75	0.96	0.98	0.98	0.99	0.98	0.89

Buildwas 19/2/1997

	Relative height of lowest transducer path								
	Level	0.16	0.23	0.29	0.35	0.45	0.56	0.64	0.79
	0.23	0.97							
Relative	0.29	1.02	1.01						
height	0.35	1.02	1.02	1.02					
of upper	0.45	1	1.01	1.01	1				
transducer	0.56	0.99	1	1.01	1	0.98			
path	0.64	0.97	0.98	0.99	0.99	0.97	0.94		
	0.79	0.93	0.95	0.96	0.96	0.94	0.92	0.9	
	0.94	0.87	0.9	0.93	0.93	0.92	0.9	0.88	0.81

Montford 19/2/1997

	Relative height of lowest transducer path						
	Level	0.09	0.18	0.27	0.36	0.45	0.54
	0.18	0.92					
Relative	0.27	0.95	0.95				
height	0.36	0.96	0.96	0.95			
of upper	0.45	0.99	0.99	0.98	0.97		
transducer	0.54	0.98	0.98	0.98	0.97	0.97	
path	0.72	0.97	0.98	0.98	0.97	0.98	0.96

Deerhurst, 5/12/1996

One of the aims of undertaking this analysis was to determine whether or not there is an optimum level at which to deploy the two velocity paths when using a twin-path gauge. It would appear from this analysis that, provided the transducers are not deployed at either the lowest and/or highest possible levels, sensible results will be obtained in the majority of cases from almost any deployment configuration. Whilst this is reassuring, it does not really provide the guidance that was perhaps envisaged when the Project objectives were initially drawn up. The data contained in Appendix F were thus further analysed to assess whether or not a general approach could be identified. This analysis consisted of considering the different matrices by both their vertical and horizontal elements to enable the lower and upper path levels to be identified. The following approach is considered to provide the most sensible combination:

Lower path Deployed at less than 0.3 of the maximum depth
Upper path Deployed at between 0.45 and 0.75 of the maximum depth.

The higher the level of the low path (ie as it approaches 0.3 H_{max}), the higher the upper path should be to ensure that a greater section of the river is sampled.

Note: In cases where the equipment is being installed at a new site, for which there are no records, the maximum depth will not be know. Instead, a design depth will have to be set. If actual levels are significantly above of below this the accuracy of the gauge may be decreased.

All but one of the 72 model configurations for the four Agency multi-path gauges that comply with this combination produce flows to within 5% of the multi-path gauge, and 74% are to within 2%. If the Buildwas data are excluded then almost 85% of the configurations are to within 2%, and **all** are within 5%.

It is thus recommended that if a gauge is to be deployed in a twin-path configuration the velocity paths are set up as described above. Velocity profiles taken with a current meter may subsequently enable the levels to be fine-tuned, but on the basis of the available data it appears that this combination will provide flows that are within 5% of those that a multi-path gauge would produce.

4.6 Uncertainty analysis

At the Project Inception Meeting the Agency advised that the project should proceed on the assumption that ultrasonic gauges work, ie that the technology is a proven one. It was agreed that no measurements would be taken to try and identify whether or not the measured path velocity was correct, not least because it was felt that the uncertainties associated with the measurement of the velocity by current meter were likely to be as large (if not larger) than with the ultrasonic gauge. Consequently, this section does not include an assessment of the theoretical uncertainties associated with the ultrasonic gauge itself. These are described in detail in BS 3680 Part 3E: 1993/ ISO 6416: 1992 (E) (an extract of which is contained in section 2.1.2 of this Report), from which the total combined theoretical uncertainty can be derived using the 'root-sum-of-squares' approach. Instead, this section will focus on the uncertainties that are associated with the use of the equipment, together with an assessment of the uncertainties in the flows derived by the gauge.

4.6.1 Gauge and commissioning

The majority of the uncertainties associated with the gauge installation are described in BS 3680 Part 3E: 1993/ ISO 6416: 1992 (E), the most relevant of which appears to be the determination of the true direction of flow at a given site. As Sections 2.1.3 and 3.3.4 have explained, any error in the determination of angle between the transducer path and the direction of flow may be magnified in the discharge computation, typically by between 1% and 3% per degree of error. Whilst the use of a floating line will assist with the reduction of this error at a site located on a gentle bend in the river, it is inevitable that there is still likely to be an error in the determination of the angle between the velocity path and the direction of flow. However, it should also be considered that this uncertainty will, to a certain extent, be offset by two related factors.

The first of these is associated with the actual use of the gauge - it has already been recommended that when the gauge is commissioned the bed correction parameter should be set to an initial value of 0.65, and then adjusted as low flow gaugings become available. This adjustment will therefore take account of any systematic uncertainty arising from any error in the determination of the true direction of flow.

The second factor is perhaps more fundamental in that there are additional uncertainties associated with the determination of parameters used by the gauge to calculate the **flow** from the measured velocity. Whilst the uncertainty in the measured velocity will be greatest for higher intersection angles between the velocity path and true direction of flow, the uncertainty in the calculation of the cross-sectional area by the gauge will follow the inverse relationship, ie it will be greatest for low intersection angles, provided that the path length is measured correctly, as it is based on the use of a sine function. To illustrate this, Table 4.6 shows the uncertainty that will arise in the calculation of the cross-sectional width for different intersection angles in a 15 metre wide channel; the uncertainties have been calculated for three different errors in the determination of the distance between the upstream and downstream transducer racks parallel to the direction of flow, which will produce differing errors in the intersection angle.

Table 4.6 Theoretical percentage uncertainties in the calculation of the width of the channel cross-section by the ultrasonic gauge for different measurement errors of the long-channel distance between the upstream and downstream transducer racks (upper values), together with the errors in intersection angle that arise from the measurement errors (lower values).

Intersection Angle	Error in determination of long-channel distance between upstream and downstream transducer racks for a 15 metre wide channel.		
	0.25 m error	0.5 m error	1.0 m error
30^0	2.6%	5.3%	10.5%
	0.2^0	0.5^0	1^0
45^0	1.6%	3.2%	6.2%
	0.5^0	1^0	2^0
60^0	0.9%	1.8%	3.6%
	0.7^0	1.5^0	3^0

Whilst it could be argued that the values shown in Table 4.6 present a worst case scenario, and that the uncertainties will also be accommodated by the adjustment to the bed correction factor, they do serve to demonstrate the importance of undertaking an accurate survey when installing the equipment. The highest uncertainty calculated in Table 4.6 of over 10% is associated with a 1 metre error in the measurement of a long-channel distance of 26 metres, or a one degree error in the measurement of the intersection angle - this is by no means unrealistic, particularly if the site is located on a bend in the river. The Blackford Bridge installation was resurveyed on three separate occasions, and the distances differed by this order of magnitude.

A further potential source of uncertainty associated with the use of the ultrasonic gauges is the degree to which they are able to measure the mean velocity across the whole of the channel cross section. This will depend on both the channel geometry and the method used to mount the transducers. The ideal situation is either a channel with vertical sides to which a rack can be bolted, as with Low Nibthwaite, or a series of ramps or mini vertical racks running up sloping river banks. Both of these solutions will ensure that no flow passes 'behind' the transducer path.

However, if vertical racks are used at a site with sloping banks, as at Greenholme, there is an increasing tendency for water to flow outside the gauged section as river levels rise. The degree to which this introduces uncertainties into the derivation of the flow will depend on the extent of this by-passing, which will obviously vary from site to site. Indeed, in some cases the near-bank flow is often an eddy or backwater, the exclusion of which may increase rather than decrease the measured velocity. It is considered that the by-pass effect was insignificant at both Greenholme and Blackford Bridge, sites where such a configuration was used. Peek have recognised the potential significance of this and have developed a software 'add-on' which allows the gauge user to derive velocity factor tables which the gauge will then use to automatically adjust the computed flows. This software is also designed to reduce the uncertainties arising from the use of a limited number of velocity paths, together with compensating for one of the paths failing during a specific event. The software was not used during the course of the Project as it is not a standard feature, and is used by a limited number of Agency Regions. Appendix G contains the manufacturer's description of the software, together with some examples of how different velocity factor tables can be developed and programmed.

The final sources of uncertainty associated with the use of the gauge are those associated with 'standard' hydrometric activities and include well lag, measurement error (eg of level and/or stage) and timing discrepancies. Again, the various elements of BS 3680 provide detailed guidance on the calculation of these uncertainties, which typically result in an estimated error of between ±1 and ±4%. These random uncertainties are likely to be similar regardless of the approach used to derive flows at a given site. For example, whilst an immersed ultrasonic depth sensor may only be accurate to within 2-3 mm, which will produce higher errors in the calculated flow as the river level rises, this resolution is no different to the stilling well level fluctuations that are known to occur at some sites as the water level oscillates, particularly during high flows.

4.6.2 Derived flows

Having considered the theoretical uncertainties associated with the principles behind the use of ultrasonic gauges, many of which will either tend to cancel each other out as described or be accommodated by setting the gauge parameters accordingly, it is possible to evaluate the uncertainties that exist in the flows derived by the gauge itself.

This chapter has already identified a number of issues relating to uncertainty in the derived flows. The first of these was the systematic error in flow calculation arising from the use of a limited number of paths, as described in section 4.4.1. The gauge will follow an over-correct-under estimation cycle as successive velocity paths come into operation. This cycle has been observed in the data collected at the field sites. As the errors are systematic they can be allowed for when using the derived flows; for example, once both of the velocity paths are submerged there will be an increasing tendency for the gauge to underestimate flows as levels rise.

Whilst this over-correct-under estimation cycle is likely to occur, the analysis of data from multi-path gauges presented in section 4.5 has demonstrated that the resultant uncertainties are relatively low. In the majority of cases the uncertainty is less than 5%, with almost 50% of the different combinations producing flows to within 2% of those produced by a multi-path gauge. Section 4.5 has also demonstrated that if the velocity paths are deployed in the recommended configuration flows may be calculated to within 2% for approximately 75% of the different scenarios.

However, it is important to remember that the analysis presented in section 4.5 relates only to measurements taken at a specific moment in time, and was undertaken with the aim of determining an optimum configuration for deploying the transducer paths. The uncertainties will vary through an individual event as the relative position of the transducer paths in the water column alters. In order to provide a realistic assessment of the overall uncertainties that exist during these transient events it is thus necessary to compare the flows derived by the gauge to the 'true' flow, whatever that may be.

To enable this assessment it is first necessary to assume that the Agency derived flows are the best approximation of the 'true' flow at a given site, even though these will have their own inherent uncertainties, depending on how they were derived. Due to the uncertainty that is known to exist in the Blackford Bridge rating curve the evaluation will use the field data calculated at Greenholme and Low Nibthwaite. Subsequent chapters will use data collected from other sites to assess the uncertainties associated with alternative approaches to using the equipment.

A total of four different sets of uncertainties in the derived flows have been identified from the Greenholme and Low Nibthwaite data sets for use in this section. Further combinations exist, and are associated with different ways of determining the mean bed level. However, as it has been recommended that this should be set to the surveyed level, and only the bed correction factor should be altered, the four different approaches used in this analysis are as follows:

1. Using the gauge with the manufacturer's default settings, specifically with the bed correction factor set to 0.8:
2. Setting the bed correction factor on the basis of the first four 15-minute flow values recorded at the site, and using these values thereafter for all gauge configurations.

3. Resetting the bed correction factor every time the level of the velocity paths is altered.
4. Retrospectively optimising the bed correction factor after an event.

The final approach is not included as a potential method for use in the field, but purely to identify the maximum performance that the gauge could achieve. This approach is unlikely to be used in reality as it requires an alternative means of calculating flows at a site to already be in use.

Typical uncertainties for each of the four approaches, over the whole of the recorded events, are summarised in Table 4.7, from which it can be seen that whilst using the default gauge parameters may produce unacceptable results, the three approaches which involve adjusting the bed correction factor all typically produce flows to within 5%. The uncertainty can be reduced to near 'optimum' levels (ie those from approach 4) by resetting the bed correction factor for each different transducer path configuration, resulting in mean uncertainties of between 2 and 3% over a whole event, and maximum uncertainties of ± 7%.

It is recognised that these values might be considered to be optimistic by some parties, particularly as they have been produced from sites where considerable energy has been expended in both the fieldwork and subsequent analysis. It is thus concluded that, provided the bed correction factor is adjusted for each different transducer path configuration, the typical uncertainties in the derived flows will be within ± 5%, with the maximum uncertainty falling within ±10%, ie half that if the gauge default parameter settings are used.

If it is not possible to undertake any calibration gaugings at a given site, for whatever reason, then it will be necessary to set the bed correction factor to 0.65 instead of the manufacturer's value of 0.8. In the case of the Greenholme data set this would increase the mean uncertainty to ± 6.5%, although the increase would have been less for Low Nibthwaite. It is thus concluded that if it is necessary to use a pre-set value for the bed correction factor, provided this is set to 0.65 the mean uncertainty is likely to be less than ± 7%, depending on the specific site.

Table 4.7 Typical and maximum uncertainties in the flows derived by the ultrasonic gauges deployed at Greenholme and Low Nibthwaite. Note that the uncertainties are in fact the mean difference between the flows derived by the Agency rating and ultrasonic gauge.

Approach	Typical uncertainty	Maximum uncertainty
1. Use manufacturers default settings	± 10 - 12%	± 20%
2. Determine bed parameters on a one-off basis, and use for all configurations	± 3.5 - 5%	± 10%
3. Determine bed parameters for each different configuration	± 2 - 3%	± 7%
4. Retrospectively optimise parameters after each event	± 1.5 - 2%	± 5%

Finally, it should be remembered that the uncertainty analysis described in this section only applies to the derivation of flows **within the observed range of river levels**. As soon as any stage-discharge relationship derived from a limited range in river level fluctuation is extrapolated beyond the observed range of levels to derive flows the uncertainties will increase. However, as subsequent chapters will demonstrate, the fact that the gauge is able to collect so much data in such a short period of time provides greater confidence in the validity of such a relationship. In particular, the greatly increased number of observations allows any hydraulic changes to be detected (for example, changes caused by a 'new' downstream control on flow); such changes may require extensive gauging by current meter before they can be accurately detected by more conventional means.

4.7 Typical operating costs

In section 3.4 the staffing implications associated with the installation of the gauge were assessed, with typical values being found to total 30 staff hours on site. Travel costs and time were excluded from the assessment as these will vary from site to site and from Region to Region. The overall operational costs associated with using the gauge in a simple twin-path configuration were assessed using the following assumptions. Wherever possible a cautious assessment was made to ensure that the outcome was an indication of the upper end of the likely costs:

1. Time taken to procure the equipment has been excluded (and should be added to the total if this process has to be undertaken).
2. Travel time and costs have been assessed on the basis of site visits. These can be multiplied by the specific distance and travel time to produce the total cost.
3. The equipment has an effective pay-back period/shelf life of four years, with the capital cost being depreciated at a fixed 25% of the initial purchase price per year for four years.
4. It will be necessary to purchase a mounting system for each new site (in reality, a total of four mounting systems enabled seven sets of twin-paths to be used during the Project).
5. No allowance has been made for spares - none of the transducers failed during the course of the Project.
6. Similarly, no allowance has been made for keeping the equipment on a maintenance contract and/or extended warranty as this is a commercially sensitive issue.
7. Once the equipment has been installed there will be a need for two visits to overcome 'teething' problems (again, this value was less during the course of the Project at most of the later sites).
8. The equipment is likely to be installed at a given site for a period of six months, during which period a total of eight site visits will be made; these will all involve 2.5 hours on site, during which other hydrometric activities can also be carried out (the minimum length of any site visit during the course of the Project was 25 minutes). Should there be no mains power available at a specific site the number of site visits is likely to rise.
9. No allowance has been made for the time taken with data processing - this is likely to vary depending on the method used to log and download the data.
10. No allowance has been made for site visits and advice from the gauge manufacturer.
11. Finally, a total of 8 hours have been allowed for the removal of the equipment from the site - again, this is a slightly higher value than the average from the six Project field sites, the additional time being included to allow for cleaning and storing the equipment back in the store.

Using these assumptions the total cost of operating the gauge in this manner was calculated, and the results are shown in Table 4.8.

It should be noted that the figures presented in Table 4.8 have been derived on the basis that a site will be visited for the sole purpose of using the ultrasonic gauge. In reality, the majority of the site visits (at least 10 of the 14) could be combined with other visits to the site by hydrometric field staff, in which case the costs can be reduced accordingly. It can be seen from Table 4.8 that the total operating cost associated with this approach is £1,311 per site, plus 67 staff hours on site, plus any additional travel time in excess of normal travel (and the costs associated with this).

Table 4.8 Assessment of the typical operating costs associated with using a twin path gauge at a single gauging station over a six month period.

Process / element	Included items	Staff time	No of site visits	Equipment costs
Capital costs of equipment	1/8 of cost of purchase at £7,285 inclusive			£911
Initial site visit	Staff time and travel	4 hours	1	
Equipment installation & commissioning	Staff time on site (over two days), travel plus mounting racks	30 hours	2	£400
'Teething problem' phase	Staff time on site plus travel	5 hours	2	
Gauge operation	Staff time on site plus travel	20 hours	8	
Gauge removal	Staff time on site plus travel	8 hours	1	
Total		67 hours	14	£1,311

4.8 Conclusions

This Chapter has presented the results from using the ultrasonic gauge at three of the Project field sites under a range of flow conditions. The equipment performed well at each of the sites, with the exception of the velocity paths failing due to high sediment concentrations during the peak of some of the high flow events. The results demonstrate that the gauge is able to measure both depth and velocity consistently and, using these measurements, compute the river flow at 15-minute intervals.

Using the default parameters suggested by the manufacturer the gauge is able to measure flows with a typical uncertainty of ± 10%. This uncertainty can be significantly reduced to ± 5% by setting the bed correction factor after completing a single current meter gauging at the site when installing the gauge. If this is not possible, setting the bed correction factor to 0.65 is likely to reduce the typical uncertainty to less than ± 7%.

Extensive analysis of data collected from multi-path gauges operated by the Agency has shown that the use of only two velocity paths is not necessarily accompanied by a significant reduction in gauge performance. Almost 75% of the modelled twin-path combinations performed to within 5% of the multi-path gauge. Where water levels lie within the identified optimum band for the twin transducer levels, almost 75% of the modelled twin path combinations performed to within 2% of the multi-path gauge.

The recommendations for setting the twin-path transducer levels to give optimum performance are:

Lower path	deployed at less than 0.3 of the design water depth
Upper path	deployed at between 0.45 and 0.7 of the design water depth

The higher the level of the lower path, the higher level of the upper path.

Finally, an assessment of the typical operating costs has shown that the use of a gauge at a field site for a period of six months is likely to cost the Agency up to 70 staff hours, plus the travel costs associated with 14 site visits, and equipment costs of just over £1,300. The travel costs will be significantly reduced if the site visits are combined with other hydrometric activities.

5 OPERATING THE GAUGE TO DERIVE STAGE - DISCHARGE RELATIONSHIPS

5.1 Introduction

As Chapter 4 explained, the gauges were always deployed as a twin path system, with two sets of transducers deployed at any one time, nearly always one above the other. During the course of the studies at each site the transducers were operated at a number of levels. The main reason for doing this was to try and determine whether or not there was an optimum level for deploying the transducer paths, as described in Chapter 4. However, operating the gauges in this way also enabled a further method of using the gauges to be evaluated, namely using the gauges to replicate a multi-path gauge over a number of events. The aim was to assess whether or not it was possible to derive stable stage-velocity relationships for different transducer path levels. If so, these relationships could then be used to generate stage-discharge relationships before extending the analysis to evaluate the consequences of having data from a limited number of paths.

This approach was followed at sites where there was a stable and consistent relationship between stage and path velocity, ie Greenholme, Blackford Bridge and Middleton in Teesdale. Whilst velocity data were collected from different levels at other sites, most notably Walcot, it was found that the relationship differed for different events at different times of the year, due to differing channel conditions. This will be discussed further in Chapter 6. At Low Nibthwaite the range in river levels was so low that it was decided the approach was unlikely to produce results that were significantly different from those based on analysis of a single event.

5.2 Greenholme

Having operated the Greenholme gauge at a total of six different path levels, as indicated in Table 4.1, stage-velocity relationships were determined for each of these paths. Plotting the velocity data against river level produced a set of near-linear curves for all levels, as shown in Figure 5.1 which plots the data for the lowest and highest paths that were used. Given this it was decided to derive the relationship using simple linear relationships. It is realised that these may not be the most suitable method at higher stages, or for use at all sites.

Six relationships were derived using this method; they are given below Table 5.1, and plotted in Figure 5.2.

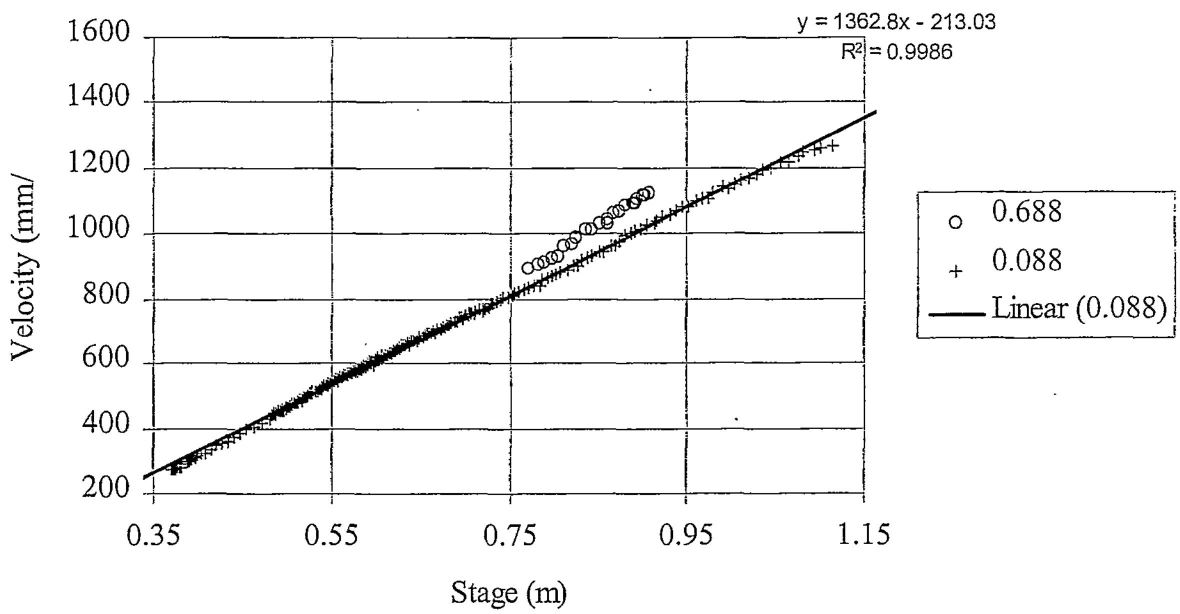


Figure 5.1 Stage velocity data for the lowest (0.088) and highest (0.688) transducer paths used at Greenholme gauging station, together with the best fit linear relationship for the 0.088 metre velocity path.

Table 5.1 Best fit lines derived for stage-velocity relationships for the six transducer paths that were used at Greenholme between January and May 1996.

Path Level	Best Fit Linear Regression Line	R^2 value
0.088	V = 1362.8 stage - 213.03	0.9986
0.188	V = 1465.6 stage - 265.2	0.9989
0.388	V = 1442 stage - 210.67	0.9958
0.488	V = 1532.2 stage - 275.97	0.9991
0.588	V = 1631.1 stage - 337.52	0.9851
0.688	V = 1755.5 stage - 265.2	0.9989

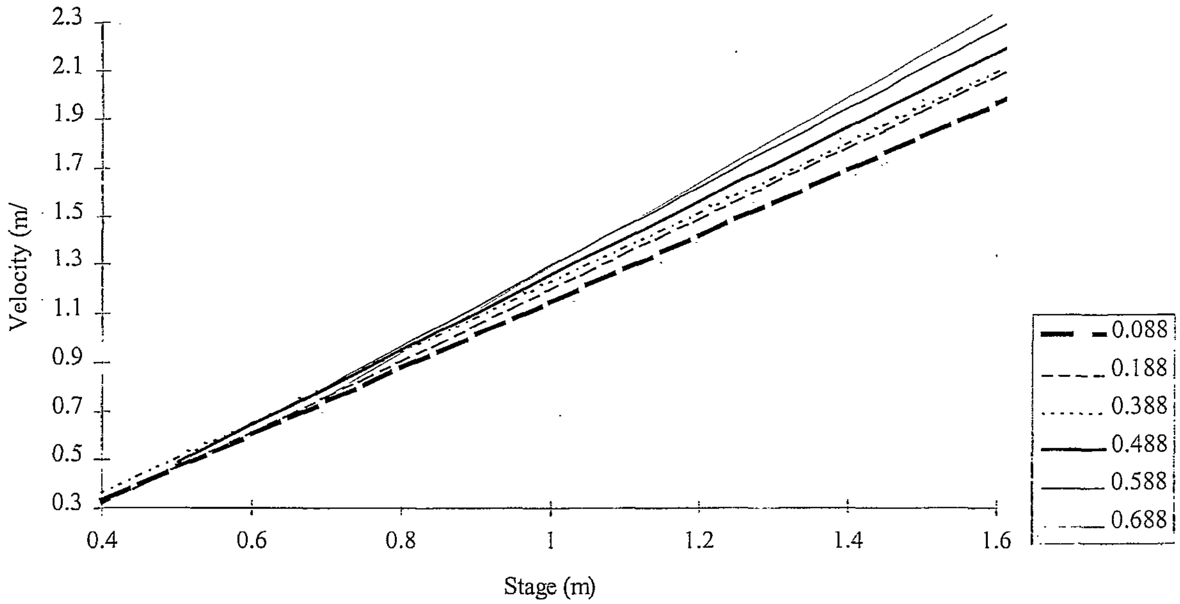


Figure 5.2 Stage velocity relationships derived for the six transducer path levels at Greenholme.

It can be seen from Figure 5.2 that the stage velocity relationships form a consistent pattern for the different velocity paths, with higher velocities being produced for the higher paths at a given stage. Whilst this is to be expected, the data contained in the Project Record and plotted in Figure 5.1 show that in some cases, most notably the 0.688 m path, the relationships are based on very limited data (in this case, 23 data points collected between a stage of 0.7 and 0.9 metres) and are still able to form a relationship that is consistent with data collected over a much wider range. The same observation was also made of the Blackford Bridge and Middleton in Teesdale data that are used later in this chapter. This would suggest that if data are collected from at least one velocity path over a wide range in flows, this will provide a suitable reference to which relationships from less comprehensive data sets at other levels can be compared and, if necessary, adjusted at the higher levels, thus reducing any uncertainty associated with the extrapolation of the relationships. The fact that the 0.688 metre path relationship was derived from only 23 data points, relating to less than eight hours during the event, and is still able to produce a relationship that is consistent with those collected over a much wider range in levels would suggest that the need for any adjustment may be small.

The six relationships contained in Table 5.5 were then used to derive a stage discharge relationship for the channel section using the same method as the multi-path gauges, and as represented in Figure 2.2, in the following sequence:

1. For a given river level the number of velocity paths that would be immersed was identified.
2. For each of the individual velocity paths that were immersed the velocity was derived using the appropriate stage-velocity relationship.
3. Q_s, the discharge for each vertical slice in the river, is then calculated using the derived velocities, as shown in Figure 2.2.
4. The total discharge for the given river level is then obtained by summing the various values of Q_s.
5. This process was repeated for different river levels at a 5 mm increment to produce the stage-discharge relationship.

The resulting relationship is plotted in Figure 5.3, which also shows Rating 08 used by the Agency for the past twenty years, along with the rating that was approved for use mid-way through the study period in March 1996. The rating curves have all been taken up to a maximum stage of 2.0 metres, yet the peak observed level was only 1.32 metres. Given this, the performance of the gauge will be considered in two ways - within the observed range of flows, and when used to extrapolate outwith this range.

