Non Invasive Techniques for River Flow Measurement

Science Report SC030230/SR
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Professor Mike Depledge  Head of Science
FOREWORD

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EXECUTIVE SUMMARY

The Environment Agency of England and Wales operates a network of over 1500 flow gauging stations. The data obtained from these stations are used for such diverse applications as flood forecasting, water resources monitoring, abstraction licensing, river regulation and habitat conservation, and are crucial to the operational activities of the Environment Agency. Whilst a number of different gauging methods are employed by the Environment Agency, control structures, such as Crump and flat-vee weirs, are the most widely used. This report reviews the potential for greater use of alternative, non-invasive methods for continuous flow measurement, considering practical issues such as cost and maintenance, as well as the accuracy, reliability and likely ecological impacts.

Gauging structures can often provide very accurate flow data, but are associated with a number of adverse environmental impacts. In particular they are known to compromise the free movement of many fish species. This applies to migratory fish, as well as coarse fish, which need to move within river systems for feeding, shelter and spawning. By altering hydraulic conditions within the river, weirs may also affect the diversity of habitat and reduce the ‘ecological status’ of the reach under the terms of the EU Water Framework Directive. Whilst many hundreds of weirs and other structures affect watercourses throughout England and Wales, the Environment Agency’s strategy is to lead by example by reducing obstructions at gauging weirs where possible. Easement methods, such as fish passes, rock chutes and baffle cascades are, for example, now widely employed by the Environment Agency. However, these approaches do not necessarily provide an acceptable hydrometric solution as they often lead to a reduction in the accuracy of discharge measurement.

Alternative methods presently used by the Environment Agency include open-channel sections rated by current metering, transit time acoustics, and electromagnetic flow meters. However, due to advances in technology a number of other non-invasive flow measurement methods have become available in recent years. Whilst these are not used, at present, at any primary gauging stations in England and Wales, the Environment Agency might wish to adopt such methods in the future. Not all of these methods, however, are well suited to continuous flow measurement. For example, some hydroacoustic devices perform extremely well as alternatives to current meter gauging, but could not readily be employed at ‘un-manned’ gauging stations. There are also a number of additional methods that are presently being developed to measure river flows on an experimental basis, but may prove viable for operational use in the near future.

Hydrometric agencies outside the UK were consulted on the types of gauging methods that are currently employed for continuous river flow measurement. A literature search was also undertaken. The following list summarises the available methods and their use for continuous flow measurement in natural channels:

Hydroacoustic techniques
Acoustic transit time (well established).
Acoustic Doppler meters (newly established).

Electromagnetic (EM) induction
Full channel width EM coil (well established).
Slab type EM meter (new method).
EM Radar methods
Microwave Doppler radar (experimental).

Imaging techniques
PIV - Particle imaging velocimetry (experimental).
RAFT - Rising air float technique (experimental).

Other methods:
Seismic induction (experimental).
Slope-area methods (occasional use).

There do not appear to be any major types of non-invasive technology for continuous flow measurement in natural rivers that are unknown in the UK but well developed or widely used elsewhere. There is, however, a wide variation in operational experience with non-invasive methods between different countries. For example, to date most experience with Doppler acoustics has been gained in the USA, whereas experience with transit time acoustic methods is more widely spread.

The principles of operation, practical implications and resource requirements are considered in this report for each of these methods, along with issues of accuracy and reliability. A comparative assessment of the different methods was then undertaken. This review has highlighted that site suitability and adequate calibration are key to successful implementation of non-invasive methods. When methods are applied at suitable sites (or if instruments are configured appropriately given the site conditions) the optimum accuracy can be within about ±5% to ±10% of gauged flows for most techniques. However, accuracy can deteriorate when operating conditions become less than ideal.

Costs of implementing non-invasive methods are generally less than implementing a gauging weir at the same site, but not always notably so. Whilst instrumentation costs associated with non-invasive methods are relatively small, the overall cost can be high, especially for those methods that require extensive civil engineering, particularly channel diversion and work across the river bed. This has been one of the main attractions of side-looking Doppler technology, which does not require laying cables or other work on the channel bed. However calibration requirements can add significantly to the expenditure required. It is also expected that newer methods will incur hidden costs when first applied as hydrometric personnel become familiar with the technology and set up new data processing and management procedures.

Finally, a number of targeted recommendations are given regarding the possible future implementation of non-invasive flow measurement technologies within the gauging network in England and Wales. This includes greater use of hybrid solutions, where one or more methods are combined at a single site. It is also suggested that a comparative assessment of the performance of different gauging methods be carried out at national level. This would give a better understanding of which methods tend to provide good quality data in practice, allowing cost and benefits to be compared more realistically.
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1 INTRODUCTION

1.1 Background

The Environment Agency has a statutory obligation to monitor river flows in England and Wales, and at present maintains a network of over 1300 permanent flow gauging stations. A number of different flow measurement techniques are utilised, including stage-discharge ratings, control structures (weirs and flumes) and, increasingly, ‘non-invasive technology’ methods such as acoustic (ultrasonic) and electromagnetic full channel flow meters.

Figure 1.1 illustrates where these different measurement techniques have been used by the Agency, whilst Figure 1.2 shows the deployment of individual gauging methods within England and Wales.

Figure 1.1: Flow gauging methods used by the Environment Agency of England and Wales

*Please note that the details shown have been derived from a number of sources and are not intended as a definitive representation of all gauging stations maintained by the Environment Agency.*
The weirs, flumes and rated-sections shown in Figure 1.2 are based on the 1990 register of gauges on the National River Flow Archive. This data set does not include all flow gauges in the Environment Agency, but remains a broadly representative sample of the current situation. In total about 670 weirs (including 80 hybrid sites where an open channel rating is used for high flow measurement) and 70 flumes are used within the network. About 190 sites are maintained as open channel rated sections. The ultrasonic and electromagnetic gauges shown in Figure 1.2 are based on Environment Agency
records from 2004. Including sites under commission, 162 ultrasonic gauges and 37 EM
gauges are used at present.

A distinguishing feature of this network is the large number of control structures in use,
particularly in lowland areas. In fact, purpose-built structures have been implemented at
over 50% of the gauging stations in England and Wales, as indicated in Table 1.1,
although open-channel rating tends to be the favoured method for gauging in upland
streams and is used at about 15% of sites overall. Non-invasive technologies are used
for continuous flow measurement at about 16% of sites, whilst a small number of
stations (“miscellaneous”) use mixed or non-standard approaches to determine flow
rates.

Table 1.1: Summary of measurement methods presently used at gauging stations in
England and Wales

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<th>Gauging method</th>
<th>Approximate percentage of stations at which method is used</th>
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Control structures have come to dominate the hydrometric network in this manner
because they offer a number of advantages over other available gauging methods.
Foremost, they provide a relatively accurate and reliable means of measuring flow on a
continuous basis with minimal calibration and little day-to-day maintenance. The other
methods, in comparison, tend to require more staff involvement if data of the same
quality are to be produced. Maintaining an open channel rating, for example, is
generally very labour intensive and calibration gauging during periods of high flow
poses a number of health and safety risks. Similarly, technology methods have often
proved difficult to calibrate, generally offer a lower percentage data retrieval and can
involve a large amount of post-processing of data.

Weirs are also well suited to the modest flows and limited depths generally observed in
rivers in the UK. However, specialised structures can also be used to target particular
flow conditions, such as the V-notch thin plate weir for gauging low flows and the Crump weir for gauging medium-high flows. The stage-discharge ratings for most types of weir can be calculated theoretically and much of the understanding of these relationships is based on research undertaken in the UK. Thus good practice for weirs became incorporated into a British Standard at an early stage (Thomas (2002) gives a useful summary of British Standards associated with use of weirs and other flow measurement methods). This and the provision of grant-aid by the Water Resources Board encouraged deployment of gauging weirs during the 1960s and 1970s. Weirs also offer opportunities for water level management and channel stabilisation.

In recent years, a number of practical, resource and environmental factors have, however, forced the UK water industry to reappraise the use of structures for gauging flows in natural streams. The following considerations have been of particular importance:

- In general, weirs provide less accurate discharge measurement during high flow conditions (where the structure may become ‘drowned-out’). This has led, in the past, to construction of ‘over-engineered’ structures, although nowadays it would be more typical either to operate weirs as hybrid solution where a cableway is used to provide a high flow rating, or to extend the theoretical range using crest tapings and up/down stream level sensors.

- Gauging structures can be very costly to install. In some cases the total installation cost can be over a half a million pounds.

- There has been particular concern that many weirs do not allow for sufficient passage of both salmonid and coarse fish. Allied to recent legislation related to the Water Framework Directive (EC Directive 2000/60/EC), this provides a powerful driver against the use of in-river structures, including those used for flow measurement.

- There are also many other issues concerning in-stream structures, including health and safety, amenity value and navigation requirements. It is essential that weirs are designed and operated in line with the Environment Agency’s Good Practice Guide for river weirs (Rickard et al., 2003).

Figure 1.3: A highly engineered structure on the River Tees
These pressures against the use of structures have coincided with the advent of new technologies able to provide accurate measurements of flow without the engineering and environmental implications of a weir. These technologies, which include electromagnetic, acoustic and radar methods, are often grouped under the term ‘non-invasive flow measurement techniques’, as they can be used on a permanent basis without adversely disturbing the physical, environmental and ecological continuity of the watercourse. This does not always mean that there is no in-stream disturbance, but that the scale of any disturbance is minimal in terms of its impact on ecology, environment and the quality of measurement.