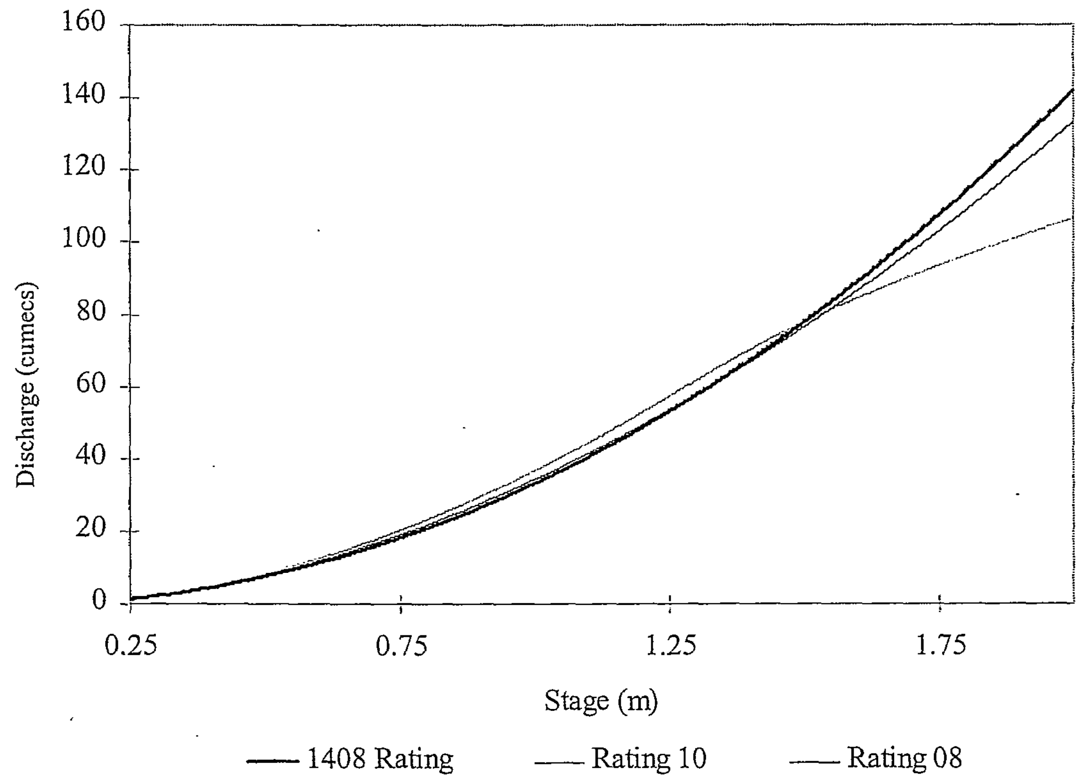


Figure 5.3 The rating curves derived by the stage-velocity method from the ultrasonic gauge (1408 Rating), the curve used by the Environment Agency between 1975 and 1996 (Rating 08) and the most recent Agency curve (Rating 10) for Greenholme gauging station.

5.2.1 Assessment of the rating within the observed range of flows

Figure 5.4 shows the deviation of the gauge six-path derived relationship from the two Agency ratings within the observed range of flows. From this and Figure 5.3 it can be seen that the 6-path derived relationship performs especially well when compared to Rating No 08 which was used by the Agency for so long. Derived flows never differ by more than 5%, and are generally within ± 3%.

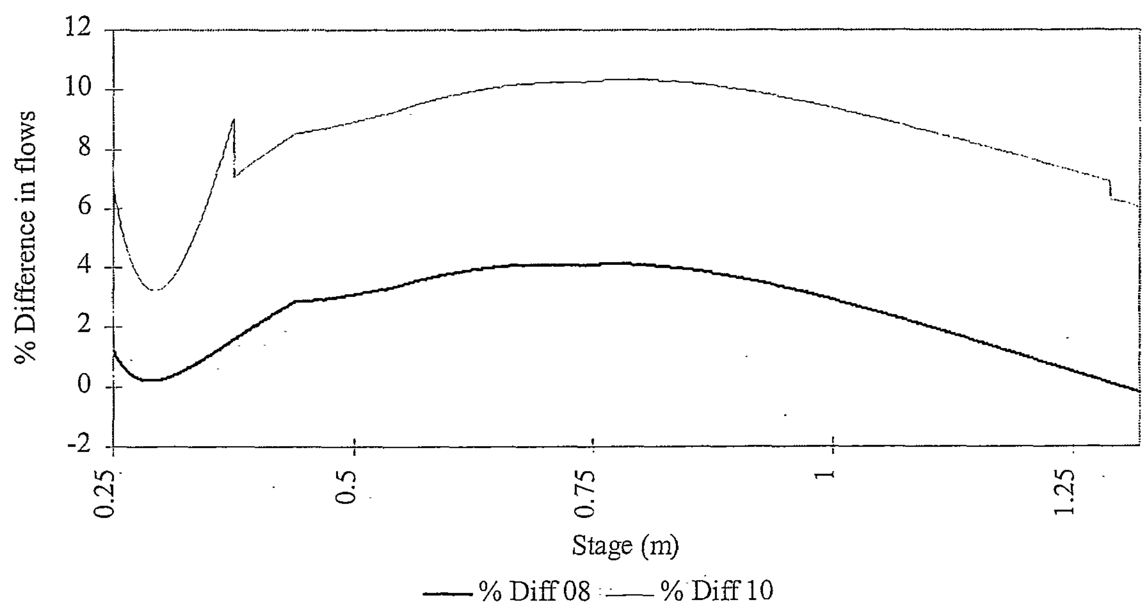


Figure 5.4 % difference between the stage discharge relationship derived by the gauge and the most recent one developed by the Agency (% Diff 10) and the Agency rating that was used between 1975 and 1996 (% Diff 08) over the observed range in flows.

To try and put the derived relationship into some kind of perspective the peak flow to occur during the entire study period as calculated by the gauge derived relationship was compared to the peak flow produced to by the Agency. The Agency peak flow of 59.269 cumecs compared most favourably to the gauge's derived value of 59.268 cumecs, a difference of less than 0.002%. It can thus be seen that when the relationship is applied to the same range of flows over which the data were collected it is able to perform very well.

One further significant difference that can be seen from Figure 5.4 is that the difference between gauge and Agency rating at low flows is greater for the new rating - this is because the gauge bed correction factor was determined by reference to the Agency rating No 8 at the start of the monitoring as this was the relationship that was in use at the time.

5.2.2 Extrapolation of the rating beyond the observed range of flows

The stage discharge ratings were all extrapolated to a stage of 2.0 metres and plotted below in Figure 5.5, from which it can be seen that even at the two metre stage the deviation from the Agency Rating 08 is less than 7% which is still quite impressive, particularly if one remembers that the highest transducer path was deployed at only at 0.688 m, and that this level was used to collect velocity data up to a stage of only 0.9 metres. It can also be seen that the 'multi-path' derived gauge rating does not follow the repeated over-correct-under estimation cycle as would be expected with a twin path installation. Instead, it would appear that the transducer paths were at such similar levels that they have effectively monitored a single water body, resulting in one single over-correct-under estimation cycle as river levels rise.

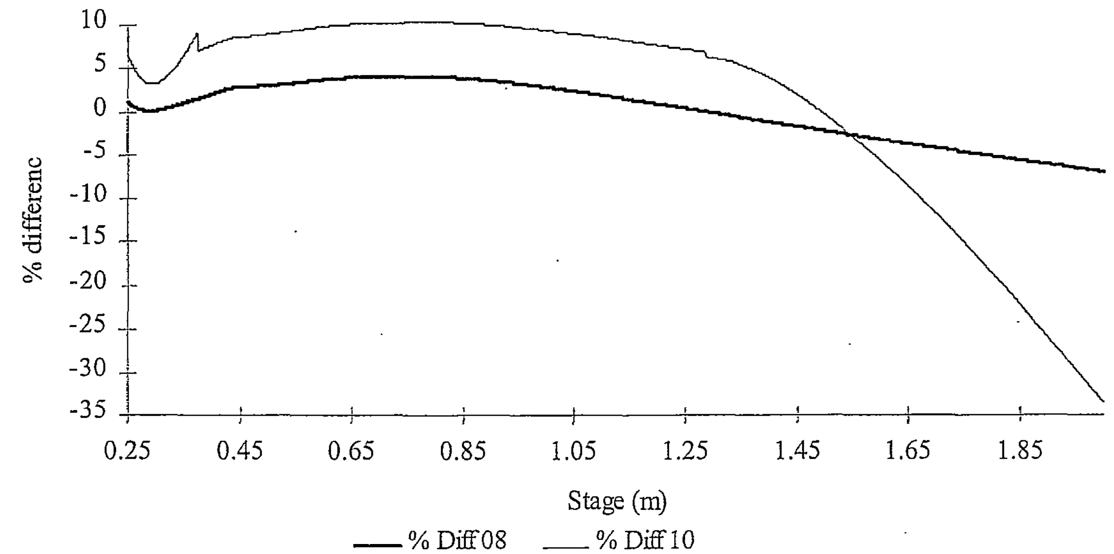


Figure 5.5 % difference between the stage discharge relationship derived by the gauge and the most recent one developed by the Agency (% Diff 10) and the Agency rating that was used between 1975 and 1996 (% Diff 08), extrapolated to a stage of 2.0 metres.

However, the performance is less impressive when compared to the newly revised Rating 10. Whilst it again performs well up to the 1.5 m level, ie close to the observed range of levels encountered by the ultrasonic gauge, above that it begins to depreciate significantly with the deviation being over 30% at the 2 m level. The 'step' in the gauge vs Rating No 10 plot shown in Figure 5.5 corresponds to the maximum recorded stage - beyond this the gauge performance significantly weakens as flows are extrapolated beyond the observed range. It must also be noted that Rating 08 also behaved in a similar way, clearly visible in Figure 5.3;

if the new Agency rating is extended to above three metres it becomes concave once more, eventually rising to meet the two upper curves.

Whilst the reason for this divergence in the ratings at a stage of approximately 1.5 metres is not certain, two potential explanations are that the weir is fully drowned at this stage and an alternative downstream control comes into play, or that there is a change in the stage-discharge relationship as the river begins to flow out of the main channel. The first hypothesis is supported by the fact that the difference in level between the weir crest and downstream riverbed is low, and the second by the analysis of the Agency multi-path gauge data presented in Chapter 4 which showed lower than expected velocity readings at high river levels, possibly due to increased friction from riverbank vegetation. Regardless of whether or not either of these hypotheses provide the explanation for why the relationship changes, it must be remembered that the change takes place at a river level that exceeds the highest recorded event during the study period. It is unreasonable to expect the gauge to be able to predict any change in channel hydraulics beyond the measured range and it must thus be concluded that, despite the apparent discrepancy between the most recent Agency rating curve and that produced by the ultrasonic gauge at high flows, the gauge appears to have produced a rating curve that agrees closely with the Agency rating over the observed range in flows.

If Figure 5.1 is studied closely it can be seen that the linear relationship fitted to the velocity data collected from the 0.088 metre transducer path appears to over-predict the recorded value. If this over-prediction continues up to a stage of 2.0 metres it can be seen that the difference is potentially significant. To explore this further, all six data series that were used to derive the linear relationships plotted in Figure 5.2 and listed in Table 5.1 were re-evaluated using a second order polynomial. The relationships were then used to predict velocities for each path at a stage of 2.0 metres, and the results compared to the values produced by the linear relationships. The results of this analysis are summarised below in Table 5.2.

The results presented in Table 5.2 would suggest that, as indicated earlier in this section of the Report, simple linear regressions will not necessarily provide the most suitable method of quantifying the different relationships between stage and velocity. Whilst they were more than adequate for quantifying the relationship within the observed range of levels at Greenholme, Figure 5.1 indicates that they may over-predict peak velocities for this site. This is confirmed by the different rating curves plotted in Figure 5.3. Replacing the linear relationships with second order polynomials reduces the mean predicted flow in the river by 12% from 2.77 to 2.43 m/s. This will have an almost identical effect on the flow prediction at this river level, without reducing the predictive ability over the observed range in flows. Consequently, were sufficient data available to produce consistent polynomial relationships, they would result in reducing the differences between the Agency rating 10 and the stage-discharge relationship produced by the ultrasonic gauge data presented in Figures 5.4 and 5.5.

Table 5.2 Predicted mean path velocities for the six transducer path levels at a stage of 2.0 metres, derived from both the linear and polynomial relationships.

Path height	Linear prediction	Polynomial prediction	No of points	% reduction
0.088 m	2.51 m/s	2.19 m/s	252	13%
0.188 m	2.67 m/s	2.54 m/s	287	5%
0.388 m	2.67 m/s	2.25 m/s	396	16%
0.488 m	2.79 m/s	2.64 m/s	126	5%
0.588 m	2.92 m/s	2.74 m/s	38	6%
0.688 m	3.05 m/s	2.22 m/s	23	27%
Average	2.77 m/s	2.43 m/s		12 %

However, it can be seen from Table 5.2 that the recorded events at Greenholme were not sufficient to produce consistent polynomial relationships; the predicted velocity for the 0.688 metre transducer path, which is based on only 23 data points, is the second lowest of the six predictions. It is for this reason that the analysis was not repeated in full using the polynomial curves; the data are sufficient to demonstrate the benefits from collecting information over as wide a range of flows as possible, whilst at the same time confirming the need for caution when extrapolating beyond the observed range. However, should the user wish to develop the rating further when using the approach 'for real', they will be able to plot the different polynomials (or whatever best-fit method is used) to establish the general pattern of the stage-velocity relationships before deciding which data sets appear to provide the most consistent pattern and develop appropriate relationships from these which are then used as the basis for deriving the stage-discharge relationship. Caution must be used, however, before using polynomials for extrapolating beyond the observed range in river levels as they can produce 'unstable' relationships.

Finally, one further positive result to arise from the Greenholme data presented in this chapter is that it provides further confirmation of the recommendations made in section 4.5 following the analysis of the Agency multi-path gauge data from other sites. This was that the lowest velocity path should be deployed at less than 0.3 of the total maximum depth, and that the upper velocity path should be deployed at between 0.45 and 0.75 of the total maximum depth. At a stage of 1.5 metres, ie the point at which the gauge performance begins to decrease, the lowest velocity path was deployed at 0.26 of the total depth, an the highest path was at 0.58 of the total depth.

5.3 Blackford Bridge

5.3.1 Derivation of rating curve for Blackford Bridge

The analysis relating to the ability of the gauge to measure flow had to be undertaken in a different order for Blackford Bridge than at other Project sites. This was due to the acknowledged uncertainty in the Agency rating for the site; in order to assess the performance of the gauge it was first necessary to establish a standard against which comparisons could then be made. It was thus decided to derive a stage-discharge rating for the site based on the stage-velocity relationships approach described for Greenholme, and then use this to assess the importance of having data from a number of velocity paths. The following individual steps were undertaken:

- The stage velocity relationships were established, as set out in Section 5.2, and plotted in Figure 5.6. For the Blackford Bridge data it was decided that a second order polynomial provided the most suitable relationship for two of the velocity paths within the observed range of data, but that at higher levels it was necessary to limit the values as the predictive nature of the polynomial deteriorated.
- The most suitable relationships were then selected for use to determine the rating. In the case of Blackford Bridge, the 0.0, 0.2 and 0.6 metre paths were used.
- The stage-velocity relationships were used to determine velocities for differing stages, rising from 0.3 to 1.5 metres above stage datum, rising in increments of 0.01 metres.
- The lowest velocity path (0.0) was used to calculate the discharge in two slices. The lower slice ranged from the mean bed level (-0.73 metres) to the midpoint between the bed and the path height (i.e. it was 0.365 metres high). This height was then multiplied by the path velocity for each stage and the path length (19.25 metres), and the result was then multiplied by the 'bed correction factor' to give the slice discharge ($Q_{1,1}$). Whilst it has been demonstrated that improvements do arise from optimising this value at some of the study sites, for the purposes of this site the value was set to 0.67. This value was obtained when the gauge was first commissioned by adjusting it until the gauge 1-minute flow corresponded with the flow derived from the Agency rating (under low flow conditions). The value of 0.67 is very similar to that suggested elsewhere in this Report (0.65) as an initial estimate instead of the Peek value of 0.8.
- The upper of the two slices to which the lowest velocity path data were applied ranged from 0.365m below stage datum to the midpoint between the 0.0 and the 0.2 metre velocity paths, i.e. 0.1 metres. Whilst in practice this could mean that the velocity path could be used to determine the lowest flows (i.e. with a stage < 0.1 m) on its own by

setting the 'slice' upper limit to the water surface, this was not necessary as the Project was concentrating on mid and high flows. The slice height was then multiplied by the path velocity and path length to determine the slice discharge ($Q_{1,2}$).

- The next velocity path was then used to determine the discharge of the next slice, Q_2, in the same way. The height of this section ranged from 0.1 metres to the water surface, until levels reached 0.6 metres at which time the next velocity path would be covered. When this occurred the upper limit of the 0.2 metre slice was set at the midpoint between 0.2 and 0.6 metres, i.e. 0.4 metres.
- Finally, the highest velocity path was used to determine the discharge of the top section of the river, Q_3. The height of the slice ranged from 0.4 metres to the water surface.
- Once each of the component discharges $Q_{1,1}$, $Q_{1,2}$, Q_2 and Q_3 had been calculated, they were summed to give the total discharge for the river for each stage.

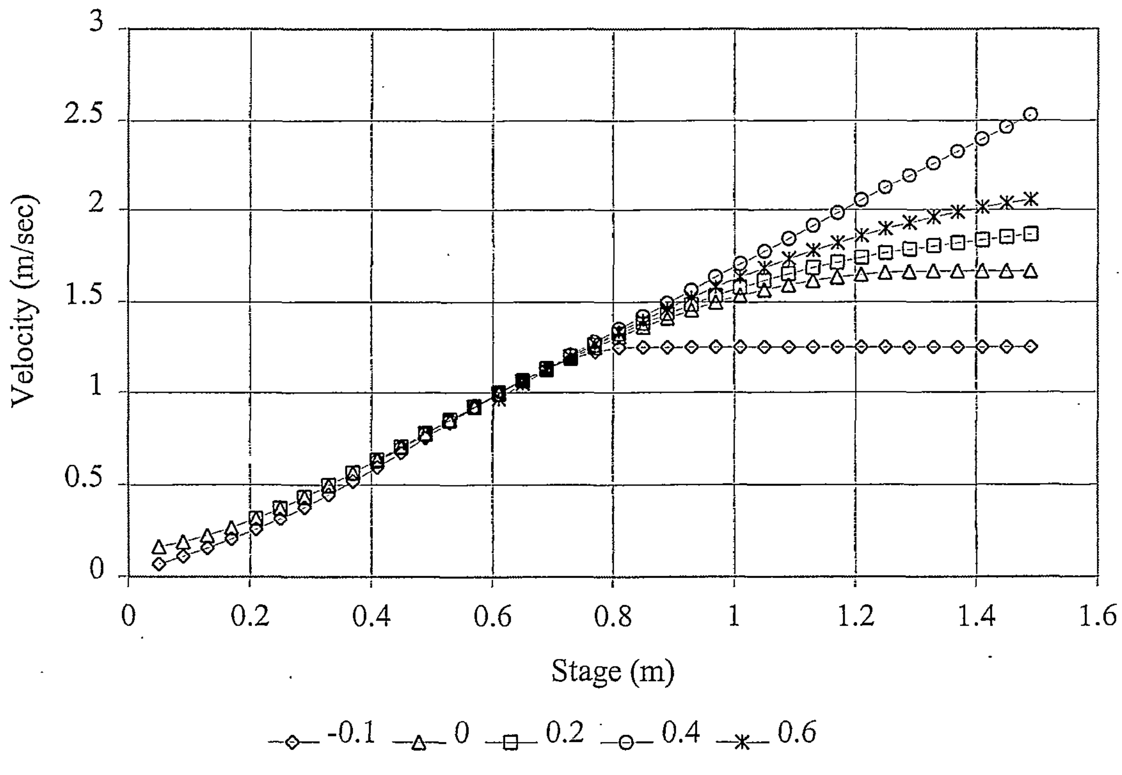


Figure 5.6 Stage-velocity relationships derived for the five velocity paths used at Blackford Bridge gauging station. Note that due to the nature of the polynomial used to extend the data series for the -0.1 and 0.0 metre paths, the velocities have been truncated off at a sensible limit. Had the relationships been used to extend the series beyond this point, the predicted velocities would have fallen. All levels are in metres, and are relative to stage datum.

The stage discharge rating arising from this analysis is plotted in Figure 5.7, together with the Agency rating for the site and a theoretical rating developed by HR Wallingford. It can be seen from this that the rating derived from the ultrasonic gauge data closely follows the Agency rating derived by current metering up to a stage of approximately 0.6 metres. At this point the gauge rating diverges from the Agency curve, producing a lower flow for a given stage. From this point of divergence it follows the same general pattern as the curve derived by HR, but producing consistently higher flows (typically by 2-3 cumecs). However, above a stage of 1.1 metres the gauge rating begins to flatten, crossing the HR rating at a stage of 1.3 metres. From this point on the gauge rating produces the lowest flow for a given stage of all three ratings.

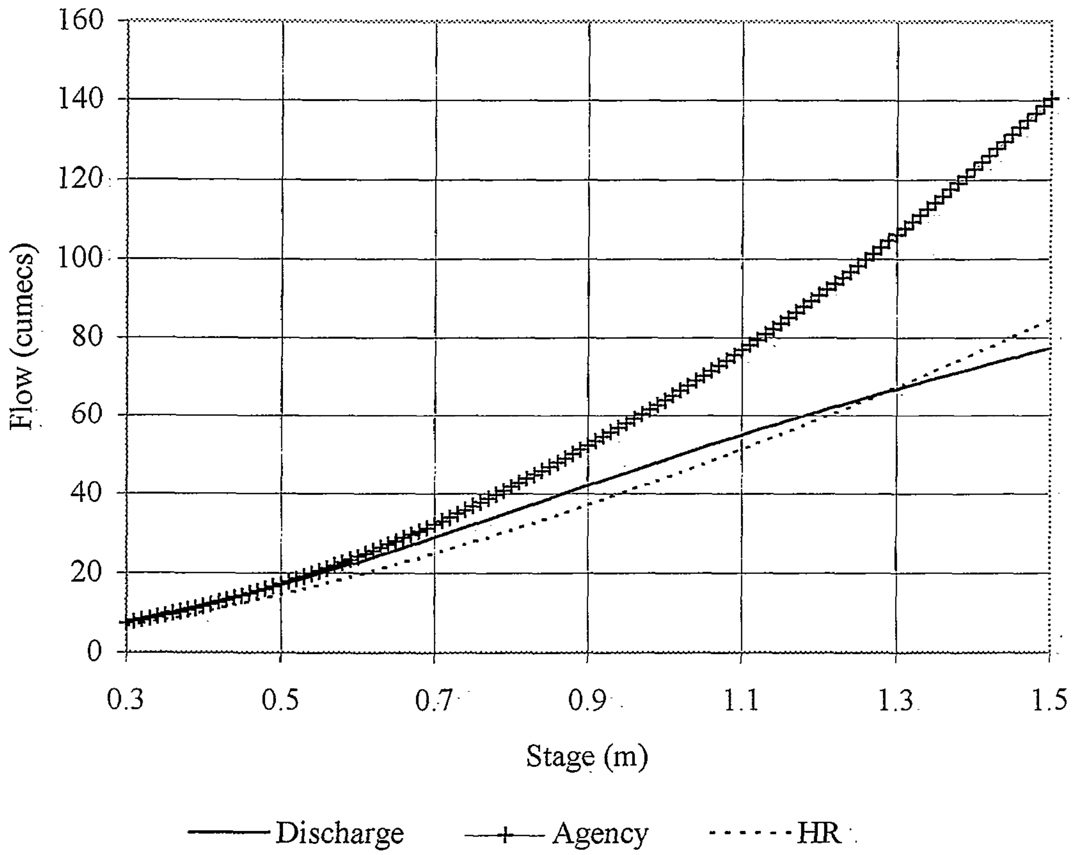


Figure 5.7 The rating curve derived by the stage-velocity method (Discharge) plotted against the Environment Agency and HR ratings for Blackford Bridge.

It would appear that, within the measured range of flows (i.e. up to a stage of 1.2 metres) the rating derived from the gauge data produces a compromise between the HR and Agency curves. Reassuringly, the gauge rating follows the Agency curve for the majority of the range calibrated by current metering (more than 95% of the Agency gaugings have been carried out for a stage of 0.6 metres or less). The Blackford Bridge Site Report in the Project Record contains details of the gaugings carried out above a stage of 0.6 metres (a total of 12), together with the entire gauging record plotted on the rating curve. It can be seen from this that the data confirm the lower half of the plot shown in Figure 5.6, ie flows as high as 56 cumecs have been gauged at a stage of 0.94 metres.

The reason for the differing values of the ultrasonic gauge rating and Agency gaugings has a number of possible explanations, including:

1. The ultrasonic gauge is incorrect;
2. The gaugings are incorrect;
3. There is a consistent bias in one or other of the measurements involved with either method.

It is considered to be unlikely that either of the first two explanations is likely to be the cause of the problem. The ultrasonic technology is well proven, and the methodology being used in this case has worked at other Agency sites. Similarly, the gaugings were undertaken over a period of more than twenty years, by a number of operators and with a variety of current meters. This would suggest that there is a consistent bias in one or more of the measurements or analytical steps that have been followed.

It has already been noted that the rating curve derived from the ultrasonic gauge flattens out over the higher part of the range. Whilst this is most likely due to the use of polynomials in the stage-velocity relationships, it is interesting to note that this is a similar pattern to that which occurs at Greenholme under the 'new' Agency Rating 09, at the point where the river begins to flow out of bank. It may also indicate the final stage of the over-correct-under estimation cycle that would be expected from the gauge rating. A recent report on Blackford Bridge noted that there is a step to the far bank at a stage of approximately 1 metre. It was thus decided to focus on the rating curves in the range 0.6 to 1.2 metres, ie between the point of divergence and the maximum level for which velocity were collected. They are thus re-plotted over this range in Figure 5.8.

When the range in levels is reduced to that presented in Figure 5.8 it can be seen that the ultrasonic gauge rating effectively crosses from the Agency to the HR curve. A report produced by the NRA in 1992 (also contained in the Project Record) addressed the issue of the Blackford Bridge rating, and concluded that at flows around a stage of 1.0 metres the rating was considered to be consistent with the measured flows. It also concluded that the theoretical rating based on a basic broad-crested weir was unlikely to be sound as the Blackford weir was a non-standard crescent shaped old mill weir with a broad crest, suggesting that this curve is less likely to be the 'correct' one. This means that we have to consider possible causes for the discrepancy of 15 cumecs (almost 24%) in flows between the Agency and ultrasonic gauge ratings at the 1 metre level. There are two possible explanations that may assist with this: differences between true and recorded river level, and consistent overestimation arising from the method used to undertake high flow gaugings. Both issues are discussed at length in the Site Report, which concluded that whilst the explanations were reasonable, they do not allow a decision to be made as to whether the Agency or gauge rating is likely to be the 'correct' one. The reality is that it probably lies somewhere between the two, with a flow of between 50 and 55 cumecs occurring at a stage of 1.0 metre. For the purposes of the Project it is questionable whether or not this really matters; other sites have been used for which there is greater confidence in the Agency rating. What has been demonstrated is that from a relatively short period of gauge deployment, and very few events, it was possible to derive a rating for a known 'problem' site that lies midway in the current range of potential ratings, and is considered to be physically reasonable.