A number of additional factors, such as ease of installation and ability to measure flows under variable backwater conditions, are promoting the use of such techniques in both open channels and closed conduits (Godley, 2000; Godley 2002). However, some non-invasive gauging methods are relatively new, and factors that might possibly limit or promote their use in rivers in England and Wales are not generally known.

In order to address the need for better understanding of these methods the Environment Agency commissioned Science Project W6-097 ‘Non-invasive Flow Measurement Techniques Review’ (under the direction of the Joint National Hydrometry and Fish Passage Working Group) in July 2003. The overall aim of the project was:

‘to review non-invasive flow measurement methods and to report on the opportunities to use them as permanent alternatives to hydrometric structures in watercourses in England and Wales’.

The project has been carried out by JBA Consulting – Engineers & Scientists, with assistance from Professor C.S. Melching of the College of Engineering, Marquette University, Wisconsin, USA. The Environment Agency’s project board comprised Alison Hanson (North West), Julian Parkin (North West), Richard Iredale (NHPT), Greg Armstrong (NFTT) and Nick Everard (Thames). This report forms the main output of the project.

1.2 Project Specification

1.2.1 Specific objectives

The specific objectives of the project were defined as follows:

- To clarify the pressures against in-stream structures.
- To identify the range of non-invasive techniques available worldwide, including established techniques and those that are being used at an experimental level, but are not sufficiently developed or tested to be classed as ‘operational products’.
- To consider the theoretical, practical and resource implications of the main non-invasive techniques.
- To outline possible future developments of research-level methods.
- To generate a list of contacts of those active in this field, and a bibliography.
1.2.2 Scope

At inception meeting stage, it was clarified that the scope of the review should include only those non-invasive methods that may be employed to measure river discharges on a continual basis. That is, those methods that are capable of producing a fifteen-minute flow record and that may be employed on a permanent basis at a gauging station. The following categories broadly describe the types of method to be considered.

- Acoustic technologies
- Electromagnetic devices
- Radar methods
- Particle imaging techniques.

The use of non-invasive technologies for making spot measurements of discharge is, therefore, not covered (in the UK mobile Acoustic Doppler Current Profiler (ADCP) units are now routinely used for spot measurement of discharge). Such methods have also been widely described elsewhere (e.g. Child et al., 1997; Ramsbottom et al., 1997). However, it is recognised that some of the basic technologies considered in the review have been, or could be, applied for this purpose.

Open channel stage-discharge ratings are, of course, the most widely used ‘non-invasive’ method of flow measurement. Once established, a rating is a relatively straightforward means of determining flow on a continuous basis, with minimal on-site instrumentation (only a level-sensor is required). However, rated sections are conventionally calibrated using spot gauging methods and are, as such, not included in the brief for this study. It is worth noting, however, that some non-invasive methods that are typically used for continuous gauging offer a means of extending rating curves over a wider range of flow conditions. For example, a recent Environment Agency Science report (Bennett, 1999) outlined a methodology for using velocity data derived from acoustic travel time measurement in the development of ratings.

It is possible to argue that dilution gauging, which involves introducing a chemical tracer into the stream, is physically non-invasive. It is unlikely, however, that dilution gauging would prove a viable method for continuous gauging and it is therefore not considered in the review.

The scope of the project does not include a discussion of individual products or manufacturers. Specific products are named for information only and any mention in this report should not be interpreted as an endorsement by the authors or the Environment Agency.

1.2.3 Consultation on the use of non-invasive flow measurement in the UK and elsewhere

A questionnaire-based consultation process was carried out as part of this review project to establish which non-invasive methods are used by hydrometric agencies in the UK and elsewhere, and to seek the views of users on the benefits or difficulties of using such methods.

Questionnaires were sent to 37 individuals in 20 countries, spanning Europe, North America, Asia and Australasia. In total 15 responses were received, in addition to a
The questionnaire review was not designed as a formal poll and so the responses have
not been analysed in any formal manner. The findings have, however, been appraised
qualitatively and incorporated into the report as appropriate.

1.3 Allied Research

This project is part of an ongoing Environment Agency strategy to minimise
environmental impacts of flow gauging whilst ensuring that the hydrometric network in
England and Wales continues to provide appropriately accurate flow data when and
where it is needed. This strategy includes restricting the number of control structures
used for hydrometric purposes in the UK (by using alternative flow measurement
techniques), as well as incorporating facilities for fish passage where it is impossible to
avoid use of weirs. The latter case includes design of compound weirs, use of fish
passes, retro-fitting of baffles, cascades and ramps to existing weirs in order to ease fish
passage, use of ‘nature-like’ bypass channels around the control, and combinations of
the above.

The review of non-invasive flow measurement is closely allied to a number of recent
and ongoing Environment Agency Science studies, including;

- **W6-029** - Review of the issues associated with installation of fish passage at
  flow gauging stations (Turnpenny et al., 2002a; Turnpenny et al., 2002b). This
  work evaluated the general effects of fish passes on the accuracy and reliability
  of hydrometric data.

- **W6-084** - Review and testing of a number of methods by which gauging
  structures can be adapted to aid the migration of fish without degrading the
  accuracy of measurement (White & Woods-Ballard, 2003). This ongoing work
  considers how existing British Standards for control structures might be
  amended to account for such changes.

- **W6-077** - Review and testing of low cost technical solutions for improving fish
  passage at Crump weirs. This ongoing research is investigating the use of
  baffles on the weir face to improve fish passage.

- **W6-085** - Review and testing of the effectiveness of baffle systems (the ‘Hurn
  Solution’) for improving fish passage at flat V gauging stations. This ongoing
  project includes testing of a pilot baffle system.

- **W6-026** - Review of fish swimming speeds and endurance – Phase 1 (Clough &
  Turnpenny, 2001; Turnpenny et al., 2001). The work showed that endurance,
  burst speeds of fish and approach conditions are relevant to ability of fish
  species to pass upstream at weirs and other structures. A second phase looking at
  additional species is currently ongoing.

- The Working Group have also developed a set of Environment Agency
guidelines for the design of flat-vee and crump weirs that will minimise the
impact on fish passage whilst maintaining the integrity and accuracy of flow
measurement structures. These are being used as an interim arrangement until the Science projects are completed.

Other recent research that is relevant to the issues raised in the report includes:


1.4 Report Format

The structure of this report was determined in consultation with the Environment Agency project board.

A discussion of the pressures against use of hydrometric structures, including factors that may drive removal of existing sites, is given in Chapter 2. The relevant legislation, such as the EU Water Framework Directive, is also discussed.

Chapter 3 introduces the range of non-invasive alternatives used, or being proposed, in the UK and elsewhere (the detailed results of the questionnaire on use of non-invasive technologies are reported in Annex 1).

The main technical review is presented in Chapters 4 to 10. Each of the main techniques is covered in an individual chapter, which sets out basic principles, operational and resource requirements, advantages and limitations. These chapters serve as stand-alone reviews (although this inevitably leads to some duplication, it does allow the reader to focus on one particular method, if needed).

Chapter 11 draws upon the detailed method reviews, and comments received from consultation, to set out a comparative assessment of the non-invasive methods. This comparison includes issues of accuracy, suitability and cost.

Finally, a number of recommendations for development or adoption of the methods are presented in Chapter 12.

1.5 References


2 PRESSURES AGAINST INVASIVE STRUCTURES IN HYDROMETRY

2.1 Introduction

One of the motivations for this review of non-invasive flow measurement methods has been the existing and continuing pressure to avoid invasive structures in rivers. These pressures stem largely from fisheries and environmental concerns. For example, a recent survey identified fisheries problems at about 18% of weirs (Science project W6-029, Turnpenny et al., 2002a).

Whilst these concerns have been aired by environmentalists for some time, changing public attitudes and Environment Agency priorities, allied with the impact the EU Water Framework Directive and other legislation, are now starting to outweigh the advantages offered by control structures for flow gauging. The cost of installing weirs, safety concerns, recreation issues and navigation considerations are additional factors that may determine whether it is appropriate to install a gauging structure at a site earmarked for gauging. For example, installation and commissioning costs may be very high, particularly if an integrated fish pass is included. It is worth noting here that there may also be positive reasons to consider other hydrometric methods on their own merits, such as better measurement accuracy during periods of high flow and so on.

The factors that may encourage the Environment Agency to prefer non-invasive flow measurement methods over weirs at new gauging sites are not necessarily the same as those pressures requiring the removal or modification of existing gauging structures. The pressures needed to force the Environment Agency to remove and replace existing structures with non-invasive techniques would have to be much greater than those required to prevent new structures being installed, the reasons being data consistency, cost and inertia. Many established structures have, for example, become integral features of the river management as a whole and cannot be cheaply or easily removed. An intermediate solution is to modify existing weirs so that they incorporate facilities for fish passage.

Nevertheless, pressures to remove weirs may be strong and can lead to their removal. For example, a gauging station weir at Skip Bridge in Yorkshire was removed and replaced with a transit-time ultrasonic station in 1999 because of the problems it caused to the movement of coarse fish species. Figure 2.1 shows the original weir and a view of the site after conversion. Turnpenny et al. (2002a) pointed to 20 other flow gauges within England and Wales that are currently being considered for modification or removal. Such pressures are likely to increase further in the foreseeable future. Thus, whilst only a small proportion of the total number of invasive structures (including weirs, flumes, sluices, culvert and bridges) in Britain’s rivers are used for flow gauging, their operation by the Environment Agency means that any potential environmental impacts need to be considered carefully if the Environment Agency is to reconcile its responsibilities for both hydrometric monitoring and environmental management.
This chapter presents a review of the pressures against the use of hydrometric structures, including factors that may drive removal of existing sites. The positive reasons for considering other hydrometric methods on their own merits, regardless of the suitability or otherwise of a ‘traditional’ structure, are noted in subsequent chapters of this report that review individual methods. The key factors to be considered are listed below, and will be discussed in more detail in following sections.