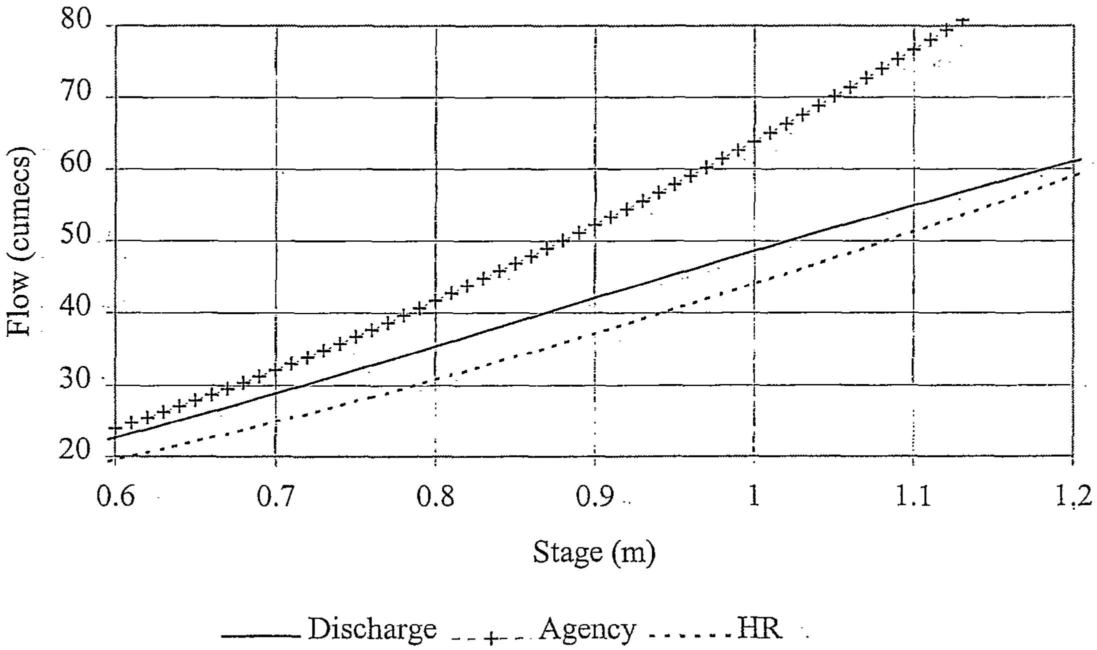


Figure 5.8 The rating curve derived by the stage-velocity method (Discharge) plotted against the Environment Agency and HR ratings for Blackford Bridge between stages of 0.6 and 1.2 metres.

5.3.2 Use of the derived rating curve to assess gauge performance at Blackford Bridge

For other field sites used in the Project the gauge performance has been assessed by looking at individual events. This has enabled the actual physical performance of the gauge (ie whether or not it works) to be evaluated, together with comparing the flows recorded by the gauge to those produced by the Agency rating. Given the uncertainty in the Agency rating outlined above it was decided to assess the gauge performance over the two main events which occurred during the course of the monitoring of the site, and compare the gauge flows to those produced by the ultrasonic gauge rating. In this way the analysis would assess the difference in flows arising from the use of a limited number of events. The two events that were used for the analysis are summarised in Table 5.3, and are plotted in Figures 5.9 and 5.10.

Table 5.3 Details of the two events used for the assessment of gauge performance at Blackford Bridge.

	Start date/time	Finish date/time	Minimum stage (m)	Maximum stage (m)	Velocity path heights (m)
Event 1	8 January 1998 at 0815	10 January 1998 at 1400	0.389	1.212	0.0 and 0.6
Event 2	2 March 1998 at 2000	10 March 1998 at 0730	0.249	1.460	0.2

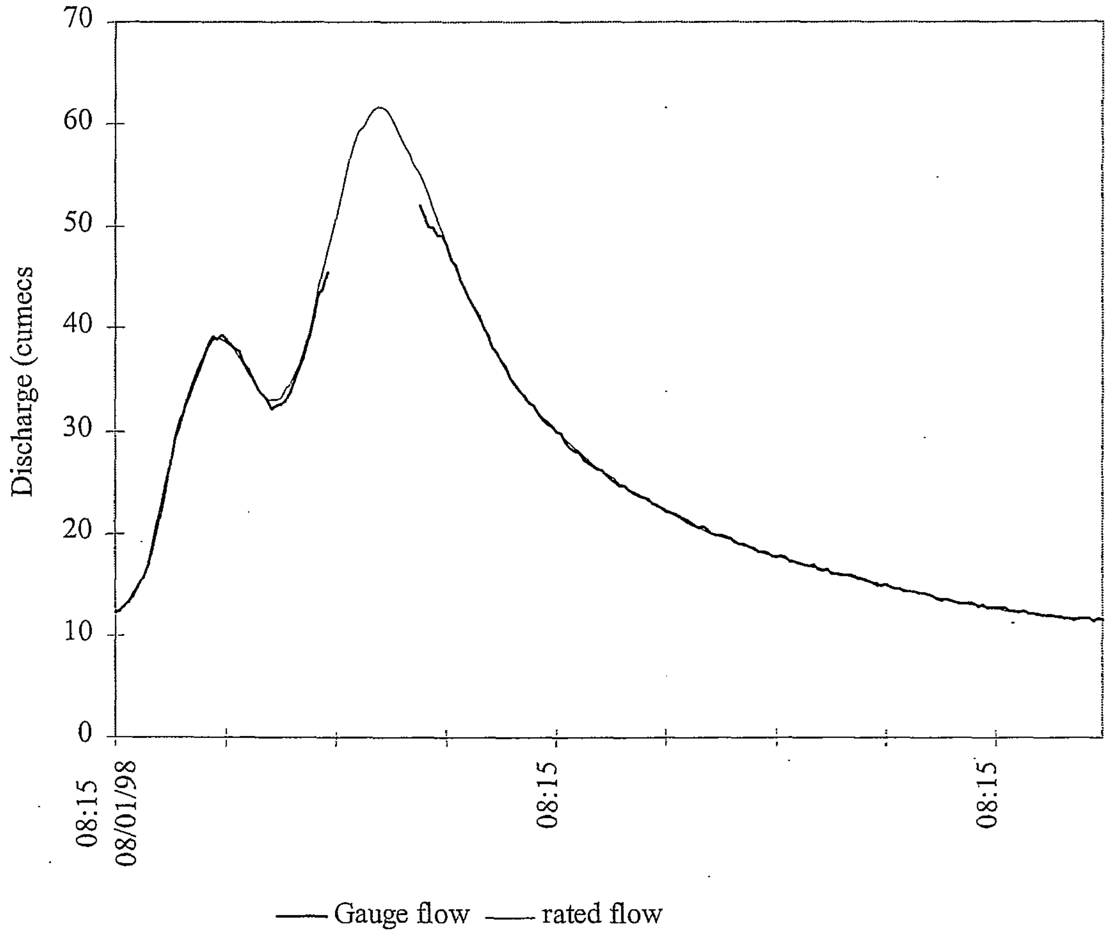


Figure 5.9 Gauge flow plotted against the rated flow (derived from the stage-velocity relationships) for event number 1 at Blackford Bridge between January 8th and 10th 1998, velocity paths at 0.0 and 0.6 m

It can be seen from Figure 5.9 that, when working, the gauge flow is virtually inseparable from the rated flow derived by the stage-velocity method. This is hardly surprising as this event formed the basis for two thirds of the relationships used to derive the rating. However, it does show that there does not appear to be any significant difference in flows arising from there being a reduced number of velocity paths which are inevitably further apart. Furthermore, and as with some of the previous sites, it can be seen that the gauge failed at the top end of the recorded flows. The boundary between the gauge working and failing was lower on the rising limb than when flows were receding (1.0 and 1.1 metres respectively), again as found at other sites. This would appear to support the view expressed elsewhere in this Report that the working limit of the velocity paths is likely to be a function of path length, sediment concentration and channel velocity.

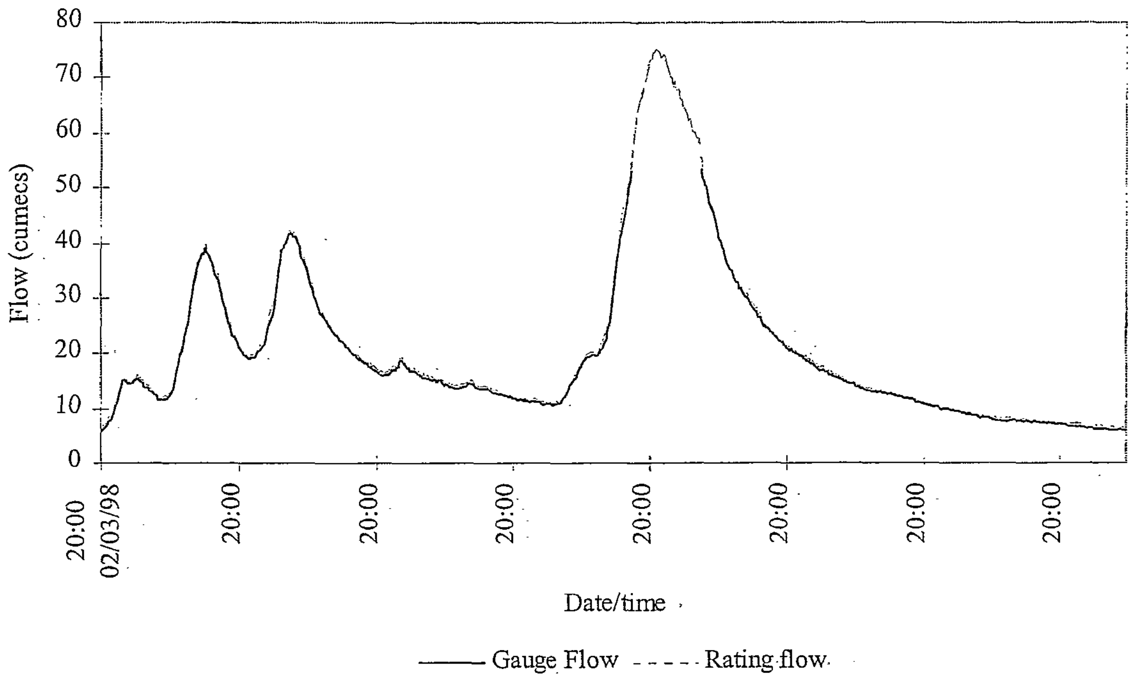


Figure 5.10 Gauge flow plotted against the rated flow for event number 2 at Blackford Bridge between March 2nd and 10th 1998, velocity path at 0.2 metres

Figure 5.10 further confirms the observations based on Figure 5.9. If anything, the gauge flow is even closer to that derived by the rating for medium-high flows (ie 20-50 cumecs), although it does tend to produce lower values at lower flows. If it is considered that the gauge only had one velocity path working during this event (the upper path had been vandalised) then the results are even more encouraging.

It can also be observed that the velocity path failed and 'reconnected' at approximately the same level on this event, equating to a stage of between 1.1 and 1.15 metres. The fact that the gauge was able to work for longer during rising flow conditions may be explained by the two lesser (but still significant) high flow events which occurred during the previous three days. It is likely that these will have flushed much of the surface sediment through the system before the main event occurred.

It is perhaps useful to place the stage at which the gauge failed on these two events into some kind of context. Table 5.4 summarises the peak over threshold data for the site.

Table 5.4 Summary peak over threshold analysis for Blackford Bridge river levels recorded between 1976 and 1999.

Stage threshold	1.5 metres	1.2 metres	1.0 metres
Number of peaks over threshold between 1976 and 1999	5	30	74

It can be seen from Tables 5.3 and 5.4 that both events at Blackford Bridge were certainly of a significant nature; event one peaked at a level similar to that which would be expected to occur once a year, whilst event two was even rarer still (it was actually the sixth highest event recorded at the site).

The level at which the gauge failed, ie between 1.0 and 1.1 metres, equates to an event that would, on average, be expected to occur twice a year. It can thus be concluded that the gauge performed remarkably well, and was able to cope with major events from a heavily urbanised catchment which is likely to have high sediment loads. Where there was data from only one velocity path for one of the events, the gauge was able to produce derived flows that were virtually indistinguishable from those produced from three velocity paths over a number of events. This leads to the conclusion that it is not necessarily the number of velocity paths that are important, but the range of levels from which data are collected for each path. However, the fact that the gauge did fail during the largest events recorded over the period is disappointing, particularly as for some users of the data these large events may be important.

5.4 Middleton in Teesdale

5.4.1 Introduction

The gauge at Middleton in Teesdale repeatedly failed to measure velocities under high flow conditions throughout the entire study period, as indicated in Chapter 3. Many different gauge settings were used, with different voltage, gain and board settings tried in an attempt to improve the data. The site was discussed at length with Peek and, following a visit to their premises in Winchester in 1998, a pair of 250 kHz transducers were loaned to the Project to see if these would improve the situation. Unfortunately this was not the case, and the transducers failed to provide any velocity data until they were removed after some six different events. It had been hoped that the bigger transducers would provide more 'punch' to the sound signal, increasing the probability that it would be detected by the transducer on the far bank. It must be noted, however, that this was the first time that transducers of this size had been used with the Peek 1408 gauge; it is not yet known whether or not they would have worked under more favourable conditions than those encountered at Middleton.

Due to the limited amount of velocity data that were collected by the gauge during the study period, and the narrow range in levels over which the transducer paths were successfully operated, it was decided <u>not</u> to use the data to derive a stage-discharge curve from a number of different stage-velocity relationships. It was thus decided to limit the analysis to comparing the flows produced by the gauge from three separate events, all using a single velocity path, to those produced by the Agency stage-discharge relationship. The results are plotted as three time series in Figures 5.11 to 5.13.

Figure 5.11 shows the data collected from the velocity path deployed at 0.4 metres above stage datum. From this it can be seen that when the gauge was able to measure a path velocity the derived flow was very close to that derived from the Agency rating. Indeed, the maximum difference was 12%, for two 15-minute values, with more than 75% of the derived flows being within 5% of the Agency data. Interestingly, the flows on the rising limb of the first 'sub' event are very close, whilst those in the 'trough' between the two peaks are significantly different. If it is assumed that the ultrasonic gauge was working in a consistent manner throughout the whole event, this would suggest that there is a different stage-discharge relationship for rising and falling levels, ie hysteresis exists. Whilst this is probable, it must also be considered that the majority of flood gaugings are usually undertaken on the falling limb due to the practicalities of getting to sites and the stability of river levels. It would thus be expected that the Agency flows on the falling limb are more likely to be 'correct' than those derived when the river is rising; hence the close correlation between the ultrasonic and Agency flows when the river is rising is more likely to be fortuitous than real.

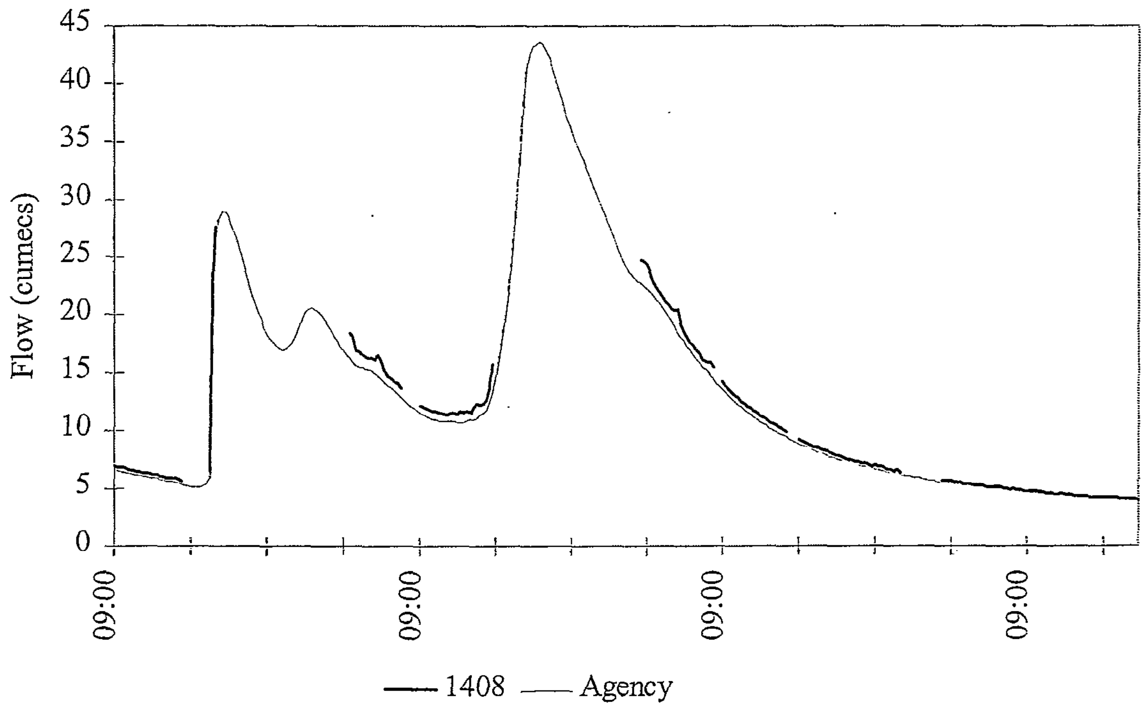


Figure 5.11 Flows derived by both the Agency stage-discharge relationship and the 1408 ultrasonic gauge for the November 1997 event. The ultrasonic flow is based on velocities recorded along a path at 0.4 metres above stage datum.

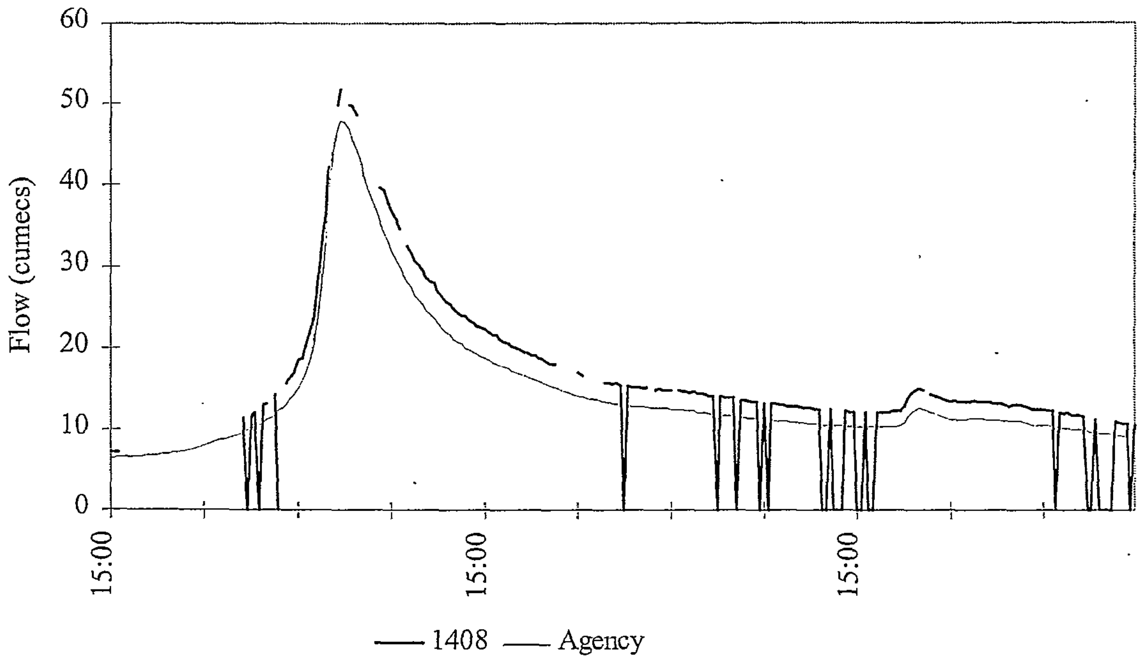


Figure 5.12 Flows derived by both the Agency stage-discharge relationship and the 1408 ultrasonic gauge for the January 1998 event. The ultrasonic flow is based on velocities recorded along a path at 0.5 metres above stage datum.

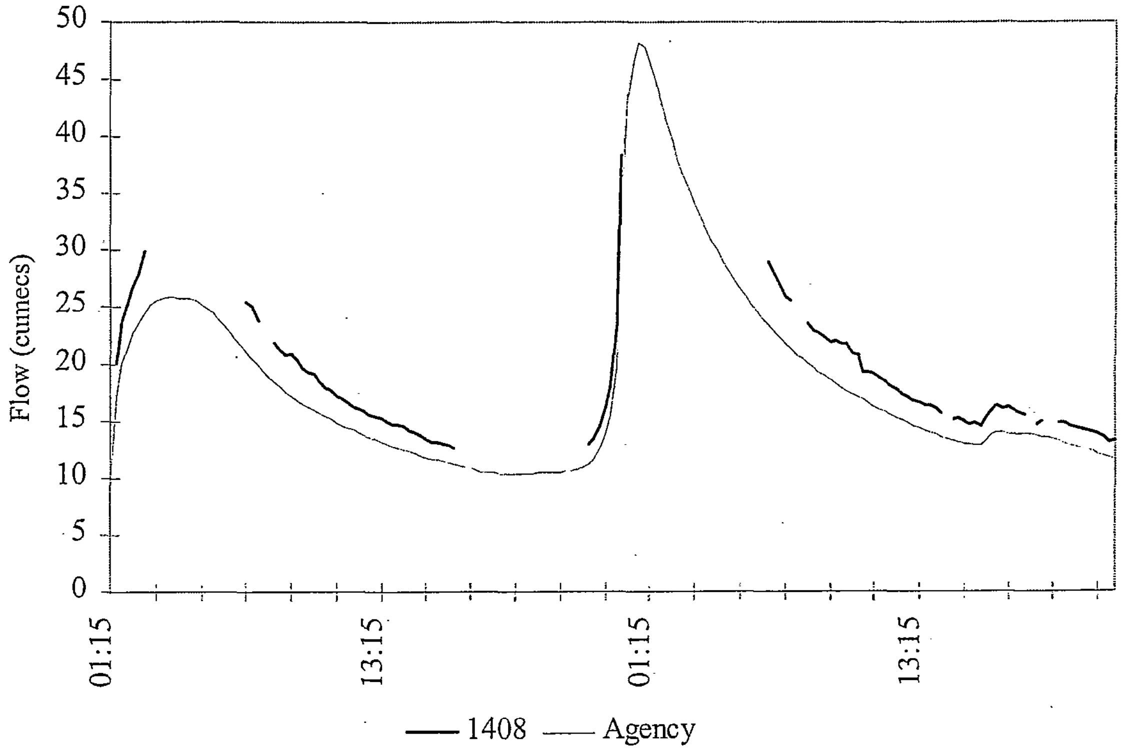


Figure 5.13 Flows derived by both the Agency stage discharge relationship and the 1408 ultrasonic gauge for the April 1998 event. The ultrasonic flow is based on velocities recorded along a path at 0.7 metres above stage datum.

The same general points observed in Figure 5.11 are seen in Figure 5.12, but on an even greater scale. Having the velocity path at a higher level results in the difference between Agency and gauge flows being greater; this fact is further demonstrated by Figure 5.13 which is based on velocity data collected from 0.7 metres above stage datum.

This increase in difference is to be expected; as the velocity path is raised it will tend to record higher velocities, and thus exacerbate the discrepancy between Agency and gauge flows. Peak levels during these events were all less than 1.38 metres; combining this with a mean bed level of -0.243 metres gives a maximum water depth of 1.623 metres (during the second event). The 0.4, 0.5 and 0.7 m velocity paths were deployed at 0.42, 0.48 and 0.60 of the maximum water depth during their respective events, with the velocity data being collected when the ratios were all much greater than this.

It may be possible to correct for this by using a power-law type relationship to represent the velocity profile using data collected from multi-path gauges. This would then allow a 'correction factor' to be applied to discharge data derived from a limited number of velocity paths. In the case of the Middleton data, this correction factor would be greater at low levels, and decrease for higher stages. At other sites, where the velocity paths were deployed at low levels, the reverse pattern might exist.

5.4.2 Determination of stage discharge relationships

Although it was decided not to proceed with developing a stage-discharge relationship based on multiple stage-velocity relationships due to the limited range of velocity path levels from which it was possible to collect data, it was still possible to derive stage-discharge relationships from the three events discussed in Section 5.4.1. These relationships are all plotted along with the Agency rating in the Site Report; Figure 5.14 is an example of one of these plots, derived from the 0.5 metre transducer path.

Unsurprisingly all three plots illustrated the same general relationship as found in Figures 5.11 to 5.13, namely the data derived from the lowest velocity path are the closest to those derived by the Agency. In addition to this they demonstrate the differing nature of the individual relationships, the most striking feature being the tendency for the relationship derived from the gauge to become 'flatter' the higher the velocity path. Whilst this does not affect the quality of fit between the two data series within the range of observed velocity data, it does influence the suitability of the relationship for extrapolating beyond this.

Best fit lines were fitted to all three sets of stage discharge data derived from the ultrasonic gauge; these are plotted in Figure 5.15, along with the Agency rating, for levels up to 2.5 metres above stage datum. It should be noted that second order polynomials were fitted to both the 0.4 and 0.7 metre data sets, whilst the 0.5 metre curve was a power-law based relationship.

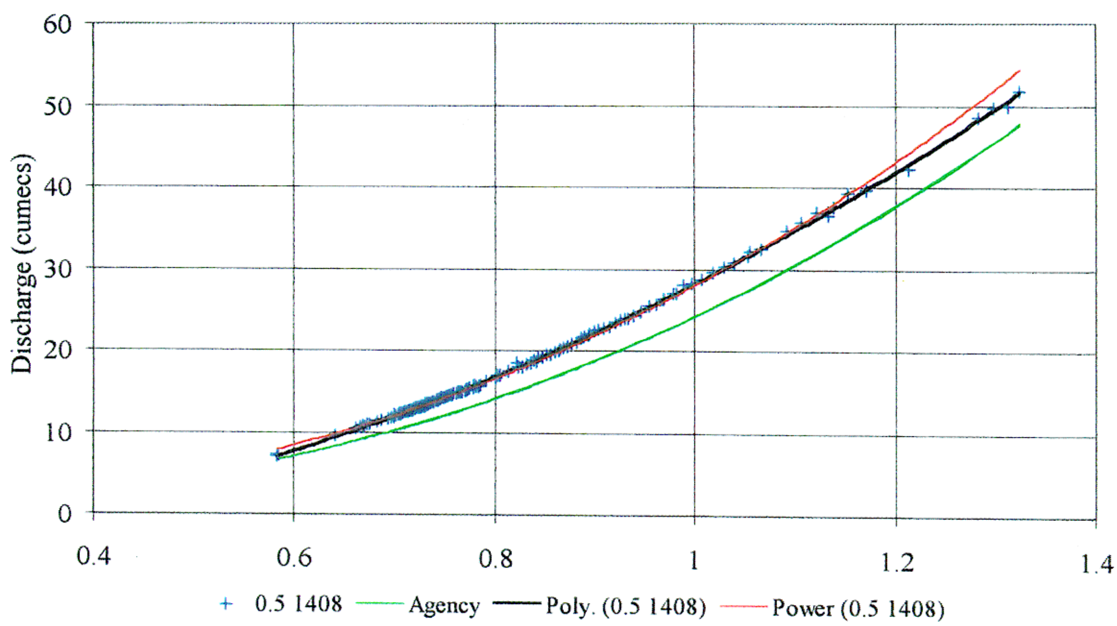


Figure 5.14 Agency stage-discharge relationship plotted against those derived from the 0.5 metre velocity path from both a polynomial (Poly. (0.5 1408)) and power-law (Power (0.5 1408)) best fit.