- Ecological pressures:
  - Impact on local ecology due to changes in geomorphology and hydraulics up and downstream of a weir.
  - Impact on fish and other species due to restricted passage across weirs.

- Legislation governing status of water bodies:
• Practical implications:
  o Cost and value – is a weir the most effective hydrometric solution?
  o Health and safety.

• Other interest groups:
  o Recreation and amenity value.
  o Navigation.

2.2 Ecological Impacts of In-stream Structures

Ecological pressures will be a key factor in determining how strongly the main types of legislation are likely to affect the viability of flow measurement weirs. For this reason it is worth focusing on these first, as they are common to several of the later sections that discuss legislative drivers.

2.2.1 Impacts of weirs on stream hydraulics and geomorphology

The introduction of a weir to a stream has a number of physical effects that may have a significant impact for some distance upstream and downstream. Such effects, in turn, impact on the local aquatic environment, causing changes in habitat up and downstream of the structure. To understand how and why these changes occur it is necessary to consider how weirs and other structures influence stream hydraulics.

Gauging weirs work by constricting the flow in such a way as to produce an artificial head difference in the channel. Provided this is sufficiently large, the head upstream of the structure becomes independent of downstream conditions (‘modular’ flow) and a unique relationship exists between the upstream head and discharge, which can be calculated theoretically if the weir dimensions are known. Bos (1989) describes these relationships in more detail. Flumes operate by forcing the flow to accelerate (usually by a converging of the sidewalls) in order to produce a unique rating between water surface profile and discharge. However, as they are rarely used for gauging flows within natural sections, and involve a much smaller head loss than for weirs, it is not intended to explicitly discuss them here.

The shape of the crest overflow governs the size of the head loss over a weir, and the width and shape of the constriction it produces. The Weirs Good Practice Guide (Rickard et al., 2003) describes some of the more commonly used crest designs. Some examples are shown in Figure 2.2.
Figure 2.2: Common gauging weir shapes (after Rickard et al., 2003).

Figure 2.3: Changes in water level caused by installation of a Crump weir.

The principal impact is on the level profile in the vicinity of the weir crest. Water levels are raised upstream of the weir, whilst a hydraulic jump and plunge pool are usually created on the downstream of the weir face, as illustrated for a typical Crump-type weir in Figure 2.3. These and other physical effects are summarised in Table 2.1. It should be noted that these impacts apply for all weirs and not just for those used for flow measurement. As indicated in Table 2.1, weirs reduce the variation in flow and level upstream. Velocities become lower and there is less seasonal variation in water level.

The introduction of a structure can also impact the sediment dynamics of a river reach. Weirs typically act as a silt trap, preventing the movement of fine particles downstream of the weir. The regulation of stream velocity upstream above the weir, together with increased water depth, will typically reduce scour and erosion in the channel and lead to increased channel stability. For gauging weirs it is, however, usual practice to regularly remove trapped silt, as this can reduce the accuracy of flow measurement if left to build up. Reduction in suspended sediment and aeration caused by movement of water over the weir crest can also, in some cases, improve water quality downstream of the weir.
Table 2.1: Principal physical effects associated with weirs (after Rickard et al., 2003)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Upstream of the Weir</th>
<th>At Weir</th>
<th>Downstream of the Weir</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity of flow</td>
<td>Slower and more uniform</td>
<td>Rapid</td>
<td>Turbulent and varied</td>
</tr>
<tr>
<td>Depth</td>
<td>Deeper with little variation</td>
<td>Shallow</td>
<td>Variable</td>
</tr>
<tr>
<td>Wetted area</td>
<td>Consistent area, even at low-flow</td>
<td>Uniform or varied according to design (e.g. notched crests have reduced area at low-flow)</td>
<td>Varies in response to changes in flow</td>
</tr>
<tr>
<td>Water levels</td>
<td>Variation tends to be relatively small over a wider range of flows</td>
<td>Fall in water level at weir is highest at low flows, and tends to reduce with increasing flow</td>
<td>Water level in the channel downstream varies in response to the flow</td>
</tr>
</tbody>
</table>

2.2.2 Impact on local habitats and biodiversity of species

Gauging structures influence river habitat by altering the river conditions for some distance upstream, and immediately downstream. For example benthic invertebrate and macrophytic plant communities are likely to change as a result of the hydraulic changes in the channel caused by the installation of a structure. It should be noted that not all environmental impacts of structures are negative and, whilst a weir can lead to loss of habitat for some species, for others it can lead to gains in habitat. Species that require different types of habitat as they grow (salmon are a good example) may also be encouraged by the diversity of habitats found in the vicinity of weirs, providing there are adequate facilities for passage around the crest. Also, unless the site chosen for the weir has some very special significance in the river (this is discussed further in Section 2.4), any displaced species may in time adjust and move to new habitats down or upstream. However, as the affected stretch of river will generally be greater upstream than downstream, the gains and losses in habitat would not necessarily balance. The overall impact, therefore, is likely to be restriction of habitat and reduced biodiversity.

The next few paragraphs briefly discuss some of the main environmental changes that may occur upstream and downstream of a weir. Obstructions to the movement of fish and other species are specifically discussed in Section 2.2.3). Further guidance of the environmental impact of river works can be found in the scoping study on the Environmental Impact of River Channel Works and Bank Protection (MAFF, 2001).

Upstream impacts
Upstream there will normally be a deepening and slowing of the river, loss of glide and riffle habitats, increased sedimentation and loss of gravel bed. This will favour slack-water species to the detriment of riffle-loving species. For example wetland species, or those that like ponds with fine sediment, such as water lily and swan mussels, will tend to colonise the area. Whilst water depths are maintained, water quality is likely to
decrease in the sluggish conditions and due to the build up of weed and vegetation in the channel. For gauging weirs, maintenance practices may involve the removal of silt and weed-cutting procedures.

In some cases, increasing the depth of flow can improve the substrate and provide more cover for young fish. For example, the Galloway Fisheries Trust (www.gallowayfisheriestrust.org) reported that a V-notch weir installed on the River Cree in southwest Scotland was found to increase the number of salmon parr surviving and also induced trout parr into the area. Contrarily, the increased depth of water upstream and removal of gravel habitats may reduce the availability of spawning areas.

**Downstream impacts**

Below the weir the opposite effects occur, with a plunge pool and faster flowing waters. These areas often provide good habitats for milfoil and invertebrates such as blackfly and stonefly, and can be good spawning sites for salmonid and rheophilic species. For example, the River Cree weir mentioned in the last section provided gravel habitat for salmon spawning, which resulted in a ten-fold increase in salmon fry. Other types of fish can also thrive in the fast flowing conditions produced below the weir. For example, barbels, which prefer flowing rivers with stretches of gravel, riffles and pools, are often attracted to areas downstream of weirs where they congregate in the deep weir pools.

**At the weir crest**

As shall be discussed in Section 2.2.3, the weir crest is likely to present an obstruction that prevents movement of fish and other species. However, the exposed surfaces of a weir crest can provide a habitat for algal and moss growth. Where slopes are not steep and fissures are present, rooted crowfoot can take hold. Wing walls are favoured sites for several nesting birds. It should also be noted, however, that such habitats are likely to be cleared from gauging weirs as part of the maintenance regime.

![Figure 2.4: Vegetation growth in slow moving deep-water upstream of a gauging structure (courtesy of Dave Stewart, HPPT).](image-url)
2.2.3 Effects of gauging weirs on movement of fish species

The ecological impacts of weirs with regard to fish movement have been known in general terms for some time. Anglers often focus on pools just below weirs where fish are known to congregate, with many fish species unable to progress further upstream. Even small weirs can prevent stronger-swimming game fish (such as salmon) from moving upstream.

Due to legislation (Section 2.3.3) most new weirs have inbuilt facilities for fish passage. Cowx (1998) reported that over 100 fish pass structures have been built in England and Wales since 1989, with a total of approximately 380 fish passes in use (although only a proportion of these are at gauging structures). It is also possible to fit fish passage structures retrospectively to existing weirs and a number of Environment Agency Science studies are investigating design options for this at present. However, many fishway structures do not afford passage to a wide variety of species. Until recently, most fish passes constructed in the UK were designed exclusively for salmon or trout and were poorly suited for coarse fish or eel species.

Why in-stream structures obstruct passage of fish

A weir (and other types of physical obstruction) is a potential challenge that an individual fish may or may not be able (either by swimming or jumping) or be willing to meet. The significance of obstructions to movement depends on the design of the weir and the species involved. Thus a particular obstruction may deter some species from using that route and will form a physical barrier to many individuals of other species wanting to pass over it. Even those individual fish that are physically able to pass the obstruction are likely to be slowed, delayed or injured during the process.

Research carried out over the last few years has allowed a better understanding of which factors influence the ability an individual fish to pass over a structure (including those designed for gauging). The most important factors are as follows:

1. To be able to pass over a structure a fish must be able to maintain an adequate swimming speed given the velocity of the water across the crest. Some game species, such as salmon, are able to achieve quite rapid bursts of speed, whereas coarse fish generally have much poorer swimming ability (Turnpenny et al., 2001). For some coarse species, little is known about achievable swimming speeds or stamina. Fish are better able to ascend rough surfaces where friction effects cause stream velocities to decrease.

2. The head loss across the crest determines the height that fish will be required to jump. Migratory species such as salmon cope better with large jumps than coarse fish species. Adult fish are also able to jump further than younger individuals.

3. There are needs for a minimum depth of flow, as (fairly obviously) fish have difficulty swimming if not fully submerged. However, too great an amount of water passing over the weir will also pose difficulties for fish passage.

4. The shape and slope of the crest may be important. Fish need to orientate themselves in certain ways if they are to easily swim up or jump any obstruction, including slopes.
5. The hydraulic conditions in the pool below are also important, as fish need to gain momentum before jumping.

Given these considerations it is evident that thin plate weirs, although not widely used, are not at all favourable to fish movement because of their non-adherent nappe and aeration. Crump and flat-vee weirs, which are both used for gauging, frequently obstruct fish movement (Turnpenny et al., 2002a). The high velocities and thin flows created by Crump weirs can be very problematic as fish are often attracted by the noisy turbulence of the hydraulic jump, which they then have to overcome before negotiating the long downstream face of the weir over which water is likely to be flowing at super-critical velocity. Flat-vee weirs also have high crest velocities, yet only a narrow area available for flow. In addition they cause flows to converge in the centre of the structure, which can be high disorientating for fish. It has, however, been shown that low Crump and flat-vee weirs do not necessarily constitute a significant impediment to salmonid fish provided the crests are low enough, there is sufficient depth of water, and that the approach is easy. Many rivers with gauging weirs have a healthy salmonid fish population. Older weirs used for impoundments may be significant obstructions to fish, as these were historically built with significant head differences, and may also be in poor state of repair.

**Impacts of obstruction to fish passage**

It is important that fish are allowed free movement within the river system for the following reasons:

- spawning,
- redistribution of fry and juveniles,
- feeding (fish make regular movements between different feeding areas),
- shelter (e.g. to avoid adverse conditions such as floods),
- re-colonisation.

Spawning, feeding and distribution of juveniles are obvious requirements of species life cycles. Re-colonisation is required following pollution incidents, washout from floods, and retreats downstream that may occur in droughts.

Different fish species move or migrate at different times of day, different times of year or at different stages in their life cycle. For instance, species such as salmon and shad are anadromic; the adults run up-river to spawn whilst juveniles move down-river to the sea to spawn. In contrast eels spawn in the sea, but move to the river system to grow. Amphidromic species such as mullet or flounder run between both sea and freshwater, spending appreciable time in each, whilst potadromic species, which include trout, barbel and many coarse species, live wholly within the freshwater system.

If fish of any species are prevented from migrating or moving as required then this is likely to have adverse consequences for the survival of both the individual and the population. Recently, Environment Agency Science project W6-029 (Turnpenny et al., 2002a) investigated of the impact of flow gauging structures on fish species. The project found that the obstruction posed by weirs had a number of specific impacts on fish populations including:

- loss of access to habitat (especially spawning habitat and feeding grounds),
• prevention of re-colonisation of denuded areas following pollution, flooding or
drought incidents,
• delay in passage (these can be significant especially where there are multiple
obstructions in the river corridor),
• increased predation risk for fish that are held up above or below obstructions,
particularly for fish that become tired or injured by the effort of crossing the
obstruction,
• reduction of population size and, potentially, reduction of genetic diversity and
therefore fitness of the population.

Fish are, of course, also affected by changes in river habitats resulting from the
installation of a weir (as discussed in Section 2.2.2), which can reduce the number of
potential spawning sites and redistribute or reduce food sources.

Fish passes
Some of the problems associated with obstruction can be mitigated or reduced by
installing a fish pass structure able to facilitate the passage of an individual fish over the
structure (Bowman and Rowe, 2002). A number of fish pass designs are widely used:

• pool and traverse fishway – an ascending series of pools divided by weirs,
• vertical slot – variant of the pool and traverse design,
• plain–baffle (Denil pass) – based on ‘U’ shaped baffles,
• superactive-baffle fish pass /ladders (Larinier pass) – uses bottom baffles,
• Hurn baffled fish pass - a prototype design currently being tested by the
Environment Agency,
• diagonal baulk,
• rock ramps and cascade structures,
• submerged orifice,
• natural bypass channel.

The design of a fish pass is important, as it can often be species specific. For example,
Denil-type fish passes tend to be used for salmon and trout, whilst vertical slot passes
are usually for shad. Pool-type fish passes are thought to be more appropriate when a
variety of species require passage.
There are a number of problems associated with fish passes and, whilst they can minimise the impact of weirs on some species, for others they are quite ineffective. An example of an effective fish pass is the vertical slot fishway installed at Torrumburry.
weir, where numbers of silver perch, golden perch and bony bream numbers decreased downstream and increased upstream to a level apparently reflecting a more natural equilibrium of the ecosystem. However, even the most successful fish pass still does not permit all species and sizes of fish to migrate, and no current fish passage solution can mitigate the many other impacts of a weir on ecosystem processes and biodiversity.

Fish passes may also not work over a large range of flows. Turbulence can be a barrier to fish passage and should be understood at a site for fish pass design. A well-designed fish pass should act as a buffer to strong currents, allowing individuals to move upstream at a range of river levels, but a poorly designed structure can actually increase turbulence in the approach. For instance, in a vertical slot fishway fish traverse up the river behind a series of alternating baffles, moving from one side to the other to rest in the eddies. The walls provide resting pools for the fish to regain their strength to reach the next slot.

There can also be problems reconciling use of fish passes at gauging weirs, as fish passes traditionally have not been designed with flow measurement in mind. Typically fish passes compromise the accuracy of flow measurement, especially at low flows where a large proportion of the flow may be conveyed through the fish pass. It is possible to build up a rating for a fish pass, allowing a rough estimate of the flow to be made, but passes tend to accumulate debris and silt, which will naturally affect the rating (Boiten, 2002).

Ongoing Environment Agency research is currently addressing the need to design weirs that will incorporate a fish pass and can also accurately measure low flows (White and Woods-Ballard, 2003). This project (W6-084) has identified a composite flow measurement structure and fish pass that meets both fisheries and hydrometric requirements. This is a flow measurement weir (Crump or flat-vee) with an offline super active Larinier fish pass connected to the main structure at the upstream end by a submerged access. The fish pass has been modelled in a laboratory tank and shown to have a stable coefficient of discharge that can be described mathematically. However, it will be some time until such solutions can be implemented in the field.

2.3 The EU Water Framework Directive (2000/60/EC)

The Water Framework Directive (WFD) is a major change in environmental legislation that specifically relates to the protection of rivers. The WFD is starting to be introduced into legislation within England and Wales and proposals on how it may be implemented are currently being developed. The Directive requires that all rivers within England and Wales should be classified ecologically, with plans developed to protect those stretches of satisfactory ecological conditions and to improve those that fall below the required ecological status. These plans are to be incorporated into River Basin Management Plans (RBMPs), which will become operational by 2012 (Holland, 2002).

The time scale for the development of the RBMPs means that the detail required for the implementation of the WFD is not yet developed or available. For this reason the significance of the WFD as a driver for non-invasive flow measurement is largely speculation, but we will explain our interpretations below and make clear what assumptions they have been based on.
2.3.1 WFD objectives relevant to river flow measurement

The key objectives of the Directive, as set out in Article 1, are to

- prevent further deterioration and protect and enhance the status of aquatic ecosystems and associated wetlands,
- promote sustainable water consumption, and
- contribute to mitigating the effects of floods and droughts.

It is the first of these objectives that might act as a driver in favour of non-invasive flow measurement, as weirs do cause changes to the ecology of rivers. The second two objectives could mitigate the pressures against weirs if the monitoring role of flow measurement could be shown to benefit sustainable water consumption and flood/drought mitigation more than it harms ecological status. This seems an unlikely interpretation, especially as non-invasive alternatives exist for river flow measurement. However, the argument could prevail on accuracy grounds (perhaps most likely for low flow measurement) should weirs be held to offer significantly better hydrometric performance.

The Directive imposes a requirement for member states to work towards and achieve at least ‘Good Ecological Status’ (GES) in all bodies of surface water and groundwater, and also to prevent deterioration in the status of those water bodies (Dunbar et al., 2002). It allows for some water bodies to be exempt from this requirement if they are Artificial or Heavily Modified. These two separate groups of water bodies have to achieve ‘Good Ecological Potential’, a different standard that reflects their differences from more natural rivers, estuaries and lakes. However, even for these groups the WFD requires that there is no deterioration of the ecological class.

![Ecological Status Diagram](image)

*Good status also requires good water quality

**Figure 2.7: Guiding principles on technical requirements for the Water Framework Directive (after Environment Agency, 2002).**
For natural rivers the ecological status can be defined in one of five classes – High, Good, Moderate, Poor and Bad. For those within the lower three classes, plans have to be developed to ensure that they will reach at least the Good class, with no deterioration in the process. For those within the top two classes, no deterioration is permitted (Figure 2.7). According to recent Agency guidance on the WFD (Young, 2002), this means that the deterioration should not cause the river stretch to drop into a lower class.

The High ecological status is, uniquely, also judged on hydro-morphological criteria as well as ecological. For rivers, the criteria that will be considered in the hydro-morphological assessment are:

- quantity and dynamics of river flow,
- connection to the groundwater body,
- continuity,
- depth variation,
- width variation,
- structure and substrate of the bed,
- structure and condition of the riparian shore.