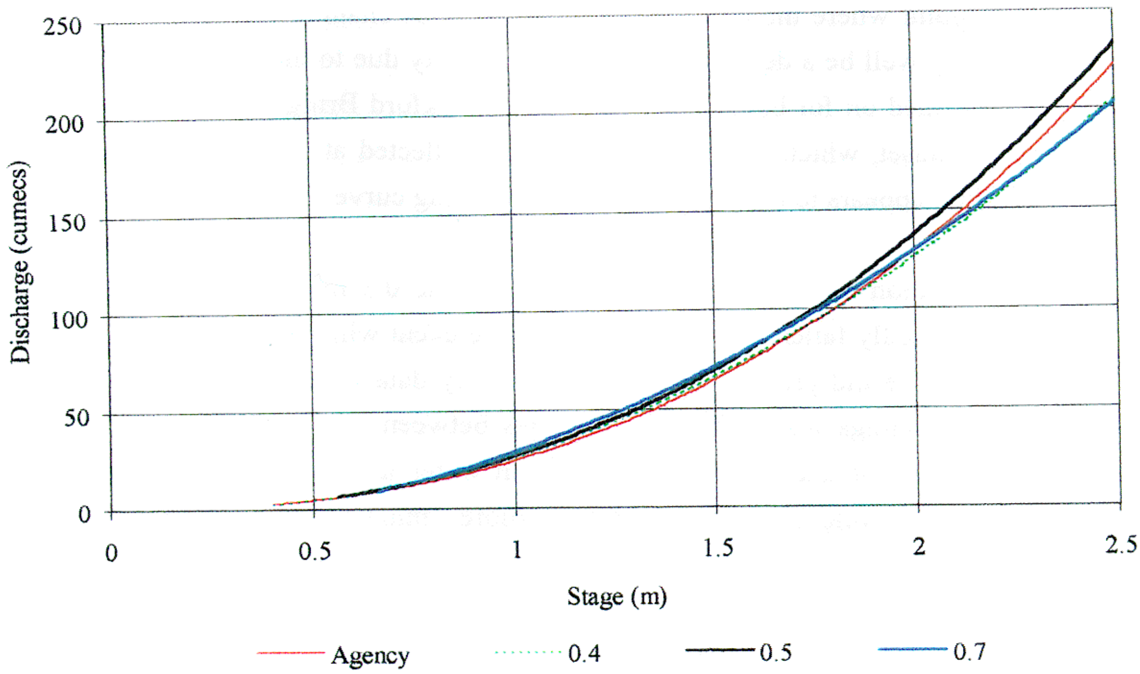


Figure 5.15 Stage discharge relationships derived from the three sets of velocity data plotted against the Agency rating for Middleton in Teesdale. 0.4 and 0.7 curves are second order polynomials, 0.5 is a power-law based relationship.

It can be seen from Figure 5.15 that all three curves appear to closely follow the Agency relationship up to a stage of approximately 2.25 metres. Above this point the power-law derived relationship for the 0.5 metre curve is the only one that follows the same pattern as the Agency relationship, which is also based on a power law, whilst the polynomial curves of the 0.4 and 0.7 metres appear to significantly underestimate the flow beyond this point. Reference to the Site Report shows that the selected curves appear to be the best ones for each data series which leads to the conclusion that, as with other sites, it is important to consider the type of statistical fit being used to extend a data series.

Even if the use of the polynomials is accepted as being less preferable to a suitable power law equation, when based on suitable data, Figure 5.15 suggests that at this site, where there is a stable relationship between stage and velocity, it is reasonable to extend the derived rating curve to over twice the observed range in levels. At a stage of 2.25 metres all four ratings are within 5% of each other.

Close study of the curves in the Site Report shows that there appears to be a 'break' in the stage-discharge relationship at a stage of approximately 1.0 to 1.1 metres; the break corresponding to a lower discharge than would have been expected from the data collected at lower levels. This is particularly noticeable in the 0.5 and 0.7 metres plots. This stage corresponds to the point where the river begins to flow out of channel on the near bank, at which point there may well be a decrease in the water velocity due to increased edge effects, as previously commented on for both Greenholme and Blackford Bridge. This may explain why the 0.5 metre dataset, which included velocity data collected at a stage of between 0.2 and 0.3 metres higher, appears to best match the Agency rating curve.

The issue of extrapolation can be further explored using the 0.5 metre velocity path data. Whilst the gauge repeatedly failed at high river levels, the event which occurred between the 8th and 12th January 1998 did provide very limited velocity data from higher river levels; a total of six velocity readings were obtained for stages between 1.5 and 1.75 metres above stage datum. (It is thought that the very rapid rise in water levels may have enabled the gauge to 'snatch' some velocity data before the more 'murky' water from the upper catchment arrived at the site).

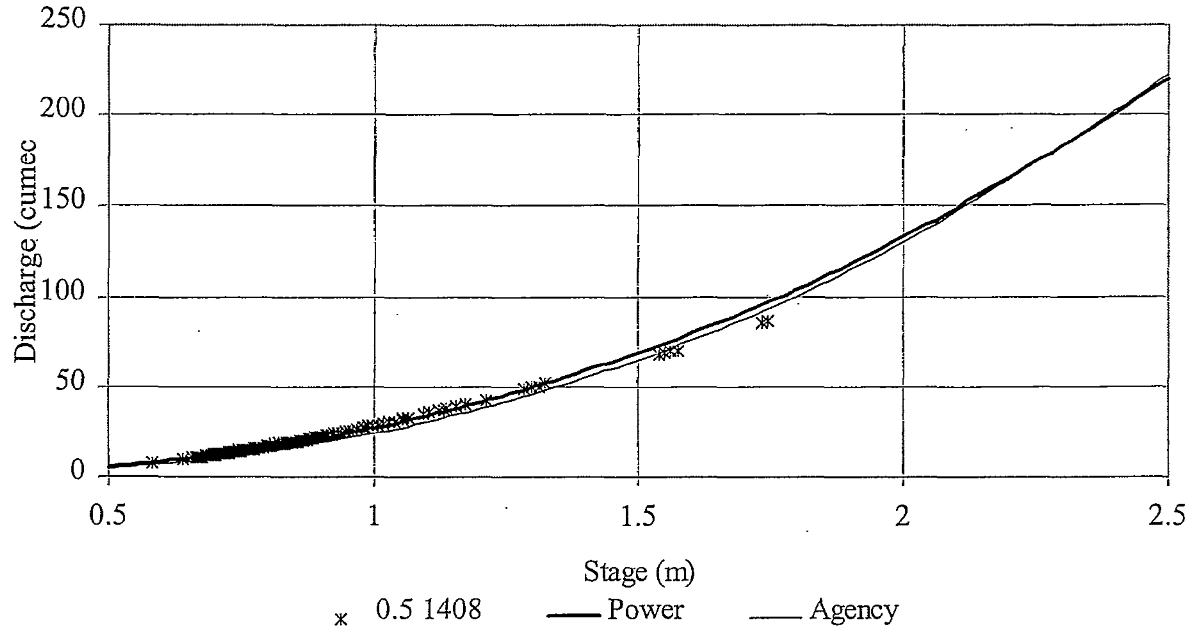


Figure 5.16 Power law rating curves for Middeleton in Teesdale calculated from the ultrasonic gauge (Power), based on the complete 0.5 metre velocity path dataset (0.5 1408) and the Agency rating (Agency).

Discharge data were derived from these six readings, and they are plotted on Figure 5.16, together with the power law ratings derived from the data and the Agency. It can be seen from this that the addition of a very small number of points in the upper part of the flow regime results in the two rating curves being much closer throughout the upper regime than those presented in Figure 5.15, confirming the conclusions that it is important to try and collect data over as wide a range of levels as possible. **Indeed, the results from Middleton**

indicate that the range of river levels over which the velocity data are collected is more important than the number of paths or the height of these paths. Figure 5.16 also shows that, at higher stages, the gauge begins to underestimate the Agency rating. This can be explained by the fact that at higher levels the gauge will only be calculating the flow for part of the channel, and there will be additional water flowing outside the section covered by the transducer path.

5.5 Limitations

The greatest single limitation to using stage-velocity relationships to derive a rating curve is the total dependency on the stability and consistency of the relationship, as with current meter gauging. This means that the hydraulic conditions in the channel must be constant from event to event, which requires the following criteria to be satisfied:

- The river bed must be stable;
- Downstream controls on the river flow must be consistent;
- Boundary conditions (ie along the river bank) should be the same from event to event.

This last point is the most difficult to satisfy as bank vegetation will vary on a seasonal basis. However, if it is assumed that high flows are usually associated with winter conditions, the influence of bank-side vegetation is usually insignificant at this time of year.

The final limitation to this approach is one which also applies to more conventional means of deriving flows, and relates to the extrapolation of the observed relationship. This can only be undertaken with any degree of confidence provided there is no change in the hydraulic conditions of the channel. Such a change might include 'bank-full' or a change in the slope of the channel banks. If there is a change, then extrapolating the relationships beyond this point is likely to result in increased errors in the derived flows.

5.6 Uncertainties associated with the approach

The majority of the uncertainties associated with using stage-velocity relationships to derive a stage-discharge rating are the same as those described in section 4.6. In almost all cases the theoretical uncertainties are exactly the same as those associated with a simple twin-path installation, the exception being the reduction of the limited path uncertainty. The most notable differences are that, in certain cases, the uncertainties will be reduced as result of using data from more than two velocity paths. In particular, the over-correct-under estimation cycle is likely to decrease or disappear altogether, as demonstrated with the Greenholme data in section 5.2.

The derivation of a rating curve from velocity data decreases the uncertainties in the derived flows by two further means. The first of these is that the accuracy of the derived flows does not suffer as a result of the transducer paths failing during a specific event as the approach uses all available data collected from a single velocity path, and extends this over the maximum observed range by reference to other data sets if necessary. This is in contrast to using the gauge simply as a twin-path unit to derive flows when, if a path should fail, the uncertainties in the derived flows increase due to the limited-path uncertainty increasing as a direct result of only being able to use velocity data from a single path. This was demonstrated in Figure 4.4 which showed that when one of the velocity paths failed during the peak of one of the events at Greenholme the uncertainty doubled from 3 to 6%.

The second reason for decreasing the uncertainty in the derived flows is that the approach automatically takes account of any changes that may occur in the channel hydraulics as water levels rise, within the observed range of flows. Again, data recorded from a velocity path during an event that did not reach the level of the change can be intelligently extended by reference to data from a path that collected data from a higher flow event.

The net result of using this approach instead of the simple twin-path installation is that typical uncertainties are reduced from ± 5% to ± 2.5% within the observed range of flows, with maximum uncertainties reduced from ± 10% to ± 5%; ie the uncertainty is halved. Whilst this is clearly of benefit in giving greater confidence in the derived flows, it must also be remembered that the improved performance of the rating in deriving flows will apply to all events that occur within the observed range of levels. Clearly, if the rating is used to derive flows beyond the observed range the uncertainties will increase.

5.7 Typical operating costs

The assessment of typical operating costs presented in Chapter 4 applies in almost exactly the same manner to this approach. There are only two potential exceptions to this. The first of these is that the staff time required to complete the site visits may be increased as a result of greater time spent on site adjusting the gauge levels, and a potential need for more site visits if there is a wide range in levels at a particular site. However, it is felt that the values quoted in Table 4.8 provide sufficient time to undertake the required field studies described in this chapter.

The second potential exception to the Chapter 4 assessment relates to the time taken to process the data, develop and assess the relationships and ratings. Almost all of the analysis presented in this chapter has been a development of that presented in Chapter 4, or on work that had previously been taken to the same stage as that presented in Chapter 4. Whilst it is accepted that the work involved with the initial development of these relationships was relatively high as a result of the approach being developed by trial and error, it is considered that the identified approach could be successfully completed in no more than three additional staff days. This three day period will involve staff from a number of different work functions, and is the only net increase in operating costs to that identified in chapter 4.

5.8 Conclusions

This chapter has demonstrated how data from the twin-path ultrasonic gauge may be used to derive stage-discharge relationships. The most obvious method of doing this is using the flows calculated by the gauge, such as that presented in chapter 4, and this approach was used for the Middleton in Teesdale data sets. It was found that whilst such an approach will certainly produce reasonable rating curves, the performance of these will depend on the level at which the transducer paths were operated. One positive finding from the Middleton analysis was that it demonstrated that collecting as few as six velocity readings at high river levels has a noticeable effect on improving the performance of the rating curve. This would suggest that at 'problematic' sites there is a potential benefit in field staff trying to be on site during a high flow event to try and configure the gauge settings (if necessary) in order to obtain intermittent velocity data where the gauge would otherwise fail.

The method described in the majority of this chapter is based on the use of stage-velocity relationships, rather than stage-discharge curves, to derive a rating curve. The analysis has shown that the relationship derived from an individual path with a very limited number of values is consistent with those based on paths at other levels which used data from a much higher range in levels. The primary advantage of using this approach is that it removes any anomalies in the derived flow that may occur if one of the velocity paths should fail during a specific event.

Whilst the Blackford Bridge analysis may appear to suggest the contrary - that there is little to be gained from increasing the number of levels from which the velocity data are collected - it must be remembered that flows from individual paths were being compared to those derived by the gauge itself from a total of only three paths. The Greenholme analysis involved comparing gauge flows to those produced by an Agency rating in which there is high confidence. This demonstrated that using the stage-velocity approach based on a number of different path levels to derive a rating curve halved the uncertainties in the derived flows, with the mean uncertainty being ± 2.5% and the maximum uncertainty ± 5%.

However, and as with the uncertainty analysis presented in Chapter 4, it must be remembered that these uncertainties only apply to flows within the observed range. If the stage-velocity derived rating curve is extrapolated beyond the observed range the uncertainty in the derived flows will also increase. The significance of this increase will depend on the nature of the channel hydraulics, and also on the type of relationship that was derived from the stage-velocity data.

Finally, it is considered that the typical operating costs if using this approach are likely to be very similar to those described in chapter 4. The only change to this is likely to be the additional time that is involved with the data analysis that the approach will involve. This is considered to be three staff days, which will bring the total operational cost up to 88 staff hours plus the travel costs associated with 14 site visits, and equipment costs of just over £1,300.

6 OPERATING THE GAUGE IN REAL TIME

6.1 Introduction

Both Chapters 4 and 5 have described the results obtained from using the ultrasonic gauges at sites where there is believed to be a stable stage-discharge relationship. Whilst many gauging stations operate on this fundamental principle, there are a number of circumstances which may result in a variable relationship. These include:

1. Unstable river bed, leading to changing hydraulic conditions during and/or between high flow events;
2. Variable downstream controls, for example downstream confluence with other rivers;
3. Downstream tidal influence causing backing up;
4. Seasonal weed growth affecting the channel efficiency.

Under all of these situations the use of a fixed stage-discharge relationship, however produced, will result in significant uncertainties in the derived flows. Fixed installation multi-path ultrasonic gauges are often used to overcome these problems by continually measuring river flow, but are costly to install. This chapter will thus evaluate the potential for twin-path gauges to be used under similar conditions.

6.2 Walcot case study

6.2.1 Introduction

Walcot gauging station, on the River Tern, has been the subject of considerable study by the Midlands Region due to the variable nature of the stage-discharge relationship. The station has a flat V weir with full height wing walls, built to conform with BS 3680 Part 4G (1990). Unusually, the weir has a crest tapping to correct for non-modular conditions. The crest tapping has a pumping system installed which is designed to prevent the inlet pipe and tapping chamber in the weir block from becoming blocked by silt.

Whilst a theoretical rating curve has been determined for the site based on the British Standard, current meter gauging from a cableway upstream of the wing walls indicates that the flows produced by the rating do not match up to the gauged flows under certain conditions. Two reasons have been identified for this:

1. Both the upstream and downstream channels are subject to considerable weed growth during the summer and autumn months, leading to differences between theoretical and gauged flows at low-medium flows.
2. During prolonged wet periods the channel backs up. The causes of this include both downstream channel constrictions and the River Severn.

6.2.2 Assessment of stage-velocity relationships

Non-modular conditions are defined by British Standard 3680: Part 1: 1991 as *the flow, over or through a structure, which is drowned when it is affected by changes in the level downstream.* Under such conditions the channel becomes less efficient, ie the flow over the weir is less than would be expected according to the weir formula. For this to happen the mean channel velocity must be less than the theoretical value.

To establish whether or not this reduction in weir efficiency occurs, and to quantify the extent to which the flows are affected, two approaches have traditionally been used. The first of these, which is at present only applicable to horizontal Crump weirs, depends on the ratio between the downstream and upstream water levels. The second utilises the crest tapping, and can be used at both horizontal and flat V Crump weirs, and depends on the ratio between the measured head at the crest tapping and that upstream of the weir block.

Rather than use an 'indirect' or surrogate measure of changing velocity conditions, the ultrasonic gauge offers the opportunity to directly monitor the relationship between stage and velocity in real time. To illustrate this, Figure 6.1 plots stage against velocity for the first high flow event that was recorded at Walcot.

A clear break in the stage-velocity plots can be seen at a stage of approximately 0.6 metres above weir crest invert in Figure 6.1. Above this point the rate of increase in path velocity decreases, suggesting that the weir becomes less efficient at this point. It is worth noting that whilst path velocities continue to rise, the peak mean velocity of 0.75 m/s is by no means large.

In addition to demonstrating that the ultrasonic gauge is able to detect any changes in the stage velocity relationship, the data presented in Figure 6.1 also provide confirmation of the modular limit for the weir. Prior to this event, which was the first significant one to yield data from the crest tapping, the Agency had considered the limit to be at a stage of 0.8 metres. Analysis of the crest tapping data following the event indicated that the modular limit was lower than this, with a 5% reduction in theoretical flows being calculated for a stage of 0.6 metres. This coincides very closely with the break in the stage velocity relationships plotted in Figure 6.1.

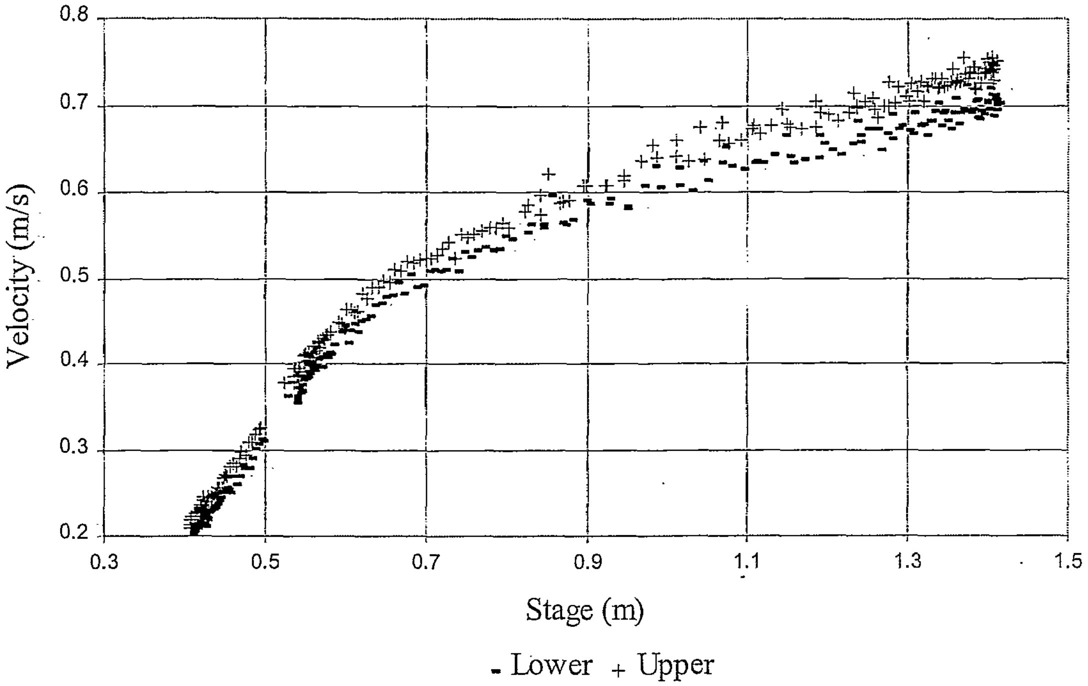


Figure 6.1 Stage plotted against velocity for the event recorded at Walcot between 18th and 20th December 1996. The upper and lower transducer paths were deployed at 0.2 and -0.1 metres above the weir invert respectively.

Having confirmed that the ultrasonic gauge is able to identify that non-modular flows occur, and that it appears to be sensitive enough to be able to quantify the modular limit, the final issue to be discussed regarding stage-velocity relationships is their consistency. Whilst the information presented in Figure 6.1 confirms the occurrence of non-modular flows, it could be argued that if the modular limit consistently occurs at a fixed stage then the weir could be regarded as a stable open channel section and be calibrated by current meter gauging above the modular limit. In order to assess whether or not this is possible it is necessary to compare the stage-velocity plots derived from data collected during different events. Ideally this would involve velocity data collected during both summer and winter months, and from the same level in the river. Unfortunately, no summer data were collected from the site, primarily because the main focus of this Project was high flows and field work was thus concentrated in the winter months, but also because weed growth caused difficulties in getting the velocity paths to function. It is thus necessary to use velocity data that were collected from similar levels (0.1 and 0.2 m above weir invert) during two events that occurred at similar times of the year (December 1996 and November 1997). These data are plotted in Figure 6.2.

It can be seen from Figure 6.2 that whilst the data collected during the two events may display a similar pattern in that both plots have a break in slope that is caused by the onset of non-modular conditions, the detail is somewhat different for the two series. The 1996 data appear to demonstrate a sharper break, at a stage of 0.6 metres as discussed above. In contrast, the 1997 curve does not begin to level off until a stage of 0.7 metres, and even then the curve continues to flatten progressively, rather than forming a near-linear relationship like the 1996 data. The data recorded during the two events would thus seem to indicate that the stage-velocity relationships differ from event to event.

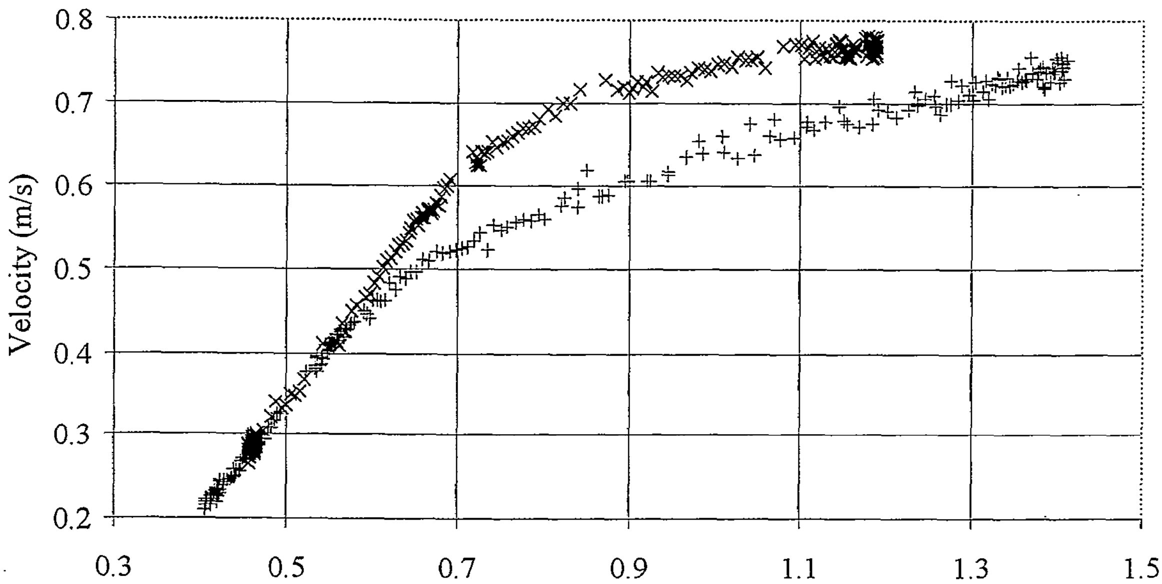


Figure 6.2 Stage-velocity data collected from two different events at Walcot. x indicates values collected from a velocity path deployed at 0.1 metres above the weir crest between 27th and 29th November 1997, whilst + indicates the data collected from a path 0.2 metres above the weir crest between 18th and 20th December 1996.

Whilst it might be argued that using velocity data collected from two different levels may be a contributory factor to the differing relationships, it can be seen from Figure 6.1 that data collected from different levels but during the same event follow the same pattern. Furthermore, the 1997 data plotted in Figure 6.2 were collected from a path that was lower than that of the 1996 data series (but still lying between the two 1996 velocity paths) and yet produces higher velocities above the modular limit. It is thus considered to be unlikely that the differences in the two data series plotted in Figure 6.2 are due to the differing path levels, but indicate a true difference in the stage-velocity relationship. A further point to note is that the potential range of the modular limit during the 1997 event (between 0.7 and 0.9 m above weir invert) spans the 0.8 m value that the Agency previously considered to be the point of departure from the weir equation. This is further illustrated in Figure 6.3 which shows the gauge velocity data from the two events, together with that from the Agency stage-discharge curve for the site, and the mean channel velocities calculated from the corrected flows (using the crest tapping approach) for the 1996 event. It can be seen that whilst the 1997 data follow a similar pattern to that produced by the stage discharge rating, the 1996 gauge data follow that derived from the corrected flows. The relationship between the two 1996 data sets is so strong that it is possible to observe a single path from the gauge over-representing true channel velocity during the lower part of the stage, but tending to under represent true velocities as the river rises.

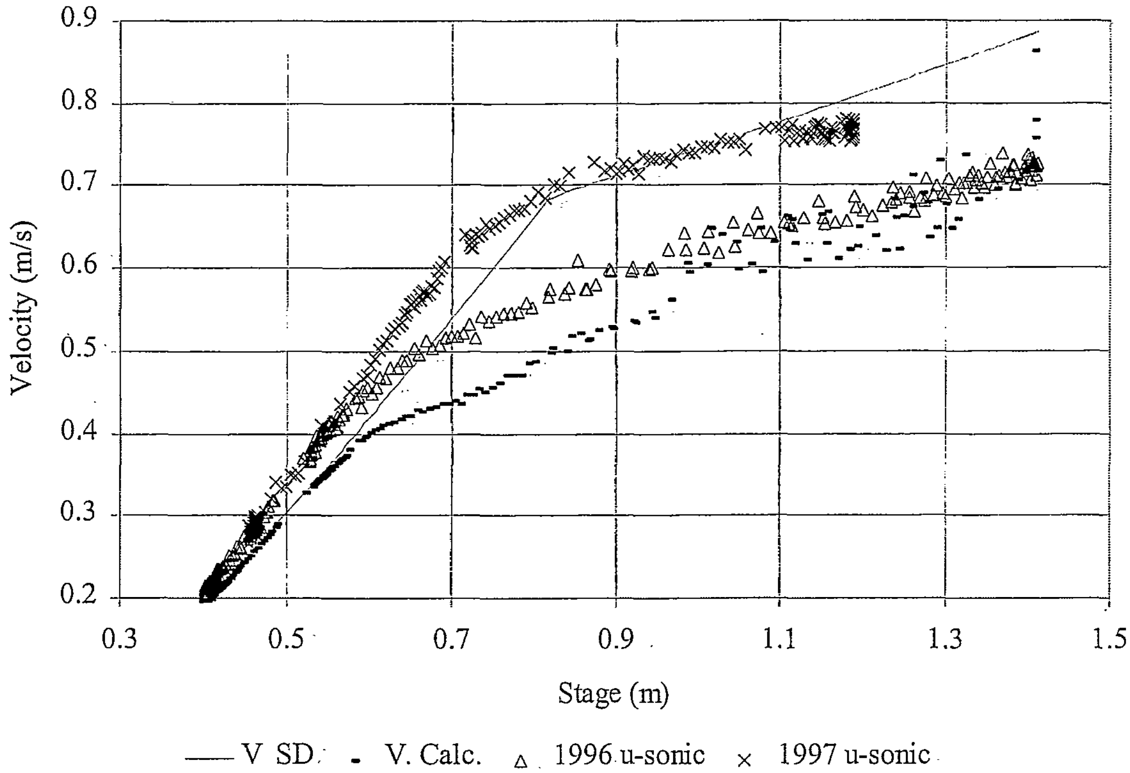


Figure 6.3 Velocity data recorded by the ultrasonic gauge during the 1996 and 1997 events at Walcot plotted with mean channel velocities derived from the stage discharge rating for the site (V SD) and the those derived from the corrected non-modular flows for the 1996 event (V. Calc.).

It can thus be seen that had a single stage-discharge relationship been used to calculate flows at Walcot for the two events there would be systematic errors in at least one of the resulting hydrographs. In order to derive accurate flows at a site such as this it is thus necessary to monitor conditions *in situ*, be it velocity or another parameter.