Flow measurement structures will change the last four of these criteria, at least for a stretch upstream or downstream of the weir. It can be argued that the ‘dynamics of river flow’ are also locally affected by a measurement structure, including rapid transitions from sub-critical to critical flow and re-circulation downstream. For the High status class, only very minor changes from the natural state of the river are permitted. Changes caused by weirs may be considered as more than ‘very minor’.

There is one further group of rivers, referred to as Protected. This group will receive special additional protection. A river may be in this group for several reasons:

- it is a source of drinking water,
- it possesses an economically significant aquatic species (e.g. shellfish),
- it is a bathing water (not likely in England and Wales),
- it is within a Nutrient Sensitive Area (zones defined by Nitrate Directive or Urban Wastewater Treatment Directive),
- for the protection of habitats or species where water status is important factor (e.g. a Natura 2000 site, see below).

These protected areas have objectives and standards that may differ from the general group of rivers. These standards may be higher than for the general group of rivers and must be maintained to ensure that the purpose of the special protection is not compromised.

In classifying river stretches for the WFD “… it is proposed that biological quality be judged on the basis of the degree of deviation of the observed conditions from those that would be expected in the absence of significant anthropogenic influence” (Foster & Griffiths, 2000). The rivers that will be used to define the expected ecology are referred to as ‘reference’ river bodies. They have not yet been identified.
2.3.2 Impacts of WFD objectives on weirs

To assess the likely impact of the WFD objectives on the use of weirs for river flow measurement, it is helpful to describe weirs as either ‘existing’ or ‘new’ because, as discussed earlier, pressures to remove existing weirs will differ to pressures preventing installation of new structures.

We consider first the pressures to prevent new weir structures. The main issues here are as follows:

- If a river has Good or better class, will the impact of a new weir on the ecology be interpreted as deterioration?
- If Good class has not yet been reached, will a weir be allowed if it slows or prevents improvement?
- For a Heavily Modified Water Body (HMWB), will a weir have a significant impact on the ecology and hence be resisted?
- Will a new weir be allowed if it changes the river to a HMWB?

When considering the pressures to remove existing weirs, the issues are as follows:

- If the river is in Good or High class with the weir in place, will there be any case for its removal?
- If the river class is below Good, and it is not a HMWB, can a weir be removed as part of general improvement?
- If the river reach is a HMWB, can a weir be removed as part of general improvement?

It was noted earlier that weirs do affect the ecology within a stretch of river both upstream and downstream of the weir. However, the length of river affected is likely to be much less than the length of a ‘water body’ as defined by the WFD. Although exactly how the water body will be defined is not yet finalised, Dunbar et al. (2002) suggested that this could be based on grouping existing river stretches as defined by the Environment Agency through the General Quality Assessment (GQA) scheme. As noted above, weirs do also affect the free movement of some species within the river, which is an important ecological impact regardless of local habitat effects, and can affect the distribution of fish within the river system.

With the information on the Directive and the impacts of weirs in mind, we can attempt to answer the above questions. A summary of the answers is given in Table 2.2. A more detailed explanation follows.
Table 2.2: Assessment of likely pressures on invasive structures according to WFD objectives.

<table>
<thead>
<tr>
<th>Water body group</th>
<th>Class of water body</th>
<th>Pressures</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>To remove weir</td>
</tr>
<tr>
<td>‘General’</td>
<td>High</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Good</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Other</td>
<td>Yes</td>
</tr>
<tr>
<td>Protected</td>
<td>Natura 2000</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Other</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Maximum</td>
<td>No</td>
</tr>
<tr>
<td>Heavily Modified</td>
<td>Good</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Other</td>
<td>Maybe</td>
</tr>
<tr>
<td>Artificial</td>
<td>N/a</td>
<td>No</td>
</tr>
</tbody>
</table>

2.3.3 Assessment of restrictions on new weirs

For proposed new weirs, it seems likely that the WFD will make it more difficult to proceed in most categories of rivers, although in some cases perhaps not much more difficult. The three classes where it appears highly likely that there will be significant added pressures not to install new weirs are as follows:

- for the High class of river, where only very minor changes of the hydro-morphology are acceptable,
- the general class of rivers that have not yet reached at least Good status (any new features that will slow the progress to the good status are likely to be resisted),
- sites where there is special protection of habitats or species (e.g. Natura 2000 sites), where the special level of protection will make changes that are likely to be detrimental to the ecology unacceptable.

In the above cases non-invasive flow measurement will have to be considered as an alternative to a new weir.

There are several categories shown in Table 2.2 as ‘maybe’. For the HMWB group, the degree of resistance towards new weirs will depend to a large extent on whether the ecological class is close to the lower boundary of its current class. If it is, then even small deteriorations of the ecology will not be allowed. However, if there is ample headroom then the ecological changes from the weir are likely to be small relative to the departures from a natural river ecology that already exist (and have led to HMWB status in the first place).

For the general rivers that already have Good status, resistance to new weirs is likely again to depend on how close the river ecology is to the lower boundary of the class; the WFD does not allow deterioration from one class to a lower one. If a weir can be installed without the status being reduced to a lower class, which will depend on the species within the river (coarse fish species are likely to be more of a problem), it is hard to see why a new weir should not be allowed.
2.3.4 Assessment of restrictions on existing weirs

Pressures to remove an existing weir will have to be greater than those to stop the installation of a new one. This is largely because of the following factors:

- there will be a continuous flow record at the site which, for consistency, it is preferable to maintain without changes to the method of measurement,
- the cost will be greater as the removal of the existing weir will have to be included in addition to the cost of the installation of a non-invasive flow measurement method,
- the initial environmental impacts of the removal may themselves be complex and damaging,
- there is an inertia resisting change that has to be overcome.

For existing weirs, it is likely that the greatest pressures for removal would be for the general rivers that have not yet achieved at least Good status. Plans will have to be developed for these river stretches to allow the river to achieve the higher status. All impediments to the higher status will be considered for change, including weirs. Of course it will depend on the specific river as to what is the main cause of the failure to reach good status and it is very unlikely that a flow measurement structure would be the sole cause. However, in these situations there will be an expectation that all features that contribute to the lower status will be changed, or considered for change, to obtain an improvement. If there are non-invasive flow measurement methods available that are arguably as good and no more expensive than weirs (if not cheaper), it may be that replacement of the weir with a non-invasive technique will be considered (even if this alone is not sufficient to achieve the desired ecological status).

Similar arguments can be put forward for the Heavily Modified Water Bodies that do not yet meet their ecological goals. However, in this case, there will be major changes to the natural river that have allowed the river stretch to be classified as a HMWB. Such changes are likely to be far more pervasive than a flow measurement weir. In this situation, the improvement achieved by removing a weir may be too small to be worth pursuing, unless its impact is particularly large (e.g. it is a complete obstruction to a wide variety of species).

For all the other groups and classes, the water body has been classified with the presence of the flow measurement structure and still it has achieved at least Good Ecological Status or potential. Without pressures to improve the status beyond the Good class (there are none within the WFD) there is no reason to remove the weir. For the protected sites a similar argument would apply – here things are satisfactory as they are. The existing weir may well have a positive influence on the ecology and its removal may well disrupt the situation.

It should be emphasised that the conclusions drawn above remain speculative as so many of the details of implementation of the Directive remain to be finalised. As stated by Foster and Griffiths (2000) “One of the most important issues for implementation of the Directive will be understanding the relationship between the different elements (biology, physio-chemical and hydromorphology) which together make up ecological quality.” The relationships between these aspects of ecological status will, of course, affect how significant the impact of the weir is.
The foregoing discussion would appear to lead to a conclusion that, in general, flow measurement structures (as well as other structures) can be thought of as detrimental to WFD objectives. There is one important caveat to be made, however. It is likely that the existing state of the river will, in some situations, be far from ‘natural’ because of the presence of weirs, some of which may have been in existence for many years.

It is easy to envisage circumstances where the current ecology of a river reach is in part a product of the flow regime imposed by artificial hydraulic controls, which could in some cases include flow measurement weirs. For example, a weir may create deeper, slower flow upstream leading to good conditions for species such as bream and perch. Conversely, preferential deposition of fines upstream of weirs may encourage gravel-bed conditions downstream, with consequent advantages for species such as dace and barbel. It is not clear whether, in situations like this, the objective of ‘Good Ecological Status’ would always be met by returning the river to a true natural condition that may in fact be detrimental to some habitat or species.

It is not yet known what lengths of river will be classed as Heavily Modified or fail to reach Good status. It is anticipated that most bodies (both general and HMWB) will achieve at least the good or potentially good status, as otherwise the cost of improving rivers is likely to be enormous. If this is correct, the main pressures on weirs for flow measurement will be restricted to the minority of river stretches that are below the required status. However, this remains to be seen as the implementation of the Directive develops.

One remaining uncertainty, albeit a minor one, is whether ‘no deterioration’ could be interpreted much more strictly as no lowering of the ecological status even within a class band. Currently it would appear that only a lowering of the class is forbidden, but it is possible that this interpretation will change with time. If this more restrictive interpretation were to be adopted, it would be essentially impossible to install any new flow measurement weirs in the future, at least in natural reaches.

2.4 The EU Birds and Habitat Directives

The EU Habitats Directive (29/43/EEC), transposed in British law through the Conservation (Natural Habitats etc.) Regulations 1994, requires the identification of Special Areas of Conservation (SACs). The 24 articles of the Directive specify a range of measures, including conservation of features in the landscape that are important for wildlife, the protection of species listed in the annexes from damage, destruction or over-exploitation, the surveillance of natural habitats and species, and ensuring that introductions of non-native species are not detrimental to naturally occurring habitats and species.

The EU Birds Directive (79/409/EEC) designates Special Protection Areas (SPAs). There are over 240 SPAs in the UK as a whole. Together with sites identified as SACs, the SPAs form the Natura 2000 network of protected conservation sites. Many of these sites are within rivers, or the whole length of a river, or are affected by river management practices – Table 2.3 gives a list of SACs on named rivers in England and Wales.
Table 2.3: SACs on named rivers in England and Wales.

<table>
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<tr>
<th>EU Code</th>
<th>Name</th>
<th>Local Authority</th>
<th>Grid Ref</th>
<th>Area (ha)</th>
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<td>SY267961</td>
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Source of data: Joint Nature Conservation Committee

The Environment Agency has a declared policy to comply with the Habitat and Birds Directives in its planning, regulatory and operational activities. This applies to all proposals, including new weirs, that require Agency approval and is a consolidation of existing statutory obligations to protect SSSIs under the Wildlife and Countryside Act (1981) and the Countryside and Rights of Way Act (2000).

The installation of a new weir requires permission (Land drainage consents under S109, Water Resources Act 1991 for works affecting bed, banks or flow of statutory main river, and S23, Land Drainage Act 1991 for the construction of a structure that would affect the flow of an ordinary watercourse). Therefore, the Environment Agency’s policy will affect the installation of new weirs. It does not cover the removal of existing weirs directly; however, there is a requirement to review some existing permissions under Regulation 50, or 3(4), of the Habitats Regulations.
The Habitats Regulations essentially require a staged risk assessment of relevant plans or projects. The risk assessment is designed not just to establish the possible ecological impacts of a new weir (in this case), but also how likely those impacts are to occur. The risk to be assessed is then a combination of the two factors, likelihood and consequence. According to Environment Agency procedures “a pragmatic approach is required with the application of risk assessment principles when the outcome is uncertain, but the precautionary principle is an integral part of the assessment under the Habitats Regulations”. The legislation is complex but it grants special protection to sites designated under the Habitats Directive. The WFD is compatible with this earlier Directive and the WFD category of ‘Protected Water Bodies’ is designed to include the sites protected by the Habitats Directive.

Many of the sites protected by the Habitats Directive are wetlands but some of them are river stretches. These stretches are unlikely to be as extensive as a WFD water body, but may be part of such a water body. If the location of a proposed new weir is within or close to one of the Natura 2000 sites then the Directive, and Environment Agency policy, require extensive consultation with other interested organisations, principally English Nature and Countryside Council for Wales. The Habitats Directive does not impose any specific limitations on the installation of new weirs that have not already been considered under the WFD section. However, the Environment Agency’s policies in relation to the Habitats Directive do describe in detail how the protection for such sites should be considered and applied.

For existing weirs, the review aspects of the Directive are most relevant. Guidance to Environment Agency staff concerning when an existing permission should be reviewed states “If the majority of the influences on a site arise from sources other than the permitted activity, it is unlikely to be a priority for early review by the Environment Agency”. The focus will be on weirs that are either within the protected site or clearly affect the ecology within the site (in other words those likely to be just downstream of a site). It could also include weirs further downstream that are blocking the movement of protected species into the site. The impact of an existing structure has to be shown to be significant for a review to take place.

Once an existing weir has been identified as needing to be reviewed the process is described in Environment Agency guidance reports. The protection of the site has three components, namely

- the physical structure,
- the species composition of relevant biological communities, and
- the distribution of these communities across the site.

The success of the site is judged by its ability to sustain communities such that the favourable conservation status is preserved. The Environment Agency states that “if an existing permission/activity fails the Habitats Regulations test then it may only continue if there are modifications to avoid adverse impact”.

There is no cost/benefit consideration in relation to the removal or changes to a weir structure. Modifications to comply with the Habitats Regulations would depend on the specific site, but are likely to be linked to either passage of fish (e.g. the installation of a fish pass) or lowering of water levels upstream, which is difficult to achieve without removal or extensive alteration to a weir. Where a weir has been shown to cause
significant damage the Directive appears to offer no option other than to modify it – resistance to the changes does not appear to be possible.

In conclusion, it is likely to be difficult to install weirs for flow measurement in or close to Natura 2000 sites. However, the removal of existing gauging structures is only to be expected where they are clearly causing a significant adverse impact on the site ecology. There are only relatively few protected river sites in relation to the number of gauging structures and possible new sites for flow measurement. Therefore, whilst the Habitats and Birds Directives are important, they seem likely to have only a limited impact on flow measurement.

2.5 Other Legislation

It is clear from earlier sections that the free movement of fish within a river is of particular importance when considering the ecological impacts of weirs. The two EU Directives considered so far give protection to various aspects of fish movement. However, there is earlier legislation for England and Wales that also provides some protection for fish, and could provide even greater incentives for non-invasive flow measurement. The most important acts are the Salmon and Freshwater Fisheries Act of 1975, the Water Resources Act of 1991, and the Environment Act of 1995. In addition, there is political pressure from interest groups that may be hard to resist, even in the absence of legal backing, and pressures to ‘lead by example’.

2.5.1 Salmon and Freshwater Fisheries Act, 1975

The Salmon and Freshwater Fisheries Act has been in force since 1975 and in that time many new flow gauging structures have been installed. A Review Report on suggested improvements to the Act was published in 2000 (MAFF, 2000).

The Salmon and Freshwater Fisheries Act applies to salmon, trout (including sea trout), freshwater fish and eels. The Act defines ‘freshwater fish’ as meaning “any fish living in freshwater exclusive of salmon and trout and of any kinds of fish which migrate to and from tidal waters and of eels.” This definition excludes anadromous fish other than salmon and sea trout. As a result, species such as shads, smelt and lampreys are not covered by existing freshwater fisheries legislation. The Act also does not cover marine species while they are in freshwater. There is also some uncertainty over the position of crayfish, although MAFF are reported to have told the Review Committee that they believed crayfish were covered by the definition of freshwater fish in the 1975 Act.

It is therefore clear that the Act covers more than simply salmonid fish although, according to the MAFF (2000) review, “One complaint frequently made to us about existing fisheries legislation is that it concentrates unduly on salmon and sea trout, with coarse fish treated as an afterthought”. This could account for the fact that many flow measurement weirs have been installed since 1975 that may cause significant problems for coarse fish, but much less for salmonids. The MAFF Review has avoided this criticism and does consider coarse fish equally with salmonids.

The Review covers many aspects of fisheries legislation of little relevance to flow measurement. However, there are some recommendations that would, if they were adopted, have a major impact on flow measurement using weirs. The MAFF (2000) Review Report states that:
“There was general agreement among those who addressed the issue that the requirement to install a fish pass in a new or modified dam or other obstruction should apply in all rivers, not just those frequented by salmon and sea trout. We agree and conclude that fish passes should as far as practicable provide passage for all fish attempting to migrate past the obstruction.”

This passage does not mention flow measurement weirs explicitly, but it is clear that such a weir would be covered under the term ‘other obstruction’. The Review includes this requirement as part of its recommendations. It is stated that fish passes should be suitable for all fish likely to use them, that they should be installed at all new obstructions and that existing structures should be modified to include some facility for fish passage. The Review Committee do allow for the Environment Agency to waive the above requirement, but this caveat is usually reserved for cases where it is necessary “to safeguard certain fish populations”, and not for flow measurement weirs. It is also important to remember that some obstructions are natural! The Review Committee refers to the use of BATNEEC (Best Available Technique Not Entailing Excessive Cost) for the design of the fish pass. However, this approach can also be interpreted to imply that non-invasive flow measurement would be considered instead, especially if no more expensive than the modification of the weir.

For existing weirs (that are not being modified) the Review Report has less to say. It does, however, make one recommendation (127) that “It should be a requirement to install elver passes (if the fish pass is not suitable for this purpose) on all new or altered dams and other obstructions, and their installation should be encouraged on existing ones”. Elver passes are reported to be “simple and inexpensive to construct” and are different to fish passes (elvers are young eels returning to the river from the sea) and are most needed close to the estuaries.

The Report cautions against assuming that all existing obstructions should have fish passes installed, as some river stretches upstream of an obstruction may have a satisfactory fish population that would be disrupted by the removal of a barrier, or installation of a fish pass. This appears to be based on the assumption that other fish species would be able to move into the stretch and change the fish population balance. The Review Committee interpret this as undesirable even though it may be closer to the natural ecology. The Report suggests that the Environment Agency’s fisheries committees or other conservation agencies should decide whether or not this is desirable in individual cases (it has been noted above that a similar situation may arise in respect of requirements under the Water Framework Directive).

In conclusion, if the changes to the Salmon and Freshwater Fisheries Act recommended by the Review Committee are accepted, the installation of new weirs would look to be all but impossible unless they can incorporate a fish pass suitable for coarse fish, or are suitable per se. In contrast, it does not seem that existing weirs would necessarily have to be fitted with fish passes, with the exception perhaps of those where elvers are present.

It seems that new interpretations of the Act are required, or that the proposed changes by the Review Committee will have to be accepted, before the Act becomes a driver for non-invasive flow measurement. The reaction of the Government to the Review Committee recommendations is not known at this time.
2.5.2 The Environment Act, 1995

The Environment Agency has a duty under the 1995 Environment Act to maintain, improve and develop fisheries. The specific clauses of the Environment Act that could impact on the installation of flow measurement weirs are:

- Section 6(6) requires the Environment Agency to “maintain, improve and develop salmon fisheries, trout fisheries, freshwater fisheries and eel fisheries”
- Section 6(1) states that “it shall be the duty of the Environment Agency, to the extent that it considers desirable, generally to promote….the conservation of flora and fauna which are dependent on an aquatic environment”
- Section 103(3) allows for the Environment Agency to make byelaws “regulating fisheries for….aquatic environmental purposes. Aquatic environmental purposes are defined as including the….conservation of fauna and flora dependent on, or associated with, aquatic or waterside environments”.