6.2.3 Assessment of derived flows

Having demonstrated the usefulness of monitoring velocities *in situ*, the next step in the assessment of operating the gauges in real time is to evaluate their performance at deriving flows. However, as the previous section has demonstrated, in order to do this it is necessary to have a reliable means of deriving the true flow. Whilst this section of the Report will have to assume that the flows produced by the crest tapping/upstream head method are as accurate as can be, there are considerable uncertainties associated with this approach. These uncertainties will be discussed further in Section 6.3.

Two events were selected to assess the suitability of the ultrasonic gauge for measuring flows in real time at Walcot. The first of these events was between the 18th and 26th December 1996, and included the velocity data presented in section 6.2.2. The velocity paths were deployed at a level of -0.1 and 0.2 metres above weir invert, and would thus be expected to under-measure peak velocities as the peak water level was over 1.4 metres above weir invert (mean bed level was 0.7 metres below weir invert). The data for this event are shown in Figure 6.4. **Note that the flows derived by the ultrasonic gauge (for both events) are as recorded; no transformation of any kind has been applied to the data, or adjustments made to mean bed level, bed correction factor etc.**

It can be seen from Figure 6.4 that, for the vast majority of the event, the flows recorded by the ultrasonic gauge closely match those derived from adjusting the weir equation using the crest tapping data. It is only at the peak of the event that there is any significant difference between the two curves, with the ultrasonic gauge calculating lower flows than the adjusted weir formula for part of the time, although the two curves do coincide for some of the values. Note that during these peak flows the iteration used to correct for non-modular conditions is not able to function 100% of the time. This is a known and documented weakness of this particular approach. One further point that can be made about the flows derived by the adjusted weir equation is how 'jumpy' they are, particularly during the peak of the event. The ultrasonic gauge data suggests that this fluctuation is not real but is a result of the iteration which is very sensitive to minor fluctuations in the crest tapping levels as the crest/upstream head ratio increases.

The stage-discharge rating developed and used by the Agency appears to over-estimate flows during this particular event by as much as 5 cumecs (approximately 25% of the true peak) compared to both the ultrasonic gauge and adjusted weir formula, whilst the modular weir equation (which is **not** used at this particular site, but is employed elsewhere by other Agency Regions) produces peak flows more than twice the magnitude of the adjusted weir equation.

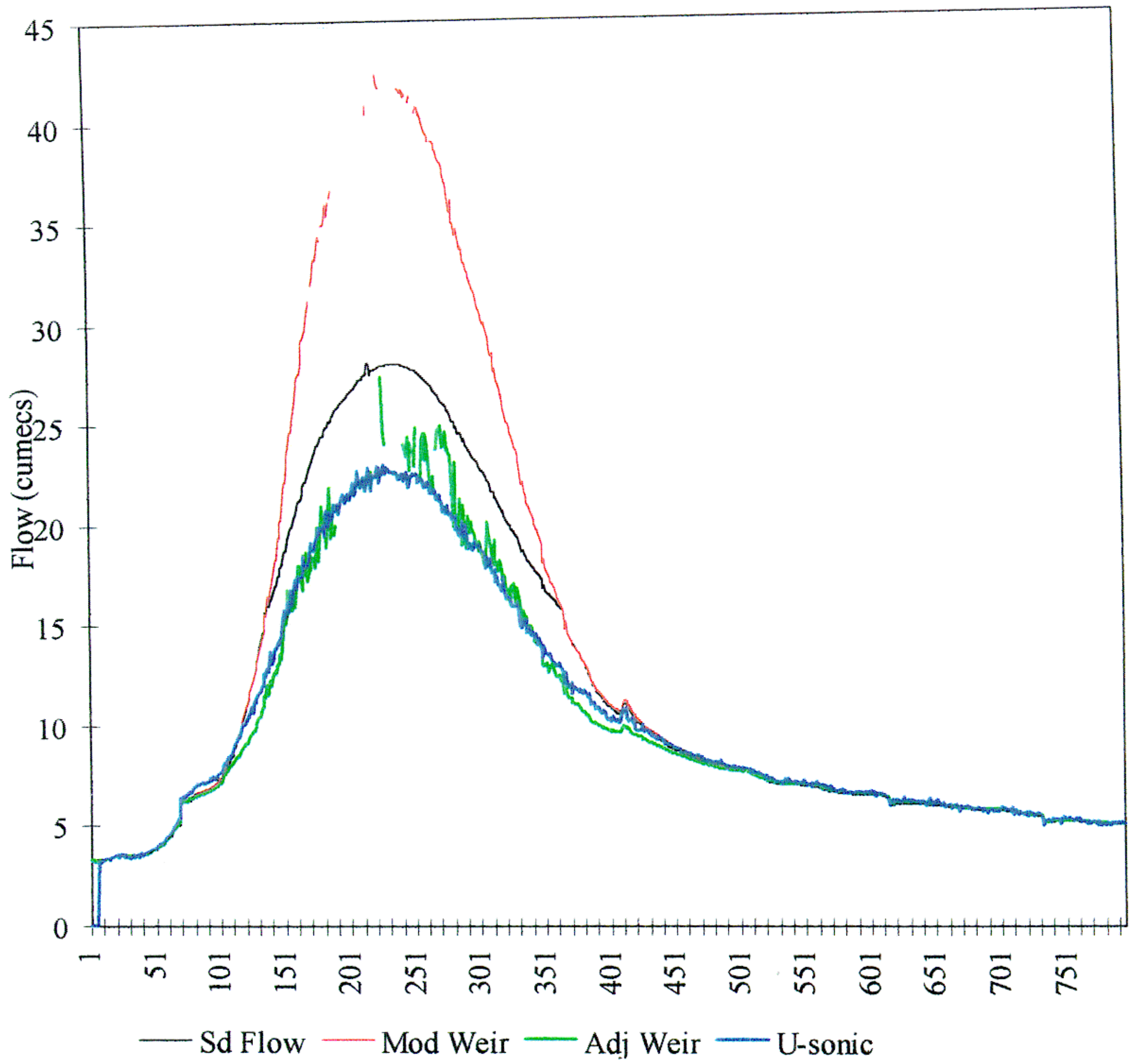


Figure 6.4 Flows at Walcot gauging station recorded between the 18th and 26th December 1996 inclusive. Sd flows are those produced by the Agency rating, Mod Weir are those from the modular weir equation, Adj Weir are the flows calculated from the crest tapping/upstream head ratio, and U-sonic are the flows recorded by the ultrasonic gauge with velocity paths deployed at -0.1 and 0.2 metres above weir invert. Note that due to the nature of the processing iterations it was not possible to calculate Adj Weir flows throughout the entire event.

For reasons that will become apparent later in this chapter there is little more that can be inferred from the flow data presented in Figure 6.4. Figure 6.5 shows the hydrographs produced by the Agency rating, adjusted weir formula (where possible) and the ultrasonic gauge with the velocity paths deployed at 0.5 and 0.8 metres above the weir invert between January 1st and 8th 1998.

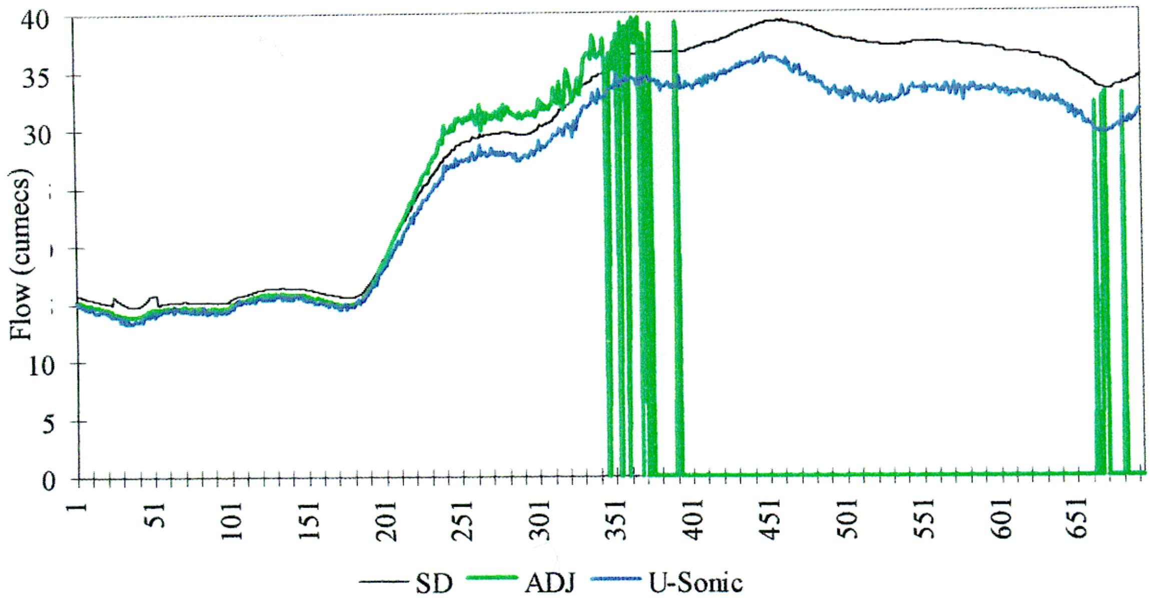


Figure 6.5 Flows at Walcot between January 1st and 8th 1998, produced by the Agency rating (SD), adjusted weir formula (ADJ) and ultrasonic gauge (U-Sonic) with the velocity paths at 0.5 and 0.8 metres above the weir invert.

The first point to be noted from Figure 6.5 is the high proportion of time that the adjusted weir formula iteration is unable to function. This is because flows were higher than those of the December 1996 event plotted in Figure 6.4. Secondly, on this occasion the flows produced by the ultrasonic gauge are closer to those of the Agency rating than in Figure 6.4. For example, the stage-discharge flow of 25 cumecs was associated with an ultrasonic gauge flow of only 20.1 cumecs in the first event, when the velocity paths were lower, compared to 23.6 cumecs in Figure 6.5. It is thought that this increase is due to two facts: the transducer paths are higher, and would thus be expected to record higher velocities, and the modular limit and/or degree of drowning may have been higher and/or lower respectively during this event.

Finally, it can be seen that on this occasion the adjusted weir formula produces higher flows for a given stage than both the ultrasonic gauge and the Agency rating. Whilst it is possible that the flows are significantly higher for a given stage during the second event, it is considered unlikely that the increase will be as much as that shown in Figure 6.5. To enable this to be discussed further, Figure 6.6 shows the stage-discharge ratings produced from both events by all three methods.

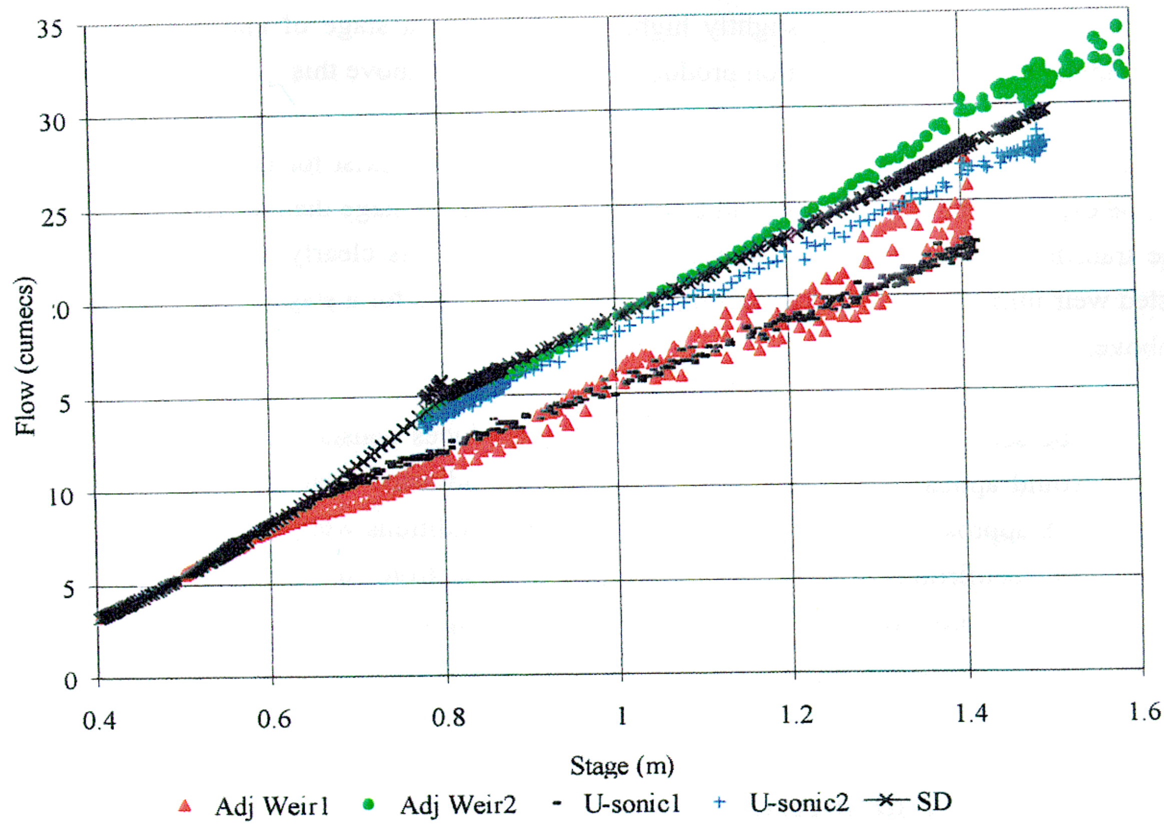


Figure 6.6 Stage-discharge ratings for Walcot derived from the adjusted weir formula in December 1996 (Adj Weir1) and January 1998 (Adj Weir2), the ultrasonic gauge in December 1996 (U-sonic1) and in January 1998 (U-sonic2), together with the Agency rating for the site.

It can be seen from Figure 6.6 that both the ultrasonic and adjusted weir flows are higher for a given stage during the second event than the first. In the case of the ultrasonic data this may be partially explained by the fact that the transducers are higher, although it is considered unlikely that this would result in flows increasing by as much as 20% (ie from 19 to 23 cumecs at a stage of 1.2 metres) given the analysis of path heights presented in Chapter 4. It must therefore be concluded that there was a real difference in the hydraulic conditions in the channel between the two events, and that the weir was able to operate more efficiently during the second event.

The increase in channel efficiency undoubtedly accounts for at least part of the difference between the two adjusted weir relationships plotted in Figure 6.6. However, when these are compared to their respective ultrasonic gauge data sets, it can be seen that the adjusted weir formula rating from the second event consistently produces higher flows for a given stage than the ultrasonic data from the same event. This is in contrast to the first event, where the flow data follow a similar pattern to that observed in the velocity analysis described in 6.2.2 and

and plotted in Figure 6.3, ie the flows produced by the two approaches are very similar, with the ultrasonic gauge producing slightly higher values up to a stage of approximately one metre, and the adjusted weir equation producing higher values above this.

Whilst it is reasonable to assume that this relationship will also exist for the second event, it would be expected that the flows would coincide up to a higher stage than the one metre level as the transducer paths were deployed at higher levels. This is clearly not the case as the adjusted weir formula produces consistently higher flow values for a stage level of 0.7 metres and above.

It can thus be seen that whilst the ultrasonic gauge produces consistent data over the two events, it would appear that the flows produced by the adjusted weir formula are less so. Although both approaches demonstrate that the channel conditions were different for the two events, further confirming that systematic errors will arise from the use of a single stage-discharge rating, a more detailed analysis of the relationship between the flows produced by the approaches suggests that there is some uncertainty in those produced by the adjusted weir formula. This uncertainty will be discussed in the next section.

6.3 Limitations and uncertainties

6.3.1 Limitations

As with Chapter 5, the majority of the limitations arising from the use of the ultrasonic gauge in real time are the same as those described in section 4.6 of Chapter 4. For example, silt or other debris are just as likely to affect a gauge deployed in this configuration as a portable installation, site conditions permitting. Similarly, the limitations relating to power supplies, access etc will also apply.

Notwithstanding these, a further limitation of using the gauges for the purposes described in this chapter is weed growth during low flows. If a weir becomes non-modular during low flows, for whatever reason, there is an increased probability that the gauge performance will be affected due to weed growth in the channel. This was the case at Walcot, as highlighted in 6.2.2. Indeed, the weed also had a significant effect on other studies that were carried out at the site, as Chapter 7 will describe. Although Walcot was the only field site that was affected by weed growth in the gauged section during the Project (Lea Hall was also affected by downstream weed), it is representative of a large number of lowland sites, particularly in southern England. It must therefore be concluded that if an ultrasonic gauge is to be used to monitor flows at a site which is known to experience both non-modular flows and weedy conditions it will be necessary to control weed growth along the line of the velocity paths.

A further potential limitation of using the gauge in this way is cost. The main focus of this Project has been the use of **portable** ultrasonic gauges, yet this chapter has described using the gauge in real time. To work on a permanent basis this will require a fixed installation, resulting in the capital cost being apportioned to a single site rather than multiple sites. For a strategically important site, such as one linked to abstraction control or discharge consent, the capital cost may be justifiable. The crest tapping pumping system installed at Walcot has cost approximately £8,000, compared to a similar capital cost of the ultrasonic equipment for a fixed installation.

6.3.2 Uncertainties

As with the limitations, the majority of the uncertainties associated with using the ultrasonic gauge to address the problem of a variable stage-discharge relationship are the same as those described in Chapters 4 and 5. For example, the tendency to over estimate velocities and flows at low levels, and under estimate at high was also observed at Walcot.

However, and as Section 6.2 has described, there is a further source of uncertainty associated with the Walcot field studies that was not encountered at any of the other field sites. This is associated with the method used to derive the non-modular flows, which is based on using the crest/upstream head ratio to establish a reduction factor (f_v). Once f_v has been established it is then used to scale down the theoretical flow produced by the modular weir equation. Whilst this approach has been shown to work well in the laboratory, and at two evaluation sites in the 1970s, Walcot is the first gauging station where it is being used to calculate flows for hydrometric purposes. The approach is highly sensitive to changes in the crest tapping level. For example, at a stage of 1.50 metres on the rising limb of the event plotted in Figure 6.5 the flows produced by the different approaches were as follows:

Ultrasonic gauge	27.8 cumecs	Modular weir equation	47.6 cumecs
Agency rating	29.8 cumecs	Adjusted weir equation	31.1 cumecs

If the crest tapping level is increased by just 5 mm the adjusted weir flow reduces to 30.5 cumecs; if the level is raised by 10 mm then the decrease in flow is almost 5% to 29.7 cumecs. It can thus be seen that any well lag present in the crest tapping system will introduce considerable uncertainty into the derived flows.

Whilst there is no direct evidence to indicate that the Walcot crest tapping well experienced any lag during either of the two events, data collected during April 1998 indicate that the well does become blocked. This is illustrated in Figure 6.7 below, which shows that the crest tapping becomes completely blocked when upstream levels are at approximately 1.2 metres shortly after 0000 on 11th April. Two 'steps' can be seen in the crest tapping plot - the first shortly after 1200 on the 11th April, and the second 16 hours later, when the well appears to become operational again. It is thought that these steps may coincide with the pumping system operation.

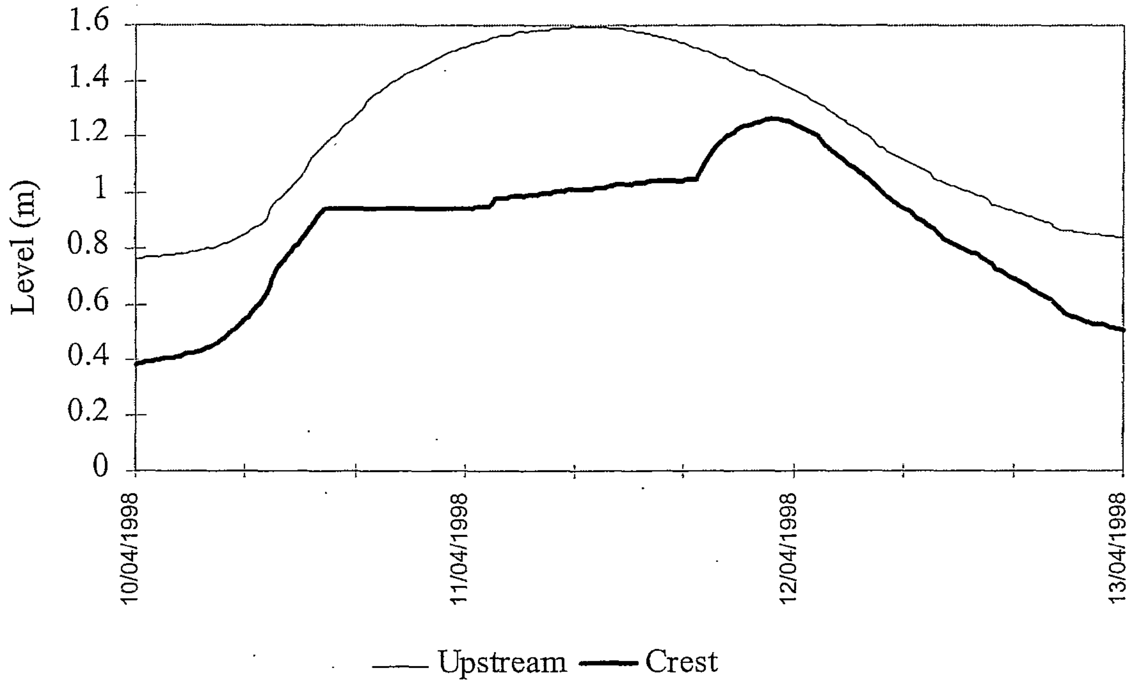


Figure 6.7 Upstream and crest tapping levels collected at Walcot between 1200 on the 10th April and 1200 on the 13th April 1998. The tick marks on the time axis are at eight hour intervals.

The above example illustrates a worse case scenario, ie the tapping becomes fully blocked. Whilst this did not occur during either of the two events used for the analysis presented in Section 6.2, it does indicate that the system is prone to silting up. This is unlikely to be an instantaneous occurrence, but is more likely to take place over a period of time. This suggests that there is a possibility that the crest tapping may have been partially blocked during the second event (when the frequency of flushing was less than in December 1996), and that well levels may therefore have lagged behind the true water pressure at the crest.

Further confirmation of the potential for well lag is provided by a theoretical analysis of the Walcot crest tapping system undertaken for the Agency flat V weirs R&D Project. This indicated that, even when unaffected by silt, the system may be physically incapable of filling the stilling well during a flood event. (The water to fill the 1.5 m^2 well is only able to enter the system via five holes 10 mm in diameter). During falling levels the well is able to keep up with the river.

It can thus be seen that whilst there is no hard evidence to confirm that the crest tapping stilling well encountered any lag during the January 1998 event, there is strong circumstantial evidence to suggest that this was likely. If so, this would account for the apparent 'discrepancy' in the flows from the adjusted weir equation approach, which were higher than expected. A higher crest tapping reading would have increased the reduction factor, resulting in the flows being reduced.

6.4 Conclusions

The results presented in this chapter have further demonstrated that the twin path ultrasonic gauge is able to establish stage-velocity relationships for an open channel section at what is known to be a 'difficult' site. Comparison with data collected from one of the few operational crest tapping systems in the UK have confirmed that the gauge is able to produce velocity data that reflect the changing hydraulic conditions within a channel, both during an event and for a number of different events. Furthermore, the results collected at Walcot suggests that the gauge offers a means of not only establishing whether or not non-modular conditions occur at a site, but may also identify the modular limit, albeit on a relatively coarse basis.

The Walcot results have also shown that the gauge is able to determine flows under changing hydraulic conditions. Because of uncertainties in the establishment of the 'true' flow at the site it has not been possible to undertake a thorough assessment of gauge performance, or to extend the analysis of the significance of the 'mean bed level' or 'bed correction factor' parameters. Despite this, the 'default' flows produced by the gauge follow a pattern that is consistent with other field sites. During low flows the gauge tends to over-estimate the true flow, whilst peak flows are under-estimated. The degree of over/underestimation depends on the height at which the paths are deployed, and the values of the gauge parameters.

Finally, the gauge appears to offer a viable alternative to established methods of measuring flows at sites which are known to experience non-modular conditions, be they variable or fixed. In terms of capital investment the gauge costs less than the crest tapping flushing system (current cost approximately £11,000), which to date has proved to be the only other suitable means of correcting for non-modular flows at flat V weir sites. Operational costs will also be similar, and whilst both approaches have their deficiencies and limitations, there is no evidence to suggest that either method is superior to the other. Certainly, the ultrasonic gauge is the only approach that can be retrospectively installed at a site that does not have an existing crest tapping.

7 ALTERNATIVE APPROACHES

7.1 Introduction

Chapters 4, 5 and 6 have all described the results from using the gauges as a twin path system at all but one of the field sites. Whilst the equipment will be used in this configuration at the majority of gauging stations, there are other configurations which may be employed should circumstances dictate. This chapter presents the results from studies that were carried out at some of the field sites to explore some of these alternative configurations.

7.2 Reflector Systems

All of the field studies described thus far have involved transducer racks being installed on both river banks, requiring cables to be installed to the far bank. In some instances this may not be possible, for instance if the far bank is vulnerable to vandalism, or if there are problems with access to the far bank. To overcome this problem ISO 6416: 1992 (E) suggests that both transducer racks are installed on the near bank and the acoustic signal is bounced off a reflector on the far bank, and details different types of reflectors that may be used.

In addition to overcoming problems associated with access and cabling to the far bank, the use of reflector systems also offers the **potential** advantage of overcoming errors associated with the alignment of the transducer path to the direction of flow as they provide a 'linear' version of the cross-path configuration. However, should the flow be non-uniform in direction, particularly during high flows, situations may arise where the problem is exacerbated rather than reduced, and the potential benefit becomes a potential disadvantage.

The main disadvantage associated with the use of reflectors is that it is often more difficult to align the transducer paths due to the reflector only being able to reflect the portion of the acoustic cone that hits it. Depending on the type of reflector that is used this scattered signal is then further weakened as it crosses the river for the second time. Some manufacturers, such as OTT, produce a reflector that is designed to reduce this scatter. A further disadvantage arises from the fact that using a reflector effectively doubles the path length, and therefore increases the signal losses arising from sediment load, aeration and weed, if present. It can thus be seen that during high flows, when the signal strength may already be reduced, reflector systems may further reduce the signal to the extent that the gauge is no longer able to function.

Given these potential advantages and disadvantages it was decided to evaluate reflector systems at some of the field sites. The first site to be chosen was Lea Hall, where there was a narrow channel with vertical walls. If these studies proved to be successful the approach would then be tried at Walcot, where the channel was much wider and less well defined.

7.2.1 Lea Hall

Work was undertaken at Lea Hall over the weekend of 15-16 February 1997 to try out different reflector systems. The period coincided with relatively high levels at the site caused by the River Dee having backed up the channel. Consequently, although levels were high the velocities were low, typically 0.1 m/s. River levels were falling throughout the study period.

A total of five different reflector systems were tried, listed below:

1. Reflecting the signal off the concrete wall.
2. An angled reflector, as described in ISO 6416: 1992 (E), made from 75mm aluminium angle mounted onto one of the transducer block supports.
3. A small reflector plate, 300 mm by 100 mm, made of 6 mm aluminium. This was mounted both vertically and horizontally, again attached to one of the transducer block supports.
4. A larger reflector plate, measuring 300 mm square, made of 5 mm steel plate and mounted onto one of the transducer block supports.
5. Finally, a steel plate measuring 1200 mm by 300 mm by 5 mm was used. This stood on the channel bed and was clamped via a horizontal brace to the transducer rack.

For all reflector trials the lower of the transducer paths was left in the original configuration at a level of 50 mm below the crest of the crump weir. The reflected path was only used for the higher path, 350 mm above the weir crest. The 'additional' transducer rack that was required on the near bank was temporarily installed immediately upstream of the weir wing walls.

Of the five different reflectors listed above only the last one worked, the 1200 by 300 mm steel plate. Intermittent readings were obtained from No 4, the 300 by 300 mm plate, but the count return was very low and did not exceed 8 out of a possible 255. It was thus decided to undertake a more extensive trial with the large reflector plate. During this trial the gauge was operated in the following sequence:

- Both upper and lower paths at original configuration;
- Upper path only, with reflector *in situ*;
- Lower path only;

- Upper path only, with reflector *in situ*;
- Return to original configuration.