The first two of these duties and responsibilities were inherited from the National Rivers Authority (NRA) and its predecessors. The strongest of these is Section 6(6), because it requires the Environment Agency to maintain and improve freshwater fisheries. Arguably, this section of the Act could apply to the removal of flow measurement weirs that are proving an obstruction to the free movement of fish (to improve fisheries) and could be used to object to the installation of new weirs (to maintain fisheries). However, these parts of the Act have been in existence for many years and the Environment Agency has not interpreted them in this way, but has developed guidelines as to what is acceptable and is addressing the issue with the current suite of Science projects.

Section 103(3) introduced a new power for the Environment Agency, and could be used to control flow measurement weirs locally by introducing local byelaws. However, it seems unlikely that this was one of the main purposes of this clause. In any case, the Environment Agency appears to have (or will have) more direct methods of controlling the installation of new flow measurement weirs and removing existing ones under the Water Framework Directive and proposed changes to the Salmon and Fisheries Act. For this reason Section 103(3) does not appear to be a main driver for increased use of non-invasive flow measurement methods.

2.5.3 The Water Resources Act of 1991

The Water Resources Act of 1991 does not appear to contain any further powers not already discussed that could be interpreted as a driver ‘for’ non-invasive flow measurement or ‘against’ flow measurement structures. However it accepts a general need to take into account future interests e.g. impoundments and licensing.

2.5.4 Conservation and political pressures outwith legislation

Up to this point we have considered only the legal basis for limiting the installation of weirs or removal of existing ones for flow measurement. However, there may also be pressures from interest groups that could encourage the Environment Agency to choose, as a matter of policy or on an ad hoc basis, to limit the installation of new flow measurement weirs and to favour non-invasive flow measurement. There is a strong feeling that the Environment Agency should be ‘leading by example’ when it comes to environmental issues.
Interest group pressure could arguably extend to the removal of existing weirs or their modification. Pressure of this kind is likely to come from the following interests:

- environmental groups with a particular interest in river ecology,
- fishing clubs or groups,
- riparian landowners (with or without fishing rights).

These pressures have to be considered in the context of the need for accurate flow measurement that is vital for many water management functions, including fisheries management.

### 2.6 Practical Implications

The discussion in this chapter has, so far, been centred on environmental drivers for the restriction of invasive flow measurement structures. However, there are a number of other factors that might lead the Environment Agency to favour other gauging methods over the use of invasive structures, at least at particular sites. These factors include:

- Cost and effort of designing, installing and commissioning the structure.
- Likely performance of the weir given the range hydraulic conditions likely to be observed at the site.
- Maintenance requirements and costs.
- Cost of removing or modifying the structure at a future date, if required due to environmental pressures.
- Health and safety issues.

This section provides a short discussion of these factors and their implications.

#### 2.6.1 Costs and site suitability issues

Costs of installing gauging structures do not necessarily discourage the use of gauging structures, provided that they can be justified by adequate hydraulic performance of the structure. Similarly, whilst the civil works for installation of a structure can be disruptive, they are not necessarily an overriding pressure against a weir.

Typical costs of installing a structure to British Standard (BS3680) are in the region of £100,000 to £300,000, but additional costs may arise if a fish pass is to be included or if there are unusual engineering implications at the chosen site. However, whilst capital costs may be high in comparison with alternative non-invasive gauging methods (further discussion on costs associated with non-invasive methods is given in Chapter 11), maintenance costs for structures are generally much lower. Maintenance costs may include removal of weed, repair of damage to crest, check gaugings and so on. Given that flow gauges are generally expected to be operational for a period of at least ten years, a structure may often prove to be the more cost-effective option in the long-term.
2.6.2 Suitability, performance and accuracy

In some cases, a structure would not necessarily provide the best solution in terms of accuracy. Aside from environmental considerations a structure is not, in general, an appropriate method of flow measurement where:

- reverse flow conditions exist, such as in tidal systems,
- the river is wide,
- the bed slope is steep,
- there are likely to be high sediment loads, or debris is a problem at the site,
- flows are unlikely to be contained within the walls of the structure at high flows,
- the structure cannot be installed to the requirements of the British Standard BS3680.

The difficulty in obtaining flow measurements during periods of high flow is an important consideration. In some cases, particularly if the designed structure has a low modular limit, there may be a need to maintain a rating curve for high flows by current metering. Without the implementation of a cableway, however, this may be difficult because of uncertainties associated with current metering at high flows and because factors relating to timing, access and other staffing priorities in times of flood may lead to few opportunities to undertake the required measurements. There is also a threat to the safety of staff at high flow conditions (it should be noted that similar problems will typically be encountered for non-invasive methods that require calibration in the high flows range). In many cases these disadvantages may become important drivers for adopting non-invasive measurement techniques rather than structures, particularly where other potential pressures are of borderline significance.

Figure 2.8: Difficulty of measuring flows at a gauging structure during high flows (photo courtesy of Dave Stewart, NHPT)
2.6.3 Health and safety risks

There are two main health and safety risks associated with weirs. The first is the specific risk facing Environment Agency staff (or contractors) who have to enter the river in the vicinity of the weir for maintenance or check gauging. There are also general risks to members of the public that use the river for recreational purposes.

Whilst it is unlikely that health and safety issues will prevent the installation of a new weir, they may add weight to arguments to remove existing weirs and, more generally, can lead to unfavourable public opinion regarding weirs. It might also be argued that alternative low-risk methods of gauging should be used if available, particularly in light of the recent trend of individuals aggressively pursuing legal redress in the case of accidents.

Risks to personnel

Hydrometry staff or contractors have to enter rivers for periodic maintenance and cleaning of weir crests, and to repair damaged structures. Entering a river can be dangerous at high flow rates, but the majority of the work can be carried out in relative safety during low flow conditions. There are also some situations where personnel may have to enter the river under higher flow conditions, such as to clear blockages lodged on the crest and to carry out check gauging.

Environment Agency personnel have clear guidance on when it is safe to enter the river. These rules do not allow staff to enter the river for clearance of blockages in potentially dangerous conditions. In addition, the application of risk assessment procedures has minimised the danger to staff. It should also be noted, however, that alternative gauging methods also require staff to enter the river for calibration or maintenance. Therefore, although health and safety are important considerations for flow measurement, there is no significant difference between the risks to staff through operation of gauging weirs compared to non-invasive techniques.

Risk to the public

The main risk to the public is the accidental danger of falling in the river at or just upstream of a weir. Some weirs have powerful flows of water with undertows present just downstream. If a person, particularly a child, is trapped in this section, they may easily drown. Fortunately, most flow measurement weirs do not have these powerful flows so the danger to life is usually limited.

However, weirs often draw the interest of members of the public. Children, in particular, are often enticed to walk out into the river when the flows expose parts of the weir close to the bank. Algae can build up on the weir making it very slippery. Most weirs are not fenced off to prevent the public venturing onto the crest.

Weirs can also pose a safety risk to recreational river users such as canoeists – the standing wave (hydraulic jump) that is present downstream, where the flow reverts from super- to sub-critical flow, can be a threat if the canoeist overturns and is trapped in the roller – although weirs can be a advantageous source of white water for such activities, as discussed in Section 2.7.1.
2.7 Other Interest Groups

2.7.1 Pressures from recreational river users

Weirs are often important recreational resources for anglers and canoeists. Good fly-fishing is often found in weir pools. However, it should be noted that anglers in general do not like changes to the river system in areas where sport fishing is established, including installation of new weirs.

Canoeists (i.e. users of kayaks) often seek out white water, so the flow over a weir can be an attraction to them. One of the most promising types of weir for canoeists is the flat-vee or shallow-vee weir. The River Witham at Grantham, for example, flows over modified flat-vee weirs constructed specifically to provide conditions suitable for canoeists (see earlier comment on dangers of canoeing over weirs). On the other hand, for canoeists in the Native American style canoe, and also rowers and sailors, the weir is a hazard that has to be avoided. Where such activities take place near a gauging weir, a boom or line of buoys is normally placed in the flow upstream to ensure that river users are aware of the weir and can avoid it.

The arguments against weirs in terms of recreation are most likely to come from the perspective of visual intrusion or health and safety. Compared to environmental and fisheries legislation, recreation issues are therefore likely to be rather weak drivers against the use of gauging structures. However, they may take on more importance locally.

2.7.2 Navigation issues

Navigation is an important issue in larger rivers, such as the Thames, Severn and Trent. It is important to maintain access for navigation on such waterways, and weirs, if used, need to include lockage or gated access. In many cases it will be inappropriate to use structures as a method of flow gauging in such rivers.

2.8 Summary

Specific pressures against the use of flow measurement structures may vary from place to place and depend on the flow regime, local fish species and environmental issues relevant to a particular site. Important considerations include the effects on water levels (and hence on habitat and biota), sediment fluxes, fish migration, visual intrusion and health and safety.

These generic drivers are also significant within broader policy and management frameworks, which are currently driving, or are anticipated to drive, decisions about the deployment of flow measurement devices. The most significant frameworks are:

- The Water Framework Directive (WFD)

The goal of the WFD, which came into force in 2000, is that at least ‘Good Ecological Status’ should be achieved in all surface and groundwater bodies. It also aims to prevent deterioration in the ecological status of water bodies. In many cases this will prevent installation of new gauging weirs.
Where there are existing ‘modifications’ to a water body there is a requirement to achieve at least ‘Good Ecological Potential’ (GEP). Modifications include features relating to navigation, flood defence, water supply and so on, and clearly some gauging weirs will be viewed as ‘modifications’, although their significance under the WFD will be assessed as part of a larger catchment picture.