Typically, up to ten sets of readings were taken at five minute intervals for each configuration. The results from these trials are shown in Table 7.1, and plotted in Figure 7.1

Table 7.1 Data collected from the reflector trials undertaken at Lea Hall on the 16th February 1997. The data are presented in order of collection, ie the first row of data were the first to be collected. Levels are in metres, flows in cumecs, and velocities in metres per second.

Stage	Gauge flow	Low path velocity	Low path count (max 255)	High path velocity	High path count (max 255)
Original path configuration					
0.595	0.265	0.090	255	0.108	255
0.595	0.264	0.098	255	0.100	255
0.595	0.264	0.093	255	0.105	255
0.594	0.263	0.096	255	0.097	255
0.594	0.263	0.098	255	0.100	255
0.593	0.264	0.096	255	0.104	255
0.593	0.264	0.098	255	0.103	255
0.592	0.263	0.092	255	0.099	255
0.592	0.264	0.100	255	0.102	255
0.591	0.264	0.097	255	0.103	255
Mean	0.264	0.096	255	0.102	255
Upper path only, reflected velocity path					
0.561	0.246			0.094	210
0.561	0.245			0.094	212
0.561	0.248			0.095	212
0.56	0.244			0.093	210
0.56	0.244			0.093	207
0.559	0.247			0.094	255
0.559	0.243			0.093	210
0.559	0.244			0.093	210
0.559	0.242			0.093	170
0.559	0.233			0.089	211
Mean	0.244			0.093	211

Table 7.1 (continued) Data collected from the reflector trials undertaken at Lea Hall on the 16th February 1997. The data are presented in order of collection, ie the first row of data were the first to be collected. Levels are in metres, flows in cumecs, and velocities in metres per second.

Stage	Gauge flow	Low path velocity	Low path count (max 255)	High path velocity	High path count (max 255)
Lower path only, original configuration					
0.561	0.127	0.098	213		
0.561	0.126	0.097	210		
0.561	0.128	0.099	212		
0.56	0.132	0.102	212		
0.559	0.125	0.096	209		
0.559	0.129	0.100	175		
0.559	0.126	0.097	169		
0.559	0.125	0.096	255		
0.559	0.128	0.099	211		
0.558	0.124	0.096	189		
Mean	0.127	0.098	206		
Upper path only, reflected velocity path					
0.546	0.207			0.081	91
0.545	0.234			0.091	79
0.543	0.097			0.038	194
0.543	0.098			0.038	211
0.543	0.088			0.034	201
0.542	0.095			0.037	159
Mean	0.164			0.064	187
Original path configuration					
0.54	0.259	0.098		0.107	210
0.539	0.271	0.104		0.110	209
0.539	0.269	0.100		0.114	210
0.538	0.269	0.105		0.107	211
0.538	0.256	0.098		0.105	208
0.542	0.254	0.094		0.107	212
0.538	0.258	0.101		0.104	211
0.537	0.25	0.094		0.104	209
0.537	0.253	0.094		0.108	212
0.537	0.258	0.099		0.106	201
Mean	0.26	0.099		0.107	209

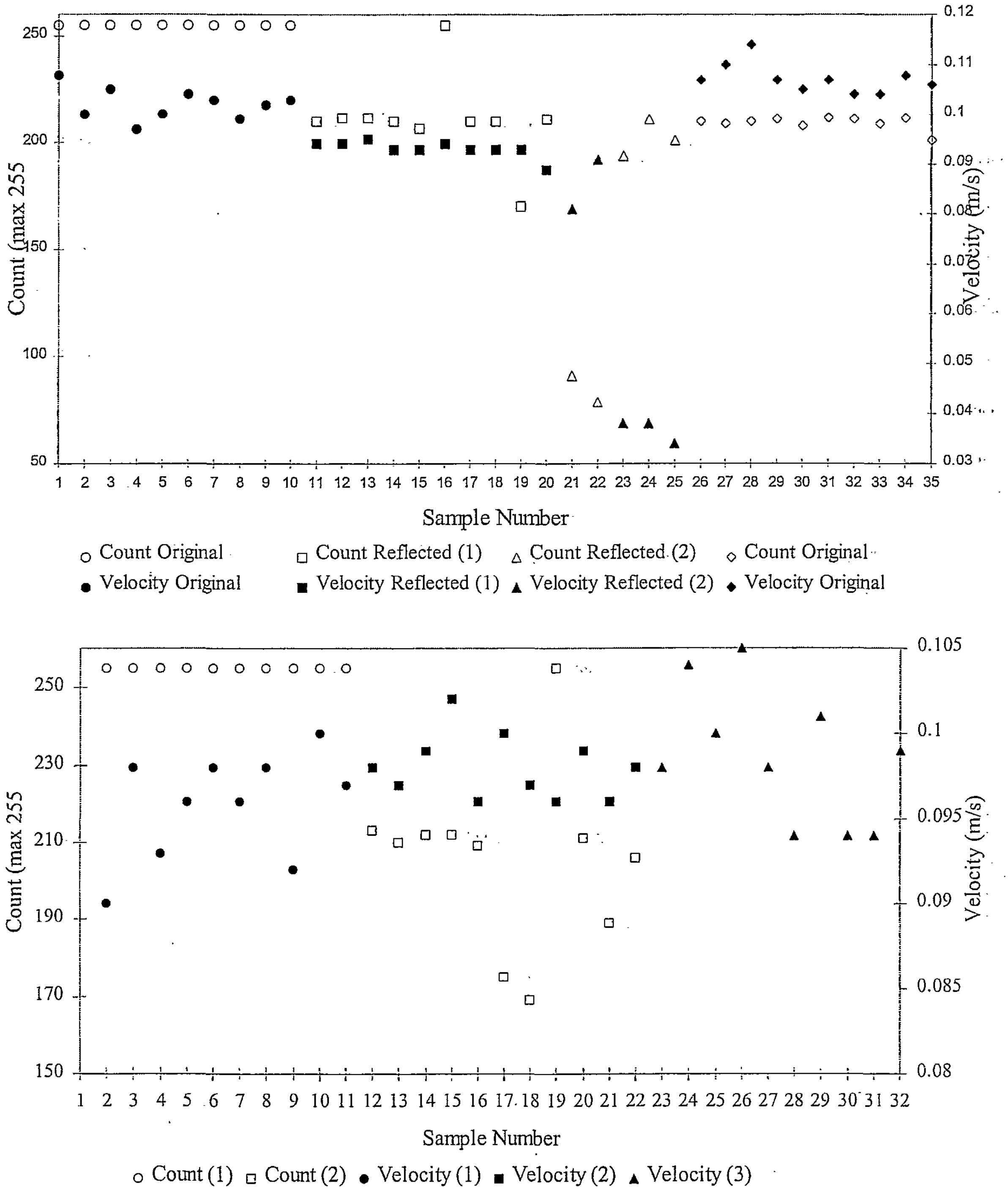


Figure 7.1 Velocity and count data for the high and low transducer paths collected during the reflector trials at Lea Hall, and as presented in Table 7.1. (1), (2), (3) etc indicates the sequence in which the readings were taken. The reflector was only used to obtain velocities along the high path, as plotted in the upper of the two graphs. All count values are out of a maximum of 255, and velocities are in metres per second.

A number of points can be made about the data contained in both Table 7.1 and Figure 7.1. These are summarised below:

- Both transducer paths recorded maximum counts **before** studies commenced in the channel. However, once work had started after the first ten sets of readings, the count of successful pulses reduced for both paths. This was due to sediment on the channel bed being disturbed whilst work was underway.
- Throughout the study period the velocities recorded along the lower of the two transducer paths appear to have increased as river levels fell. Consequently, river flows did not significantly alter during the period, even though levels in the River Dee may have.
- Similarly, the data from 'original' velocity configuration for the upper transducer path were also higher at the end of the study period than at the beginning.
- The first set of 'reflected' velocity data (Velocity Reflected (1)) plotted in Figure 7.1 are slightly lower than the original set of velocity data. This is physically reasonable if it is remembered that these data were collected from further upstream of the weir, where the acceleration effect as the water approaches the weir crest will have been less.

These observations appear to indicate that the reflector trials at Lea Hall were successful in that they not only confirmed that the reflector was able to provide consistent and reasonable data, but that subtle differences in the flow characteristics could also be detected. However, the data relating to the second set of reflected data are much less reassuring. In addition to recording very low count values, often less than 100, this set of data also recorded much lower velocities. It is not known why this is the case, particularly as the very low velocities are actually associated with the highest 'count' values. What it does indicate is that the reflector system appears to be less dependable than the straightforward configuration. When this is combined with the fact that it took considerably longer to align the reflector than the velocity paths, it would suggest that the reflector system should only be used where absolutely necessary.

7.2.2 Walcot

The success of the reflector trials at Lea Hall led to the decision to extend the evaluation at one of the larger channels used for the Project. It was decided to undertake further trials at Walcot, where access to both banks was straightforward and it was known that the gauge performed well under all flow conditions. Trials were undertaken on 16th September 1998.

Due to the relatively low river flows only one of the transducer paths was submerged at the time the trials were undertaken. On arriving at the site the previous day it was found that this path had failed due to extensive weed growth in the channel. This was cleared, together with the weed along the anticipated line of the reflected path. An additional transducer rack was installed on the near bank, some 30 metres upstream of the weir crest, and the trials were undertaken in the following order:

- Seven sets of velocity data were collected from the original configuration at five minute intervals.
- The reflector was then installed and aligned, following which a set of six velocity readings were taken at five minute intervals.
- Finally, the transducers were returned to the original configuration and a set of six velocity readings were taken, again at five minute intervals.

The collected data are shown in Table 7.2, and plotted in Figure 7.2.

The first and most dramatic point to note from these data is the reduction in the count values for the reflected configuration data set. Mean count values fall from the maximum of 255 to only 101. Unlike Lea Hall, this is not due to disturbed sediment in the channel - note that the second set of velocity collected with the original configuration at the end of the study recorded maximum count values of 255. Instead, it is probable that this reduction in count is due to increased attenuation of the acoustic beam, arising from the path length increasing from 20.8 to 41 metres. Whilst it might be argued that this signal loss may also be due to increased interference from weed, great care was taken to ensure that the reflected transducer path was as clear as possible from all weed.

Table 7.2 Data collected from the reflector trials undertaken at Walcot on the 16th September 1998. The data are presented in order of collection, ie the first two columns of data were the first to be collected from the original configuration.

Original Configuration		Reflector Configuration		Original Configuration	
Path velocity (m/s)	Count (max 255)	Path velocity (m/s)	Count (max 255)	Path velocity (m/s)	Count (max 255)
0.260	255	0.291	122	0.256	255
0.252	255	0.266	118	0.256	255
0.258	255	0.287	19	0.263	255
0.259	255	0.271	109	0.263	255
0.257	255	0.269	113	0.257	255
0.258	255	0.264	124	0.261	255
0.260	255				
Mean values					
0.258	255	0.274	101	0.259	255

The second point to note is that, in direct contrast to the data collected at Lea Hall, the reflected path velocity data values are higher than those collected from the original configuration. The mean sub-set velocities increase from 0.258 to 0.274 m/s, before falling to 0.259 m/s. In both relative and absolute terms the transducer racks were much further upstream of the weir crest than at Lea Hall, resulting in negligible influence on the water velocity. However, a much more significant factor is that the upstream channel is significantly shallower than that close to the weir - typically 0.5 metres compared to almost twice this. It can thus be seen that even when pooling and 'dead zone' influences are considered, the velocity along the upstream reflected path will be much higher than that along the transducer path used by the original configuration. The actual difference, based on mean path velocities of 0.258 and 0.274 m/s, is of the order of 0.03 m/s (ie twice the difference of the two values), or 12% of the original configuration mean path velocity.

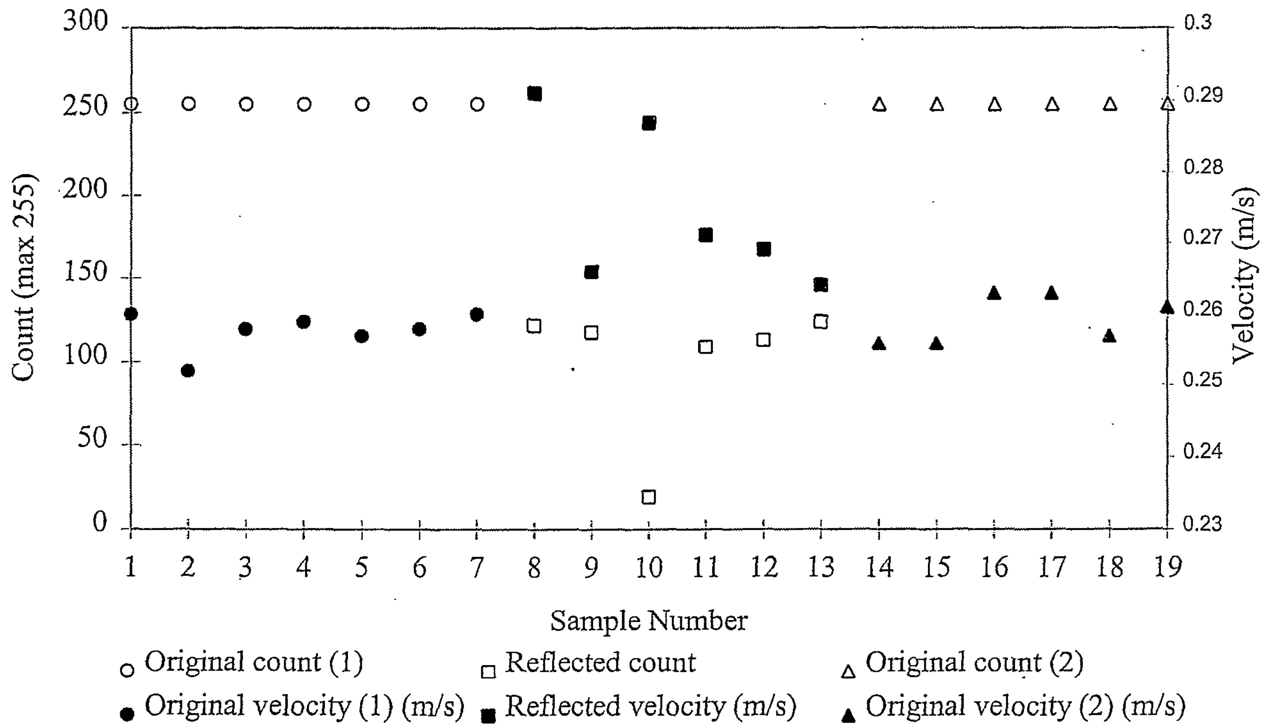


Figure 7.2 Velocity and count data for the single transducer path collected during the reflector trials at Walcot.

It can thus be seen that the studies at Walcot serve to confirm and build on the findings at Lea Hall. Whilst the gauge is able to work with a reflected velocity path, the amount of the acoustic signal that is successfully detected is greatly reduced. Typical count values were more than halved for a channel that is between 15 and 20 metres wide. If it is remembered that this was under low flow conditions, when sediment loads were low, it can be seen that the probability of gauge failure during high flows and associated higher sediment loads will be increased. However, should it be absolutely necessary to use a reflector system, the Walcot studies have further confirmed that the equipment is sensitive enough to detect subtle changes in the channel velocities as channel geometry changes.

7.3 Multi-level operation

One potential approach that was identified at the start of the Project was to alter the level of the transducer paths **during** an event whilst staff were on site. During the course of the Project this was successfully completed at sites where it was possible to gain safe access to both transducer racks. These sites were Greenholme, Lea Hall, Walcot and, to a lesser extent, Middleton in Teesdale. The most common benefit of this was to clear any debris from the transducers, although it was possible to set the transducer paths at different levels for the remainder of the event. Whilst it is questionable whether or not this actually increased the usefulness of the data collected during a single event, it did mean that the gauge could be left 'ready' for the next event with the transducers at a new set of levels. This was particularly useful at Walcot, which involved a considerable amount of travel to reach, but was also useful at Greenholme where successive events occurred within a couple of days of each other. As visits to this site were primarily governed by battery life, this did mean that travel times were reduced as much as possible.

One further advantage of this approach was that it enabled detailed velocity profile data to be collected from Lea Hall during a number of events. The channel at Lea Hall is badly affected by backing up from the River Dee, which often results in near stationary conditions in a relatively deep channel. Under these conditions the weir equation for the Crump weir is effectively meaningless. Given the deep and narrow channel, and the fact that the water velocities can be very low under these conditions, it may be desirable to assess the nature of the velocity profile under these conditions. This data may then be used in trying to identify an alternative solution to the monitoring of flows at the site.

Detailed velocity profile data were collected between 0810 and 0900 on 1st March 1997 from nine different transducer path levels. Five one-minute readings were taken at each of the nine levels, and the mean path velocities are plotted in Figure 7.3 below. It can be seen that, even under such low flow conditions, the gauge is sensitive enough to provide consistent data that enable the velocity profile to be derived. Low velocity readings were obtained near to the channel floor, and increase with depth up to a level equivalent to the weir crest. Peak velocities were found in the 350 mm of water immediately above the weir crest, before decreasing towards the water surface at 0.625 metres. It is thus concluded that the gauge is suitable for use under these conditions if required.

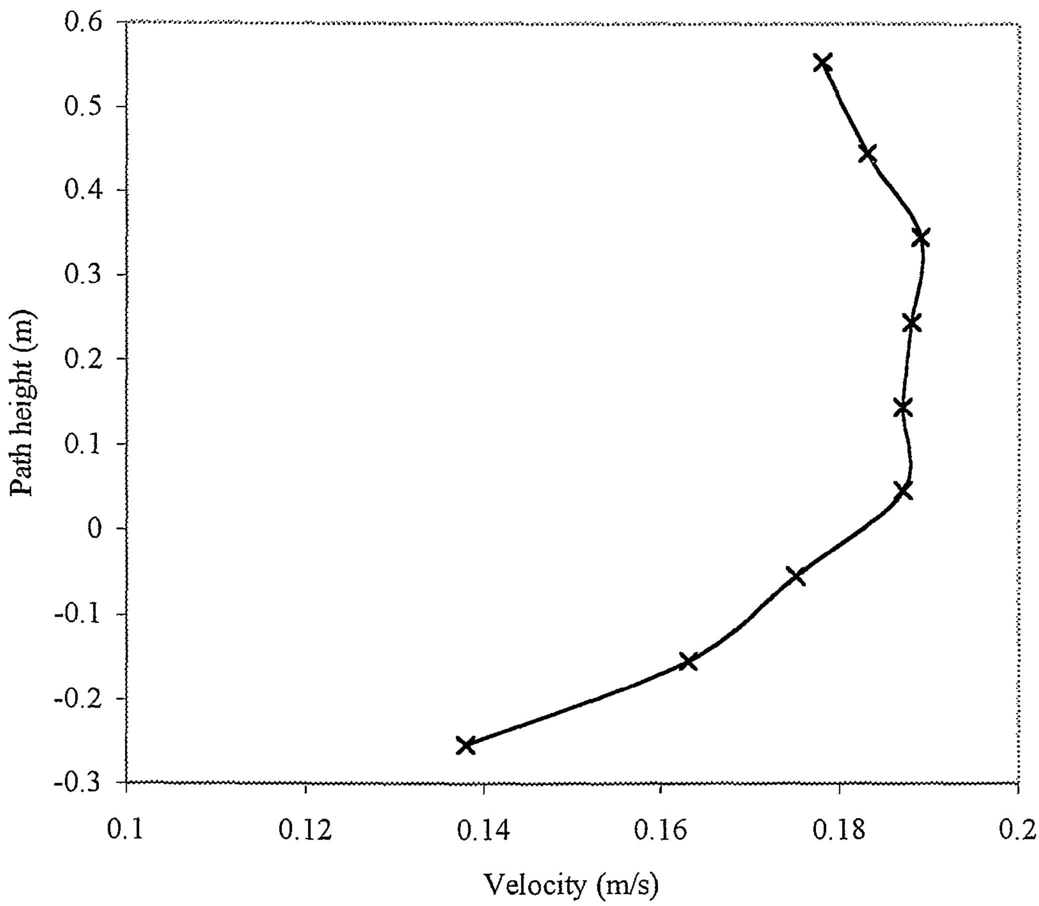


Figure 7.3 Velocity profile data collected at Lea Hall on 1st March 1997 when the channel had backed up. Individual data points are the mean of five one-minute readings at each level. The mean river level during the study period was 0.625 metres.

7.4 Non-horizontal transducer paths

The final alternative approach to using the twin path system was discovered by chance. Whilst adjusting the transducers during a high flow event at Greenholme it was noted that the gauge is less sensitive to path alignment in the vertical plane. This was found when raising the upstream transducers by an initial 200 mm, when it was noted that maximum counts were still being recorded by the gauge. Due to the rapidly falling stage it was only possible to raise the upper path by this amount before it was out of the water. However, the lower path was raised by a further 200 mm, giving a total vertical misalignment of 400 mm. Even at these settings the gauge was still giving maximum counts, and the velocities were between those of the upper and lower paths when operating in the horizontal plane. The recorded data are given in Table 7.3.

Table 7.3 Data collected at Greenholme during the event of 1/2 May 1996 when the upstream transducers were raised 200 and then 400 mm above those on the downstream rack, before returning the transducers to their original levels. The data show that there may be scope for setting at least one of the paths up in this way.

Initial transducer settings at 0.088 and 0.588 metres above stage datum		
Stage	Upper Path Velocity	Lower Path Velocity
0.897	1.122	1.007
Both transducers raised by 200 mm on upstream rack		
0.894	1.133	1.025
0.893	1.133	1.030
0.891	1.131	1.027
0.890	1.119	1.027
0.887	1.117	1.024
0.885	1.130	1.023
Lower transducer raised by 400 mm on upstream rack		
0.882		1.035
0.883		1.031
0.882		1.031
Transducers reset to initial levels		
0.873	1.081	0.978
0.874	1.085	0.984
0.873	1.080	0.982

Whilst these observations were not explored further within the Project, a number of potential uses can be considered. It might be desirable to set up the lower velocity path along a 'vertical diagonal' to sample as much of the water column as possible during low-medium flows, and leave the upper path at a much higher elevation to pick up velocities at the peak of high flow events. This offers even greater benefits when the weighting applied to the lower path velocities by Peek in the gauge software is taken into account. Another alternative might be to set up both paths as 'vertical diagonals'; but to do this as a pair of crossed paths if skewed flow is suspected.

(Note: The Peek multipath gauge at Shardlow on the River Trent has a non-horizontal lowest path to account for an extremely asymmetrical cross section.

7.5 Conclusions

This Chapter has presented the findings from a number of studies that have complimented the main focus of the Project, even if some of them were discovered by chance. Whilst some of these results are far from complete, they do serve to indicate that a potential user of the equipment does not necessarily need to be confined by the more 'standard' approaches presented in Chapters 4-6. Instead, they should feel free to investigate alternative configurations if site conditions should dictate that this is necessary. The equipment has proved to be sensitive enough to detect subtle changes in channel geometry and transducer path configuration, whilst still providing consistent data. As the results from the earlier chapters have indicated that the actual height of the transducer paths is not always the most important factor in determining the accuracy of the gauge, some of the approaches identified in this chapter may provide a useful way of reducing some of the uncertainties associated with channel and flow geometry, or at least confirming whether or not a potential problem exists.

8 CONCLUSIONS AND SUMMARY FINDINGS

8.1 Overview of results

This Report has described the results from a research Project that was undertaken between November 1995 and March 1999. The Project evaluated the potential for using portable twin-path ultrasonic gauges to calibrate gauging stations, and involved deploying two gauges at a total of six field sites.

On the whole the gauges performed well at the majority of the field sites under the majority of conditions. Both level and flow were measured in a consistent manner at a wide range of sites under both low and high flow conditions. The most notable weakness in the gauge performance was the tendency for the velocity paths to fail under conditions of high sediment concentrations during high flow events. No quantified data were collected during the course of the Project to confirm whether or not there is a specific sediment concentration or load that causes the paths to fail, but supporting data from another study were presented to support the findings.

As a result of the field studies at the different sites a number of specific recommendations have been made to enable the gauges to be deployed in an efficient manner. Many of these recommendations have built on the requirements of ISO 6416: 1992, and provided a practical interpretation of the requirements of the Standard, whilst others focus more on obtaining the optimum configuration and results from the equipment. These recommendations have been summarised in Appendix H, which will hopefully serve as an *aide memoir* to any hydrometric staff actively engaged in deploying similar equipment at Agency gauging stations, whilst Appendix D contains results that are specific to the equipment used during the course of the Project.

The Report has presented an analysis of results obtained by using the data collected by the gauges in a number of ways, even though for the purposes of the Project all of the gauges were effectively deployed in the same way. At the simplest level, it has been shown that deploying the gauge as a twin path unit and using the flows calculated by the gauge results in a surprisingly good performance. Typical uncertainties in the derived flows are equivalent to $\pm$ 5% over a high flow event, with maximum uncertainties being of the order of $\pm$ 10%. This level of performance can be obtained by optimising one of the parameters used by the gauge, the bed correction factor, from measuring the flow by conventional means at the time the gauge is installed. If this is not possible a slightly lower performance can be obtained by initially setting the bed correction factor to a value of 0.65 instead of the manufacturer's setting of 0.8.

Data from Agency multi-path gauges were analysed in order to try and identify an optimum level at which the two transducer paths should be deployed if only a twin-path installation is to be used. It was found that deploying the lower of the transducer paths at a level equivalent to less than 0.3 of the maximum depth, and the upper path at between 0.45 and 0.75 of the maximum depth, produces results that were within ± 5% of the optimum for all cases, with almost 75% of results being within ± 2%.

The typical operating costs associated with using the gauge in this manner over a suitable study period have been assessed. It is considered that to deploy the gauge for a six month period, during which time a total of 14 site visits are made, will cost the Agency some 67 staff hours, £1,311 in equipment costs, and the travel costs and time taken to travel to and from the site 14 times.

Although using the gauge as a simple twin-path system may produce acceptable results, the approach is vulnerable to problems associated with intermittent path failure which may introduce a systematic error into the derived flows. Whilst the gauge manufacturer has produced software that is designed to correct for this, as well as allowing for differing channel geometries, the Project has found that deriving stage-discharge relationships from the collected data results in the flows being derived in a more consistent manner.

The Project has also demonstrated that the uncertainty in the derived flows can be further reduced by operating the velocity paths at a number of different levels. By using the collected velocity data to derive stage-velocity relationships for the different path height it is possible to replicate the performance of a multi-path gauge. Stage discharge relationships produced from this approach are able to derive flows to within ± 2.5% in most cases, the maximum uncertainty being ± 5%. To obtain this increase in performance need not involve any additional time on site, although it is estimated that a further three days' staff time will be needed to analyse the data, develop the relationships and rating, and assess the performance of the rating once the field studies have been completed.

In order to operate the gauge by the methods described above it is essential that the site has a stable stage-discharge relationship. The Project has shown that where this is not the case, ie where a site has a variable modular limit and/or experiences non-modular conditions, deploying a twin-path gauge to collect data in real time offers a viable alternative to the methods used by the Agency at present. The equipment is sensitive enough to detect subtle changes in the stage-velocity relationships under differing conditions, and is able to calculate flows that reflect the hydraulic state of the channel at that particular time. It has also been shown that the equipment may, under certain conditions, offer a more consistent and dependable method of calculating flows than approaches recommended in the British Standard such as crest tappings.

In addition to using the gauge in the more conventional configurations, specific studies were also carried out at a number of the field sites to assess alternative configurations. It was found that whilst reflector systems can be used to collect data from a site where access to one of the river banks is limited, the performance of the gauge is reduced as a result of the increased path length. Consequently, the gauge is more likely to fail as it becomes more vulnerable to suspended sediment loads, and it is recommended that this particular configuration is not adopted unless absolutely necessary. Other studies demonstrated that the gauges can be used to collect data from more than two levels during an event in order to compile velocity profiles, and that the gauges can be deployed with non-horizontal velocity paths should the need arise. The conclusion from these additional studies is that the user should not feel confined to the more traditional configurations, but should feel free to try alternatives should a particular site require this.

For all of the studies and methods described in this report the respective limitations and uncertainties have been assessed on both a theoretical and practical basis. It is considered that whilst there are various theoretical uncertainties associated with the use of the equipment, some of these cancel each other out, and the majority of them are effectively taken account of if the gauge parameters are initially set on the basis of the observed flow conditions at the time of installation, as previously mentioned. In practice the net uncertainties are likely to be of the order described earlier in this section of the report, *provided that there is no change in the direction of flow or channel hydraulics as the river levels rise.* The majority of the uncertainties described in this report apply within the observed range of levels. As soon as any of the methods are used to extrapolate relationships and derive flows beyond the observed range the uncertainties will increase in almost all cases. Whilst some of the Project results would suggest that the data can be extrapolated without too much of an increase in the uncertainty, this is only the case if the channel hydraulics are stable and the channel itself has a regular geometry.

8.2 Assessment of Project objectives

The overall aim of the Project was to determine the feasibility of using the ultrasonic method to calibrate gauging stations, and to assess the limitations, accuracy and optimum configuration of the method. Chapters 3-7 inclusive have described the studies that have allowed this aim to be achieved, and the Project results have been summarised in Section 8.2 above. Section 1.3 identified ten specific objectives that were to be addressed as part of the Project.

In order to assess the overall success of the Project it is useful if these objectives are assessed on an individual basis:

a) **To identify practical problems of application and limitations of the method.**

Chapter 3 identified the practical problems associated with the use of the equipment, and chapters 4-7 have all described the various problems that were encountered with the different gauge configurations. The limitations of the equipment have been identified, and these are used as the basis for recommending further research in the final chapter.

b) **To determine the accuracy of the equipment under a range of conditions from ideal to the borderline of application.**

Chapters 4-7 have all attempted to place the gauge flows into perspective by comparing them to those derived by the Agency by a variety of different methods. One of the reasons that Middleton in Teesdale was selected as a field site was because it was considered to be a 'borderline' site, and would thus enable the gauge to be assessed under these conditions.

c) **To determine the optimum configuration.**

Chapter 4 presented analysis of velocity data from multi-path gauges that were used in an attempt to determine the optimum configuration for deploying the two velocity paths. Chapter 7 has described alternative configurations to the standard 'parallel paths', and described where such a configuration might be appropriate.

d) **To recommend a standard practice where this is feasible.**

This objective is addressed in Chapters 3, 9 and Appendix H.

e) **To note areas of remaining uncertainty in the accuracy of results.**

Chapters 4-6 have all included a section which describes the uncertainties associated with a particular gauge configuration. Whilst these uncertainties may be site specific to a certain extent, it is felt that they are also indicative of the general situation.

f) **To assess typical costs of the method based on realistic equipment costs and life, and manpower requirements.**

This objective was addressed in Chapter 3, and in Chapters 4-6.

g) **To test and report on the performance of ultrasonic equipment at structures over a range of mainly high flows and non-modular conditions. The structures will have an existing accurately known modular rating and will also be typical sites for future application.**

This single objective is probably the one which best summarises the overall aims of the Project, and is addressed throughout the whole of this Report.

h) To use any existing suitable ultrasonic gauging stations in a manner which replicates the portable equipment.

Chapter 4, section 4.5, specifically addressed this objective.

i) To produce a Report on each site tested, and incorporate this in the final Project Record.

The Site Reports are all contained in the Project Record.

j) To produce:-

A Project Record;

A Technical Report;

An R&D Note.

This objective has been addressed through the production of the three documents described above.

It can thus be seen that all ten specific objectives have been fully addressed during the course of the Project.

8.3 Conclusions

On the basis of the findings presented in this report it is concluded that portable ultrasonic gauges operating on the time of flight principle can be used to calibrate both new and existing gauging stations under a wide range of flow conditions. The gauges worked well under most conditions at the majority of the field sites, and produced consistent data in all cases. They provide a viable and cost effective alternative to more conventional means, albeit with some limitations of their own. It must also be remembered that the gauge did not work effectively at all of the study sites; one less than ideal site (Middleton) was chosen to try and fully test the operational range of the equipment, and it was found wanting under these most testing conditions.

The Project has demonstrated that by using the equipment it is possible to obtain a rating curve that derived flows to within ± 5% or less from very few events. Perhaps the most useful data set collected during the Project was from Greenholme, yet only five events during a relatively dry six-month period were recorded at this site. On the basis of the data collected from this site alone it can be seen that the ultrasonic gauge offers a more efficient means of deriving a rating curve for new or ungauged sites than some of the alternative approaches currently used by the Agency. These findings are supported by some of the other field sites, although it must also be noted that the performance of the gauge at Middleton in Teesdale was less impressive in that it was unable to measure the higher flows that occurred at this site.

If a site is of particular strategic importance the uncertainty in the derived flows can be reduced by collecting data from a number of velocity levels. If flows are required from a site for a one-off study then suitable data can be collected from a smaller number of paths, although there will be higher uncertainties in the derived flows. The final chapter contains guidance on the selection of the most appropriate approach to be used for a range of purposes. The chapter also describes some areas that would benefit from further research, and provides some thoughts on how the results of this Project can be taken forward for implementation by the Agency.

9 RECOMMENDED APPROACH FOR IMPLEMENTATION

9.1 Introduction

One of the initial objectives of the Project was to recommend a standard practice, where feasible (objective (d) in section 1.3). What was not specified, however, was whether this objective related to the use of the equipment at a technical or practical level, or whether it was concerned with more fundamental issues that may be decided at either a Regional or National level, such as whether or not the Agency consider that the results obtained from the equipment form an appropriate alternative to those derived from more 'conventional' methods.

This chapter will attempt to address the potential issues that may arise at a strategic level regarding the use of the equipment. Factors which relate specifically to the use of the equipment at a local level, once a decision has been taken to deploy a gauge, are also covered in section 9.4. This is largely based on the recommendations made in chapter 3.

Whilst this Report has attempted to address issues in an objective manner, much of the content of this chapter will involve subjective opinion. The majority of this has been formed by the research contractor during the course of completing this work over a three year period, supported by lengthy discussions with Agency personnel and the equipment manufacturers. In particular, many of the conclusions thus formed have been discussed with Mr David Gibbard who, in addition to working for Peek Measurement, is also a member of the British Standard sub-committee for hydrometric instrumentation. It is understood that the sub-committee is currently considering potential alterations to the existing version of BS 3680 Part 3E: 1993, and may incorporate some of the Project findings in this.

9.2 Implementation at the National and Regional scale

The factors to be considered at a Regional or National scale are of a more fundamental nature than those at the local scale, and are as much to do with general policy as specific action. The publication of the Bye Report has resulted in the Agency having to focus on the issue of high flow measurement, and the completion of this R&D Project is particularly timely in this regard. This section will introduce some of the points that will need to be considered at the wider scale before the results of this Project can be fully implemented at the local scale.

Some Agency Regions have already decided to use ultrasonic time of flight gauges to calibrate both new and existing gauging stations, and others are following suit. The research contractors have provided assistance and advice to those who started this work in late 1998, and it is hoped that the publication of this Report will assist others who wish to venture down the same path. However, before the approaches described in this Report are widely adopted, it is likely that the following issues will have to be considered by either the National Hydrometric Group and/or the Area Water Resource and Flood Defence management teams:

1. Is the approach a viable alternative to existing methods, ie ratings derived by current meter gaugings or those derived from applying the appropriate British Standard to a structure which is built to the Standard? The results from this Project suggest that the answer to this question is a definite 'Yes', with the Project results indicating that the approach may actually be an improvement rather than a mere alternative in some cases.

2. At present the gauging station classification system used by the Agency makes some allowance for the inclusion of ultrasonic gauges, but is still considered by some Regions to be far from ideal. Is there a need for the system to be further developed to take account of the twin-path approach and, if so, will the opportunity be taken to address some of the other concerns about the classification system?

3. Whilst multi-path gauges are now widely accepted as providing accurate flow data, is the same true for twin-path gauges? If not, what are the reasons for this? There is certainly a perception in some Region/Area offices that twin-path gauges are a poor compromise of specification and cost, and that if there is a need to monitor flows at a site then a multi-path gauge should be used. Whilst it is true that a full multi-path gauge will provide more accurate data than a twin-path unit, the Project results suggest that the improvement in performance may not be as great as expected. There may thus be a need to 'spread the word' about the relative performance of twin and multi-path gauges.

4. Is there a need for specific training in the use of twin-path gauges for the hydrometric staff, and if so how can this be incorporated into the existing training system?

5. Are there any research issues that still need to be resolved? Section 9.5 outlines the two main factors that the Research contractor considers to merit further research, but there will almost certainly be others.

6. Finally, if it is decided to adopt the approach at a National/Regional level, what are the resource implications of this? Whilst this Report has described the typical costs associated with the purchase and use of the equipment, it may be possible to increase efficiency by pooling resources, particularly manpower.

9.3 Implementation at the Area scale

9.3.1 Introduction

The issues to be considered at an Area scale are primarily of a pragmatic nature, the most important single factor being the selection of the site itself. Once this has been identified, the next issue to be resolved is the approach that is to be adopted. This section of the Report will thus provide guidance on this; section 9.4 provides further guidance in actually deploying the gauges at gauging stations.

9.3.2 Selecting the appropriate approach to using the equipment

This Report has described three different approaches to using the twin-path gauges:

1. Deploying the gauge solely as a twin path unit, and only collecting velocity data from two different levels in the river ('Twin path only' approach).
2. Collecting velocity data from more than two different levels, and using this to derive a rating curve based on a series of stage-velocity relationships ('Multi path' approach).
3. Operating the gauge as a twin path unit in real time to provide continual flow data for a given site ('Twin path, real time').

A fourth potential approach can be added to these, and involves initially operating the gauge as a twin-path unit to assess whether or not velocity data need to be collected from more than two different levels. This approach is referred to as the 'Twin>multi path approach'.

n deciding which of the four approaches to use a number of different factors need to be considered. Whilst some of these will compliment each other, some will also be in direct conflict (for example, resource availability and quality of data). Figure 9.1 summarises the principle issues that need to be considered, together with suggesting a method of selecting the appropriate approach.

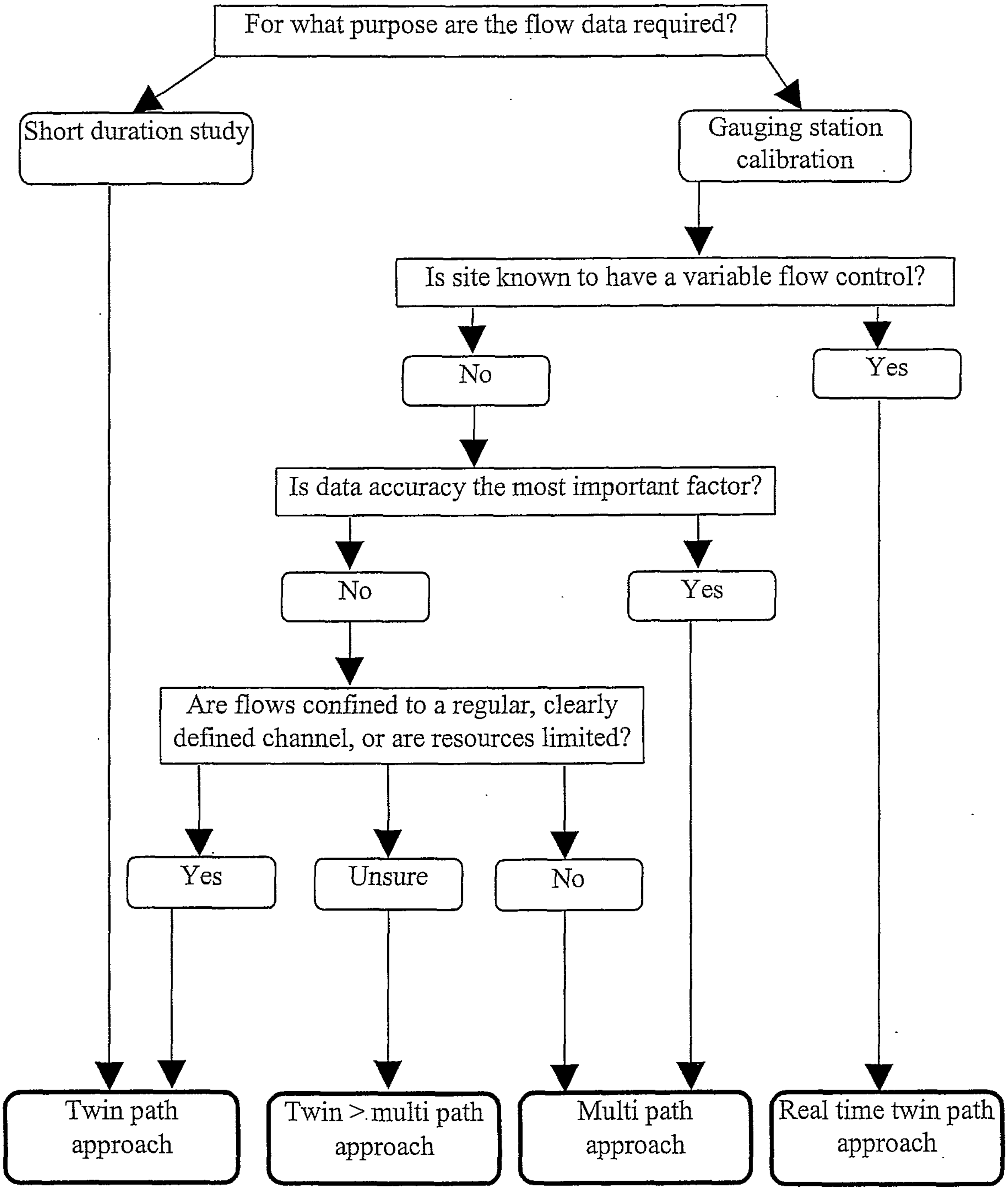


Figure 9.1 Decision tree for the selection of the appropriate method of gauge deployment.

9.3.3 Data collection and analysis

All gauges used during the Project had their EPROMS configured to enable the collection of individual path velocities in addition to the standard variables of depth and flow. Whilst this option has financial implications in the case of the Peek 1408 gauge, **it is strongly recommended** that when any gauges are purchased and/or configured, the decision is taken to record all four variables.

When analysing the data collected from the gauges it is important to ensure that the data are not misused. For example, there should be evidence that any stage-velocity relationship is stable and consistent during different events before electing to derive a stage-discharge relationship based on stage-velocity relationships. This will require at least one of the velocity paths to be operated at the same level for more than one event. The channel configuration and topography should be considered when deciding how far to extrapolate any relationships derived from the gauge data. For example, whilst it was possible to extrapolate the rating curve at Greenholme beyond the observed range in river levels, this was only possible whilst flows were still within channel. Once the main channel was over-topped the gauge rating began to depart from that derived by current meter gaugings. Similarly, the upper limit of the main river channel at Blackford Bridge also coincided with the point of departure between the Agency and gauge derived ratings.

9.4 Recommendations for deploying the gauge on site

Once it has been decided to deploy an instrument at a site by one of the identified methods, and the general locality of the study site has been identified, it is recommended that the following sequence of events is followed. This sequence is a summary of the points contained in Chapter 3, together with additional information and experience gained from the Project.

1 Undertake preliminary assessment of site and channel

Depending on the nature of the channel and flows this is best carried out from both the river bank and in the channel itself. The 'ideal' site will have a uniform cross section, a straight approach and downstream channel, a stable flow control and steep channel sides that will contain high flows. The river bank survey will assist with channel alignment and slope, whilst the walk in channel will assist with a preliminary assessment of the channel cross section at various points.

2 Carry out detailed survey of identified site

Once a suitable reach has been identified at the study site a more detailed survey should be carried out. This will include the four cross-sections identified in Figure 3.2, together with an assessment of flow direction as shown in Figure 3.7, and an assessment of the channel slope/sides at the identified point for deploying the transducers. If an existing gauging station is to be used it is useful if the transducers span the intake to the stilling well as the station records can then be used to provide a backup set of river level data should the depth transducer fail.

3 Install mounting system

Having surveyed the channel reach the appropriate mounting systems can be identified and fabricated. Depending on the identified approach, as described in section 9.3.2 above, this may be a fixed level system (two level operation only) of a multi-level system, such as that shown in Figure 3.3. Once fabricated the system can then be installed in the river, as described in section 3.2.2.

4 Install gauge, transducers and cables

Once the mounting system has been installed it is then possible to install the gauge itself. It is recommended that, where available, the plug-in extension leads are used as this makes the process much more straightforward. Transducers are mounted on their respective racks, and cables led back to the gauging station. Preference should be given to aerial routing of cables from the far bank; if this is not possible, and there is no bridge available, then short link 3/8" (10mm) galvanised chain has been found to be suitable for carrying the cables across the river bed. The depth transducer should, where possible, be deployed in the main channel, at a level some 200 mm below the envisaged minimum river level. The velocity path transducers can be aligned using a pipe as described in section 3.2.3. In the station itself, mains power is to be preferred to battery systems.

5 Commission gauge

Once the gauge has been installed and connected to cables and power supplies it is commissioned in accordance with the manufacturers instructions. For the Sarasota/Peek 1408 gauge it is recommended that the bed level parameter is set to the surveyed level. The bed correction factor can then be optimised with reference to a calibration gaugings - if this is not possible, then set the parameter to 0.65. The minimum cover can be set to 25 mm above the top of the transducer to maximise data collection. The direction of flow parameter can be measured *in situ* as described in 3.3.4 and shown in Figure 3.7.

6 Operate gauge

Once the gauge has been commissioned it is recommended that it is rechecked after a couple of days to ensure that all is well - ideally another calibration gauging will confirm the setting of the bed correction factor. After this the timing of the next site visit is dictated by either the power supply (if battery, the visit will have to be before the battery draws down), routine station visits, or the occurrence of the next event. When data are available from a minimum of two events it will be possible to assess the stability of any stage-velocity relationships derived from the gauge data. This will then determine whether or not it is possible to operate the gauge at more levels, and for how long.

Finally, the duration of the gauge deployment at a given site will depend on the number of events that are recorded, and the level of accuracy that is required, as described in section 9.3.2. Once sufficient data have been collected for the original objectives to be satisfied the gauge can be removed for use at another site.

9.5 Recommendations for further work

Chapter 8 has demonstrated that the Project has successfully addressed all of the specific objectives described in section 1.3. With any research Project further issues may be raised that require additional attention. This Project has been no exception and, whilst it may be true that it has answered many questions, there are two issues that the contractor feels should be addressed by further research. These issues are both related to the same issue, namely the inability of the gauge to work at Middleton in Teesdale, and are as follows:

1. **It is recommended** that the Agency undertakes further research to assess the relationship between gauge performance, sediment load and air entrainment. Whilst the limited evidence suggests that the problems at Middleton were caused by sediment rather than air entrainment (and this is further supported by the gauge performance at other sites), it is far from certain that this is the controlling factor. It is suspected that the relationship is not a simple one, but is likely to be a combination of sediment concentration, path height, length and possibly velocity. Until the controlling factor can be quantified in some way, the only way of establishing whether or not a gauge will function at a particular site is to install it and see if it works.

2. **It is further recommended** that the Agency build on the results of this Project and evaluate other gauges alongside the Peek 1408 unit. Alternative manufacturers such as Accusonic claim that the incorporation of features such as variable gain (ie variable amplification of the acoustic signal) significantly increase the operational range of the equipment. However, as the equipment costs up to three times that of the Peek 1408 unit, it would appear to be sensible to establish whether or not 'you get what you pay for'.

Both of these issues could be addressed by carefully structured research at a single site. One obvious possibility would be Middleton itself, but a more suitable alternative might be found where the 1408 unit would work for a wider range of flows. The critical factor in determining the suitability of a potential study site will be the range of sediment concentrations that are encountered.

The second recommendation leads to a final one which, whilst arising from this Project, is not specific to ultrasonic gauges. A considerable amount of time was spent identifying potential field sites for this Project, and as the results presented in this Report have indicated not all of these were ideal for a variety of reasons. The main problem was finding sites where there was high confidence in the Agency derived flows and yet which encompassed a range of site types. This precluded the exclusive use of sites with a British Standard control structure, and even where this type of site was used it has been demonstrated that there is still considerable uncertainty in the derived flows for a variety of reasons. The availability of data from other Agency R&D Projects was found to compliment the work undertaken with the ultrasonic gauge, whilst the data from this Project also assisted with the flat V weirs Project.

The final recommendation to arise from this Project is thus that the Agency should consider identifying a number of key sites which would then form a short-list for future R&D Projects. The list need not be exhaustive, but could usefully include a range of sites in different Agency Regions at which research could be more usefully focused.

APPENDIX A - BIBLIOGRAPHY

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APPENDIX B

Summary site data sheets

Greenholme

Catchment: Irthing

Region: North West

Channel width: 22m

No. of levels used: 6

Site description: Open channel site with informal flat V control structure downstream of study reach, bedrock sill parallel to far bank.
Upstream bed is at same level as weir, which may become non-modular at high flows.
Wide range in levels and flows, and site has been well gauged by Agency.

Work completed: Unfortunately the study period coincided with an exceptionally dry period of weather so only five significant high flow events were recorded, during which the 500KHz transducers were operated at a total of 6 different levels.
The gauge was operated from an external 12v battery supply at this site.

Summary findings: Depth transducer works well in open channel.
Confirmation of gauges ability to work from 12v supply.
Limited failure due to sediment loads.
Performance of gauge within and beyond the observed range of levels assessed.
Stage velocity approach developed.

Low Nibthwaite

Catchment: Crake

Region: North West

Channel width: 9m

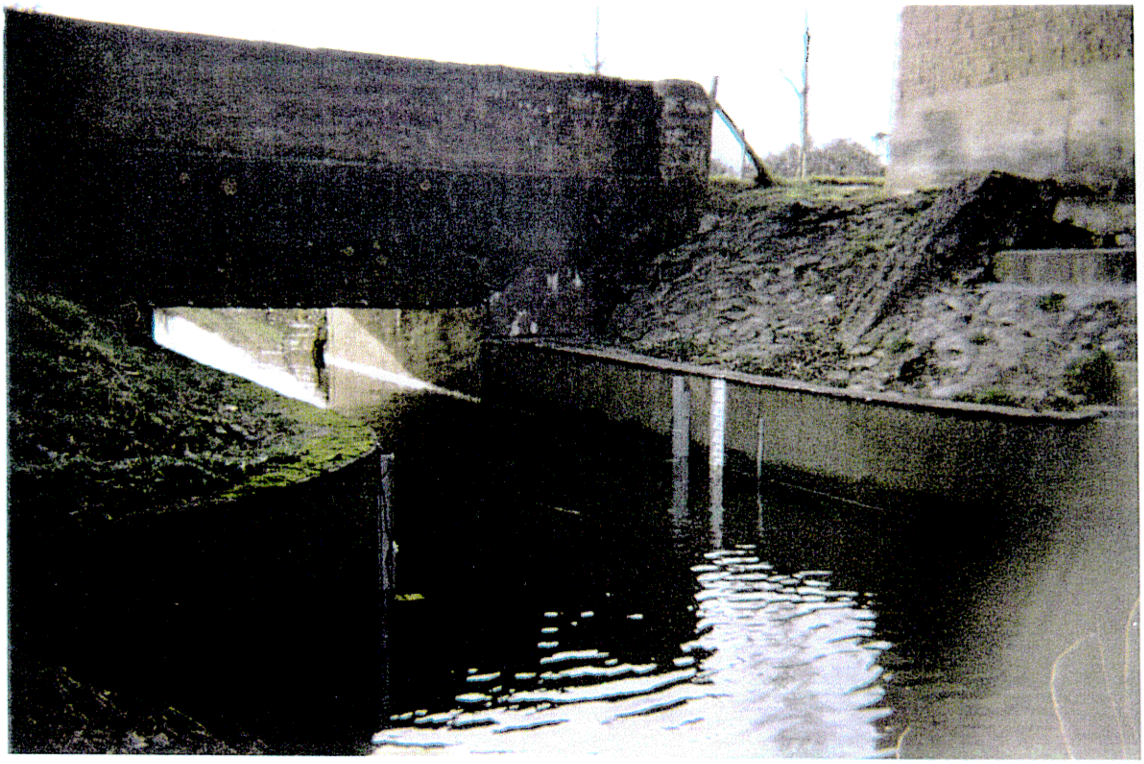
No. of levels used: 8

Site description: Open channel site downstream of Lake Coniston with informal flat V weir bed control.
Channel has vertical sides in study reach- a product of the former mill on the site, and is relatively deep.
Some 200m upstream of gauging station the site flows through a series of minor rapids.

Work completed: Gauge operated from both battery and mains supply.
Different transducers evaluated.
Single and crossed path configurations used, with paths having different angle to the direction of flow.
Very small range in levels limited the range of different levels that could be used for the velocity paths.

Summary findings: Problems with the power supply were identified.
Confirmation that both 500KHz and 1MHz transducers worked in channels of this size.
No significant difference found between the velocities recorded by the crossed paths.

Lea Hall



Catchment: Allcot Brook

Region: Wales

Channel width: 3m

No. of levels used: 8

Site description: Artificial channel with Crump weir immediately upstream of road bridge with vertical concrete wingwalls of limited approach length immediately downstream of a major bend in the brook. The site is subject to significant backing up from the River Dee, which renders the station rating useless under such conditions.

Work completed:
In-channel depth transducer.
Single path and reflector systems used.
Velocity profile studies during backed up conditions.
Limited stage-velocity data.

Summary findings:
Gauge able to work well in small channel with 1MHz transducers for both depth and flow.
Reflector system worked, albeit with drop in signal strength.
Velocity profile studies undertaken in very short time - much quicker than with current meter.

Walcot

Catchment: Tern

Region: Midlands

Channel width: 15m

No. of levels used: 10

Site description: Concrete 1:20 flat V weir with high wingwalls built to British Standard specification with operational crest tapping which incorporates a flushing system.
Site becomes non-modular due to weed and/or high flows.
High flows calibrated by current meter gauging using cableway upstream of site.
Silt build up at site is minor.

Work completed: Transducers operated at 10 different levels over a wide range in flows.
Reflector system trials undertaken at same time as weed growth was at seasonal maximum.
Both modular and non-modular flows monitored by gauge.

Summary findings: Confirmation of gauge's ability to detect minor changes in stage - velocity relationships under varying hydraulic conditions.
Reflector system found to work, albeit with similar loss of signal to that found at Lea Hall.
Flows derived by gauge corresponded well with those obtained by other methods.

Blackford Bridge

Catchment: Roch

Region: North West

Channel width: 25m

No. of levels used: 5

Site description:	Wide open channel site with poor rating over medium-high flows. Study reach immediately upstream of old mill weir, and downstream of gentle but extended bend in river. Catchment is highly urbanised, resulting in flashy spates with high suspended sediment loads.
Work completed:	Transducers operated at five different levels over a number of significant high flow events. Different cable routing systems used to convey cables from the far bank.
Summary findings:	Flows derived by both standard twin-path configuration and by using gauge to derive multi-path rating using stage-velocity approach. No reliable rating to compare these flows against. Short link, 3/8" galvanised cable successful at supporting cable across river during high flows, and through periods of heavy weed growth.

Middleton in Teesdale

Catchment: Tees

Region: North East

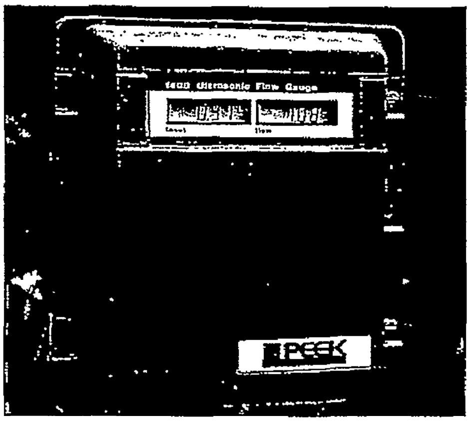
Channel width: 23m

No. of levels used: 3

Site description:	Wide, open channel site with non-standard flat V low flow control, downstream of a series of small rapids. Study reach spanned cableway which has been used to provide good rating for the site. Steep upland catchment results in very flashy response, with levels rising by over 3 metres in some events.
Work completed:	Both 250 and 500 KHz transducers evaluated. Racks mounted in relatively deep and fast moving water. Gauge evaluated over many high low events, with transducers deployed at six different levels.
Summary findings:	Gauge struggled to work due to site conditions. Data were only collected from three levels, and for a limited range in river levels. When working, gauge flows agreed well with Agency rating. No improvement was found by using 250 KHz transducers. Mounting racks withstood complete immersion and high flows.

APPENDIX C

Specification for the Peek 1408 gauge used for the project



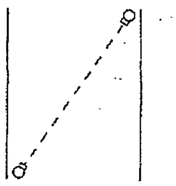
- Single/dual path configurations
- No need for flume or weir
- Unaffected by backwater/river traffic
- Non-intrusive
- Suitable for channels from 1m to rivers of 100m

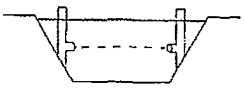
Introduction
Peek Measurement's Ultrasonic 1408 Open Channel Flowmeter is a velocity-area meter operating on the "time of flight" principle. Applications include:

- rivers
- canals
- final effluent from sewage treatment
- hydro electric power
- water supply
- out of range rating of weir

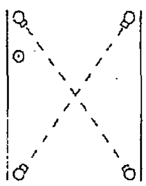
Features of the Ultrasonic 1408 Open Channel Flowmeter:

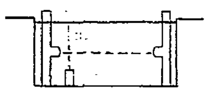
- velocity-area flow measurement
- non-obstructive
- no head loss
- tolerant of skew flow conditions
- reverse flow measurement capability
- rugged waterproof enclosure
- complies with BS3680 part 3E / ISO6416
- suitable for relatively clean, non-aerated water



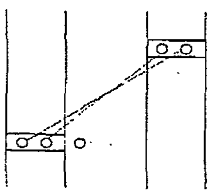


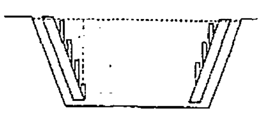
Basic Velocity Meter





Flowmeter with Cross Paths and Depth Transducer





Flowmeter with in-line paths on Sliding Rack and Depth Transducer.

General Specification:

Overall Accuracy:		Typically 2 to 5% The overall accuracy is affected by several factors, ISO 6416 refers.
Transducers:	Frequency:	200Hz to 1MHz dependent upon path length and minimum water depth
	Tolerance:	Normally ±2% but where required can be matched to ±1%
	Divergence:	Beam angle typically 5°
	Immersion:	IP68 to 50m depth
Flow Meter:	Displays:	2 off 6 digit LCDs for flow, depth and water velocities
	Path Length:	1.5 to 150m
	Environment:	-10 to +40°C
	Enclosure:	Wall or pole mounted, with IP65 protection
	Dimensions:	Typically 395mm W x 420mm H x 285mm D
	Weight:	Typically 24Kg

Power Supply:	110v/240v AC, 12v DC Internal battery back up option for up to 6 hours operation in the event of mains failure. Solar/wind power options available. Consumption typically 12W depending on configuration.
Output Signals:	Serial RS232 Parallel - 16 bit or 4 x BCD Analogue - 0 to 5v or 4-20mA Volt free contacts for data or alarm
Output Device Options:	Telemetry outstations, Data Loggers, Chart Recorders, Totalisers, Printers

Options:

Alternative Depth Input:	From shaft encorder, bubbler, pressure sensor via BCD format.
Setup and Diagnostics:	Path setup data:- length, angle height can be setup via Gauge Configuration Programme (GCP) via a portable pc. Also provides means of detailed interrogation for diagnostics.

Ordering Information:

Product Description	
1408	Ultrasonic Transit Time Open Channel Flowmeter: Includes Enclosure, Processor, Transducer i/f LCD Display, Mains PSU, with 6 hour battery back up
Instrument Mounting	
W	Wall mounting kit
P	Pole mounting kit
Transducer Options	**Transducers required in pairs per velocity path (1 or 2 paths) and 1 for depth path. Each transducer is supplied with 3m cable with waterproof connector and instrument adapter.**
T2	200KHz Transducer for path lengths over 80m
T5	500KHz Transducer for path lengths 10 to 80m
T10	1000KHz Transducer for path lengths less than 10m
Transducer Cable Extensions (can be plugged in series)	
EX20	20m extension cable
EX50	50m extension cable
Input/Output Options (up to 2 allowed)	
A	Dual Analogue Output
B	BCD Dual Parallel Output
D	Depth Input (BCD Parallel)
Setup	
GCP	Gauge Communication programme for pc and cable
Options	Please ask about: Advice on configuration/suitability Transducer mounting systems Peripheral equipment - loggers, printers, telemetry Alarm conditioning, via volt free contacts Installation and onsite service Auxillary Depth Gauges Long cable extensions Serial Output Intrinsically Safe versions

APPENDIX D

Results specific to the Peek/Sarasota 1408 gauge

Power supply.

- The gauge is able to function equally well from either a 12-volt DC or 240-volt AC power supply.
- When operating from a 12-volt supply a 115 amp hour cell is just sufficient to power the gauge for a week.
- If a mains supply is used this should be wired directly into the gauge, and not via a 12-volt trickle charge as this may cause electrical interference.
- If the power supply should fail, and the internal backup is fully utilised, some of the gauge constants and parameters will become currupted. Should the power supply be reconnected, the gauge will need to be reprogrammed before it is used to monitor flows. This finding precludes the operation of the gauge by means of a float switch which would otherwise enable the effective working life of an external 12-volt DC supply to be extended.

Transducers, cables etc.

- The 500KHz transducers worked well at all of the field sites; the 1MHz transducers worked in the small channels in which they were deployed (up to path lengths of approximately 15 metres), but it was not possible to obtain data from the 250KHz units.
- If conditions allow the depth transducer should be deployed in the channel itself, preferably as deep as possible whilst still being above the level of the river bed.
- In all cases it was possible to align the velocity paths using a length of pipe of suitable diameter; an oscilloscope was not required at any of the sites.
- There appears to be a reasonable degree of flexibility in the alignment of the transducer paths - possibly as much as 5^0.
- The waterproof Fischer cable extension sockets proved to be both reliable and robust, and did not fail at any time during the project. The only problems that were encountered with the cabling was with cable joints that had been soldered.

Gauge programming.

- The mean bed level parameter should be set as surveyed, relative to stage datum.
- Initially the bed correction factor should be set to 0.65 instead of 0.8; this value can be revised following current meter calibration if required.
- The minimum cover parameter over the velocity paths can be set as low as 25mm above the top of the transducer.
- The minimum cover parameter for the depth transducer should be set as high as possible to blank out any spurious electrical interference. Adjusting the parameter on site by trial and error will allow this to be carried out: too high a value and the depth reading will quickly stabilise to a depth in excess of the true water cover over the transducer. The aim should be to 'blank off' any signal equating to a depth just less than the minimum anticipated stage at the site.

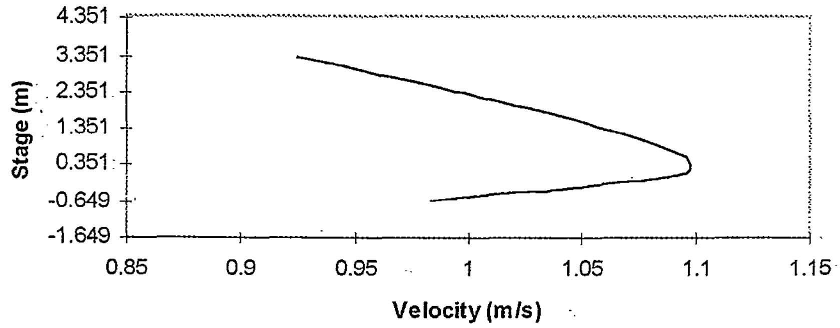
Other observations.

- When the velocity paths are not working the gauge assumes a specific value for the velocity of sound, which is then used to compute the measured depth. Any differences due to differing water temperature will cause an error in the measured depth; the magnitude of this difference will depend on the difference in temperature between the water body being measured and the assumed velocity of sound value. Hence, the degree of error is likely to be seasonal. Whilst this will not affect the measured flow values, as no flows can be measured if the velocity paths are not working, it will affect the true level at which the velocity paths start to be 'fired' once the gauge thinks they are immersed once more. Clearly, it will also affect the recorded depths if there is no other source of depth measurement at the site.

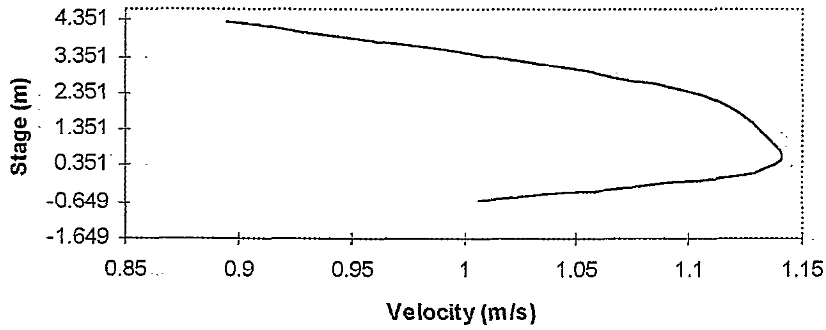
APPENDIX E

Velocity profiles derived from data measured from Agency multi-path gauges.

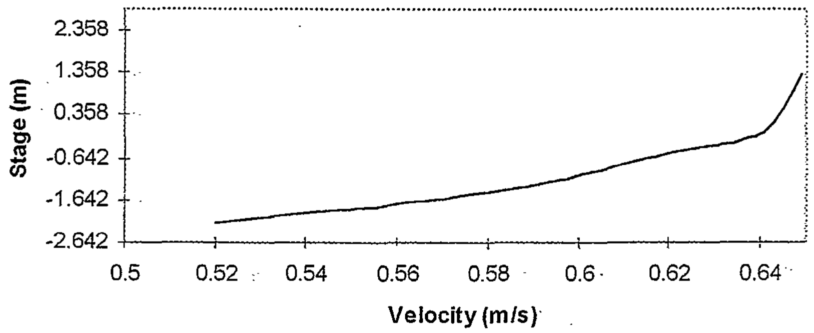
In all cases the y-axis boundaries reflect the river bed and water surface at the time the data were recorded.



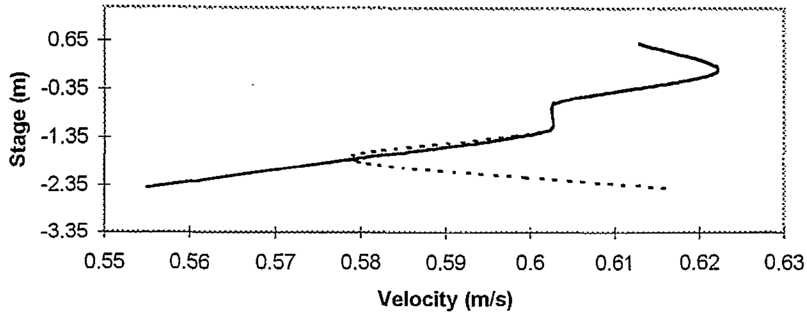
Montford, 4/12/1996



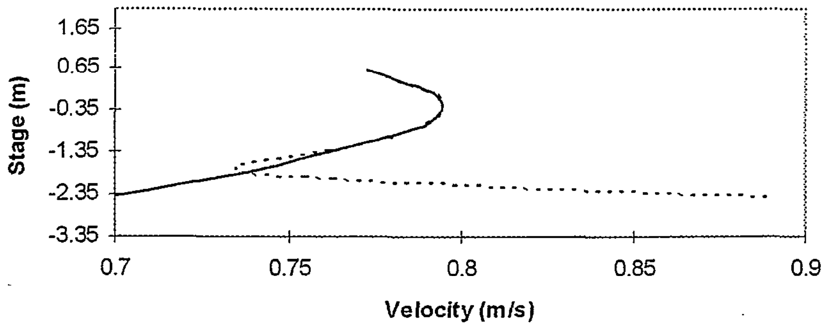
Montford, 19/2/1997



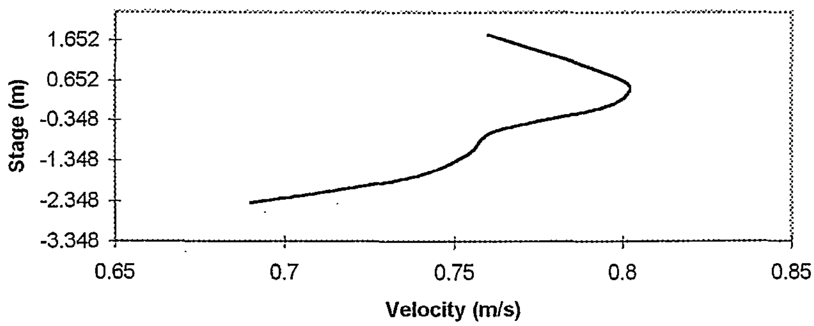
Deerhurst, 5/12/1996



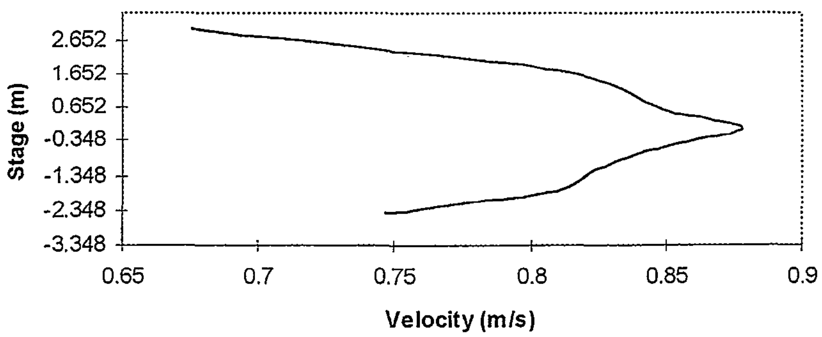
Saxons Lode, 2/12/1996



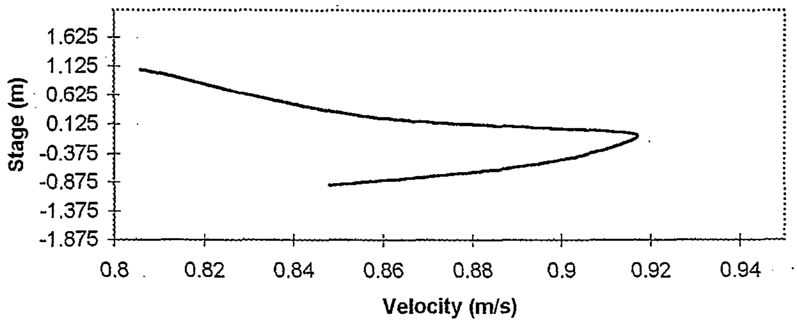
Saxons Lode, 5/12/1996



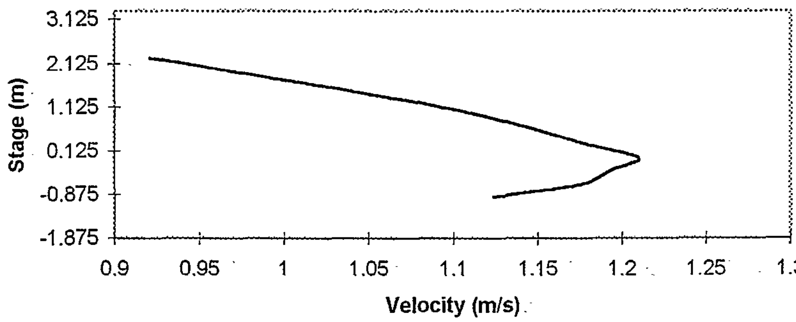
Saxons Lode, 19/2/1997



Saxons Lode, 26/2/1997



Buildwas, 2/12/96



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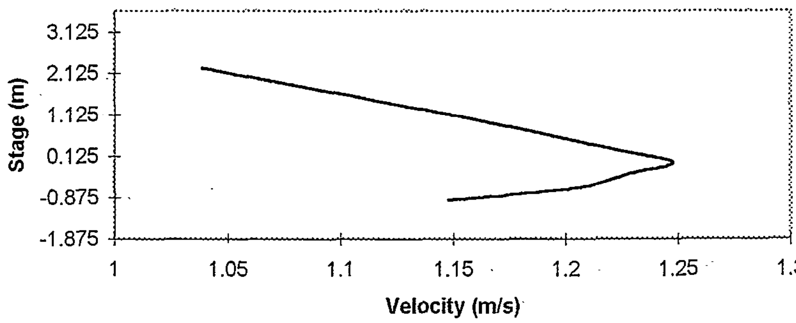
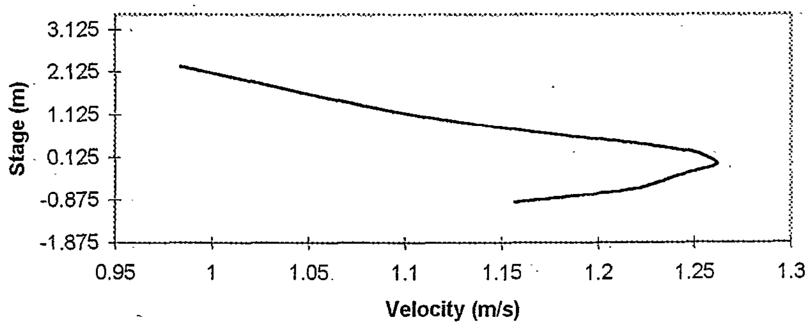


Buildwas, 26/2/97



Buildwas, 19/2/1997

APPENDIX F

Tables of varying performance of twin path configuration compared to flows derived from multi-path gauges

In all cases the x-axis represents the lower of the two velocity paths. All levels are expressed as a fraction of the total water column. Cell values indicate the degree to which the twin-path model was able to replicate the multi-path data. Shaded cells indicate configurations that produce a flow to within 2% of that derived using the full dataset

	0.24	0.31	0.39	0.46	0.54
0.24					
0.31	1.04				
0.39	1.05	1.05			
0.46	1.06	1.06	1.05		
0.54	1.01	1.01	1.01	1	
0.74	0.98	0.99	0.99	0.98	0.94

Buildwas 2/12/96

	0.18	0.24	0.3	0.36	0.41	0.57
0.18						
0.24	1.09					
0.3	1.1	1.1				
0.36	1.11	1.11	1.1			
0.41	1.09	1.09	1.08	1.08		
0.57	1.04	1.04	1.04	1.04	1.02	
0.79	0.95	0.97	0.97	0.98	0.96	0.91

Buildwas 5/12/96

	0.17	0.23	0.28	0.33	0.39	0.53
0.17						
0.23	1.09					
0.28	1.1	1.1				
0.33	1.1	1.11	1.11			
0.39	1.1	1.1	1.1	1.09		
0.53	1.01	1.02	1.02	1.02	1.01	
0.75	0.96	0.98	0.98	0.99	0.98	0.89

Buildwas 19/2/87

	0.17	0.23	0.28	0.33	0.39	0.53
0.17						
0.23	1.06					
0.28	1.07	1.07				
0.33	1.08	1.09	1.08			
0.39	1.07	1.07	1.07	1.06		
0.53	1.02	1.03	1.03	1.02	1.01	
0.75	0.96	0.98	0.98	0.98	0.97	0.92

Buildwas 26/2/97

	0.17	0.24	0.3	0.37	0.47	0.58	0.67
0.17							
0.24	1.02						
0.30	1.05	1.05					
0.37	1.04	1.05	1.05				
0.47	1.02	1.03	1.03	1.02			
0.58	0.99	1	1.01	1	0.97		
0.67	0.97	0.98	0.99	0.98	0.96	0.92	
0.82	0.93	0.95	0.97	0.96	0.94	0.9	0.87

Montford 4/12/96

	0.16	0.23	0.29	0.35	0.45	0.56	0.64	0.79
0.16								
0.23	0.97							
0.29	1.02	1.01						
0.35	1.02	1.02	1.02					
0.45	1	1.01	1.01	1				
0.56	0.99	1	1.01	1	0.98			
0.64	0.97	0.98	0.99	0.99	0.97	0.94		
0.79	0.93	0.95	0.96	0.96	0.94	0.92	0.9	
0.94	0.87	0.9	0.93	0.93	0.92	0.9	0.88	0.81

Montford 19/2/97

	0.09	0.18	0.27	0.36	0.45	0.54
0.09						
0.18	0.92					
0.27	0.95	0.95				
0.36	0.96	0.96	0.95			
0.45	0.99	0.99	0.98	0.97		
0.54	0.98	0.98	0.98	0.97	0.97	
0.72	0.97	0.98	0.98	0.97	0.98	0.96

Deerhurst 5/12/96

	0.17	0.28	0.39	0.5	0.61
0.20					
0.33	0.97				
0.46	0.99	0.98			
0.58	0.99	0.98	0.97		
0.71	1	0.99	0.98	0.96	
0.84	0.98	0.98	0.97	0.95	0.95

Saxons Lode 2/12/96

	0.17	0.28	0.39	0.5	0.61
0.17					
0.28	0.96				
0.39	0.99	0.98			
0.50	1.01	1	0.99		
0.61	1	1	0.99	0.98	
0.72	0.98	0.98	0.98	0.97	0.95

Saxons Lode 512/96

	0.17	0.27	0.38	0.48	0.59	0.69
0.17						
0.27	0.97					
0.38	0.97	0.97				
0.48	0.98	0.98	0.97			
0.59	1.01	1	0.99	0.98		
0.69	1	1	0.99	0.98	0.98	
0.90	0.96	0.97	0.96	0.95	0.96	0.95

Saxons Lode 19/2/97

	0.14	0.23	0.32	0.4	0.49	0.58	0.76
0.14							
0.23	0.98						
0.32	0.99	0.99					
0.40	1	1.01	0.99				
0.49	1.03	1.03	1.02	1.01			
0.58	1	1.01	0.99	0.99	0.99		
0.76	0.96	1.01	0.97	0.97	0.98	0.94	
0.93	0.87	0.91	0.91	0.92	0.94	0.91	0.86

Saxons Lode 26/2/97

APPENDIX G

Peek flow compensation software details

5.1 Introduction

The purpose of this software modification is to allow the user the option of intelligently adjusting the flow calculated by the 1408. It is aimed at achieving some compensation for the limited number of velocity paths that can be fitted to this type of flowmeter.

For most flow metering applications the water velocity profile of the river or channel indicates varying velocities throughout both its width and depth. While an ultrasonic path will accurately measure the varying velocity across the channel at its particular height, the accurate sampling of the vertical profile is dependant upon the number of paths positioned throughout the depth range. The ideal solution therefore is to have ultrasonic paths in many different vertical positions to remove the flow measurement error known in ISO 6416 as "Limited Path Uncertainty".

However for some applications where known velocity profiles are available sufficient accuracy may be achieved by sampling the velocity in 1 or 2 vertical positions, and then adjusting these results using factors dependent upon the current water level.

This flow compensation software allows for such an adjustment to be made, in a manner that is completely configurable by the user. Factors are entered for various water levels that the user decides, to give as complex an adjustment as may be required. From the data points entered the 1408 can then extrapolate the required factor for any other water level throughout the range.

It should be noted that this compensation is implemented within the 1408's flow computation. Therefore the velocity displays will always reflect the measured velocity.

5.2 Description

An additional command has been added to the GCP main menu with the title "F5. Velocity Factor Tables". Selecting F5 gives the user access to 4 programmable look up tables. These allow multipliers to be entered throughout the level range for the 2 paths when they are both operational, and also if either path is faulty.

Each look up table has the following format :

SARASOTA ACOUSTIC GAUGE - VELOCITY DATA

Velocity factors for path L (H not working)

Mean Bed Level - 0 Path Height - 0.4

Level	Multiplier
0	1
1	1
1.5	1.2
2.0	1.5
2.5	1.8
3.0	2
4	1
4	1
4	1
4	1

Bottom section multiplier - 0.8

F1:Change F9:Exit

As can be seen for each of the four combinations up to 10 multipliers can be programmed at water levels that the user determines. A minimum of 2 multipliers must be entered into each table to represent 0 (or the AOD bed position) and maximum level. All the remaining level positions should be set to a figure greater than the maximum level and the multipliers set to 1.

If no flow compensation is required when the software is initially installed the multipliers for the 0 and maximum level should be set to 1.

When entering the water levels these need to be in ascending order. However when entering the corresponding multiplier this may follow any pattern throughout the level range set.

To enable total configuration each table also incorporates a bottom section multiplier. As described in section 1.2 of the handbook this is fixed at 0.8 for the standard software, but for the flow compensation software this can be set by the user. When 2 paths are fitted to the 1408, this factor should be ignored for the "Path H (L working)" table.

5.3 Programming Examples

For assisting the user there follows 2 examples of how the tables can be programmed.

Example 1

Site Information

A 1408 is installed in a channel with a depth range of 1 to 4 metres. One path is fitted at a height of 0.5 metres. Velocity measurements taken at the site give the following comparison for different water levels between the channels average velocity and the velocity at 0.5 metres (the height of the 1408 path) :

DEPTH	VELOCITY AT 0.5 METRES	AVERAGE VELOCITY	VELOCITY RATIO
1.0	0.4	0.4	1.0
2.0	0.5	0.7	1.4
2.8	0.6	1.0	1.667
3.5	0.7	1.5	2.143
4.0	0.6	1.2	2.0

From the information available the velocity in the bottom 0.25 metres compared to the velocity at 0.5 metres is 0.75.

GCP Entry

As the 1408 has only 1 path the "F1. Path L (H not working)" table is the only one to be set up. Using the above information the table is programmed as follows :

Level	Multiplier
0	1
1	1
2	1.4
2.8	1.667
3.5	2.143
4	2
5	1
5	1
5	1
5	1

The bottom section multiplier is set to 0.75.

Example 2

Site Information

A 1408 is installed in a channel with a depth range of 1 to 3 metres. Two paths are fitted at heights of 0.4 and 0.8 metres.

When fitted with 2 paths the 1408 splits the channel into 3 areas (section 1.2 of the Handbook refers), which will be at 0.2 and 0.6 metres. As both paths are always in the water, the area to which path L velocity is applied will always be the same. Therefore it is unlikely that any compensation needs to be programmed for the "F2. Path L (H working)" table, apart from perhaps the bottom section multiplier.

Velocity measurements taken at the site give the following comparison for different water levels between the velocity at 0.6 metres (the height of the 1408 H path) and the average velocity in the top section of the channel (i.e above 0.6 metres) :

DEPTH	VELOCITY AT 0.8 METRES	AVERAGE VELOCITY*	VELOCITY RATIO
1.0	0.5	0.5	1.0
1.5	0.7	0.8	1.143
2.0	0.8	0.95	1.188
2.5	0.9	1.1	1.222
3.0	1.0	1.3	1.3

* For the top section of the channel.

From the information available the velocity in the bottom 0.2 metres compared to the velocity at 0.4 metres is 0.7.

GCP Entry

The only data programmed into the "F1. Path L (H not working)" table is the bottom section multiplier. This is entered as 0.7.

From the information in the table above the "F4. Path H (L working)" table is programmed as follows :

Level	Multiplier
0	1
1	1
1.5	1.143
2.0	1.188
2.5	1.222
3.0	1.3
4	1
4	1
4	1
4	1

As mentioned above the bottom section multiplier for this table is ignored.

If compensation is required if either path becomes faulty, then data needs to be gathered that relates the velocity at the height of the working path to the average velocity. Example 1 refers. The data gathered for path L is then entered in the "F1. Path L (H not working) table. The data gathered for path H is then entered in the "F3. Path H (L not working) table.