Where river reaches fall within Special Areas of Conservation (SACs) or Special Protection Areas (SPAs) as defined by the Habitats and Birds Directives, they are likely to also receive designation as Protected Areas under the WFD. This can result in very severe restrictions being placed on the sites, and control structures are unlikely to be allowed.

- The Salmon and Freshwater Fisheries Act (1975)

The restriction on movement of game and coarse fish is a primary issue associated with in-stream structures. The Act provided legislative powers requiring new obstructions to include facilities for fish passage.

Some of the new legislative developments are likely to make existing weirs subject to modification or removal if they are causing a significant obstruction to the free movement of fish, especially coarse fish. It will always take a greater impact on the ecology to cause an existing weir to be modified or removed than to prevent the installation of a new one. For this reason, it is expected that a number of existing gauging structures may come under pressure to be modified or removed, but this will depend on the local circumstances and is likely to be a problem for only a small proportion of existing stations.

A number of other strategic considerations may encourage the Environment Agency to adopt alternative gauging methods in the future. These include costs and accuracy. If non-invasive methods can provide measurement of acceptable accuracy at lower cost, these would be more likely to be used in the future, although any saving in capital cost must be balanced against recurring costs associated with maintenance and calibration requirements.

Of particular concern is whether modified weirs can provide sufficient accuracy of measurement. If new designs for flow measurement weirs allow slower-swimming coarse fish to pass, without reducing the accuracy of low flow measurement, new weirs could continue to be installed. Otherwise, it will become increasingly difficult to promote use of gauging weirs, especially if non-invasive techniques can deliver flow measurements of a similar accuracy.

2.9 References


3 OVERVIEW OF NON-INVASIVE FLOW MEASUREMENT TECHNIQUES

3.1 Introduction

This chapter provides a high-level overview of non-invasive flow measurement methods, including techniques that show potential for future development as well as those which are currently in routine use. Some of the main issues relating to use of non-invasive methods, such as calibration requirements and site suitability, are introduced. Later chapters of this report address the main methods in greater technical detail and discuss their practical hydrometric implications.

A variety of methods can be used to measure open channel flows non-invasively. It is useful to group these methods as follows:

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Current metering is the traditional method of flow gauging used in many countries, and the technique used has not changed much in the last hundred years. Other traditional approaches include dilution gauging and use of conveyance calculations, such as used in the slope-area method. As discussed in Chapter 1, dilution gauging and stage-discharge ratings are not covered in this report. The slope-area method, however, can be thought of as potentially offering a means of continuous estimation of discharge and is covered in Chapter 10.

‘Technology’ methods have been used for measuring flow over the last 30 to 40 years, and are gradually becoming more widely applied. Only hydroacoustic and electromagnetic induction methods are widely used for discharge measurement in open channels at present. Other technologies, including Doppler radar, are still at developmental stage, but are likely to become commercially available for continuous flow gauging within the next few years. In addition a number of methods are currently being applied experimentally, such as ‘seismic induction’, which relies on sensing vibrations produced by flowing water to estimate discharge, and particle imaging methods, in which stream velocity is determined from time-lapse digital photography. The different technologies are discussed in further detail in Section 3.2.

For most technology methods, the primary measured variable is the velocity along a specified flow vector, often called the index velocity. This means that a calibration between the index velocity and mean channel discharge is required, as discussed in Section 3.3. Advantages and limitations of technology methods are introduced in Section 3.4.
3.2 Technologies for Non-invasive Flow Measurement

3.2.1 Overview

A ‘family tree’ of flow measurement technologies suitable for use in open channels is shown in Figure 3.1. All the methods shown can be considered as non-invasive.

This tree diagram identifies specific technologies, which can be grouped into four generic families; acoustic methods, induction methods, Particle Imaging Velocimetry (PIV) and radar methods. Broadly speaking, all of the basic methods can be adapted for continuous use. However, some individual technologies cannot be deployed in this way and are shaded out in Figure 3.1. For instance, acoustic Doppler current meters are used in the same manner as conventional propeller meters, and must be discounted as a permanent gauging method, even though other acoustic Doppler devices can be used on a continuous basis. Sections 3.2.2 to 3.2.5 provide further explanation of the technologies shown in Figure 3.1.

Figure 3.1: Families of technologies for non-invasive flow measurement

(shading indicates technique is not suitable for continuous flow measurement)
3.2.2 Acoustic methods

Acoustic methods are probably the most widely used of all non-invasive gauging techniques. They use acoustic signals to determine stream velocities via sensors placed within the stream. Signals in the ultrasound frequency range are used (15 to 200 kHz).

Two different techniques are employed; transit time methods, which have been widely used for permanent gauging of flows since the 1960s (Newman, 1982), and Doppler methods, which are a more recent development (Gordon, 1989). Some of the latest systems use a combination of the two approaches – changing from transit time to Doppler measurement of velocity depending on the flow conditions.

Acoustic transit time methods

Here the time taken for acoustic pulses to travel from bank to bank is used in the determination of the average stream velocity. The signals are transmitted between transducers on opposite banks, and a number of arrangements are possible. For example, a multi-path configuration uses a series of paths in the vertical and is better able to characterise the mean velocity of water flowing through the cross section than a single path. The transit time method is discussed in detail in Chapter 5.

Acoustic Doppler methods

Acoustic Doppler instruments determine stream velocity by measuring acoustic signals reflected from suspended particles (called scatterers) moving with the water column. They are widely known as Acoustic Doppler Velocity Meters or ADVMs. In contrast to travel-time methods, ADVMs are well suited to flow measurement in streams which have higher concentrations of suspended sediment. There are two main types of acoustic Doppler device: those using continuous beams and those using pulsed beams, the pulsed beam method being the more sophisticated.

Continuous beam devices tend to operate from a fixed point in the channel, usually on the bed in the centre of the channel (an ‘up-looking’ configuration). These devices measure the average Doppler signal from all particles encountered within the beam path, in order to determine the mean velocity vector along the path, although the measurement is often biased towards the velocities of strongest scatterers. An index velocity calibration is required to convert the measured vector to a value that is representative of the channel mean.

Pulsed beam devices are usually operated either as profilers, which take into account the distance reflected signals have travelled when calculating the average velocity, or using range-gating techniques which can be used to record velocities from specified layers or sections of water (i.e. to define the vertical velocity distribution). Profilers can be operated from the surface or channel bed, although surface profilers, widely known as Acoustic Doppler Current Profilers (ADCPs), must be deployed from a moving boat or raft and are better suited to spot gauging of discharge rather than continuous flow measurement. Many pulsed Doppler instruments use dual or triple beams which, combined with state-of-the-art algorithms, can be used to measure mean velocity. Both pulsed and continuous ADVMs are discussed in more detail in Chapter 6.
3.2.3 Induction methods

Induction methods can be thought of as measuring some fundamental physical property that occurs due to movement of water through the stream channel. Electromagnetic induction is a well-established method of measuring velocity. Seismic induction is a new technique that is still at an experimental stage.

**Electromagnetic induction (EM)**

A body of water moving through a magnetic field generates an electromotive force (or voltage) according to Faraday’s Law of Magnetic Induction. The magnitude of this force depends on the water velocity, the magnetic field strength and the conductivity of the water. Such effects do occur in nature due to the Earth’s magnetic field, but for freshwater rivers a much stronger magnetic field, generated artificially using an electromagnetic coil placed above or below the channel, is required for a measurable voltage to be induced. A calibration between voltage and mean velocity is then used to determine the discharge. The technique has been used in the UK since the late 1970s (e.g. Newman, 1982) and is described in more detail in Chapter 4.

**Seismic induction methods**

In the seismic induction method, it has been proposed that geophysical vibrations in the earth around a turbulent watercourse can be related to the discharge rate. The method is discussed further in Chapter 9.

3.2.4 Doppler radar and lidar methods

These methods determine stream velocities based on the Doppler reflections of electromagnetic waves in the radar and visible light frequency ranges. They are non-contact methods in the sense that the instrumentation is located above the stream surface. In terms of continuous streamflow measurement, these techniques can be viewed as developing or new technologies.
Microwave Doppler radar
Here a remote radar transmitter (located between 10 and 100m from the stream) is used to beam shortwave or microwave (frequencies above 300GHz) signals on to the water surface, where they are reflected with a Doppler frequency shift proportional to the surface velocity. The surface must be sufficiently reflective for the method to work well, but measuring velocity from above does avoid many of the problems inherent with submerged sensors (such as sensor disturbances, density and distribution of acoustic reflectors). The disadvantage of this approach is that an index velocity calibration is required to relate the surface water velocity to the mean stream velocity. A number of Doppler radar systems are currently being investigated in the USA (e.g. Costa et al., 2002, Plant et al., 2003) and elsewhere (e.g. Yamaguchi and Niizato, 1994) and a number of commercial devices are now becoming available. The technique is already used commercially for measuring flow in artificial channels and conduits.

Lidar (Light Detection and Ranging) is a similar technique to radar, but uses lower frequency signals in the near-visible light range. The technique is now routinely used for determining river stage and bed profiles (Banic and Cunningham, 2002). However, use of lidar for streamflow measurement is in the early stages of development, and has yet to be fully proved as a concept (e.g. see Kavaya, 2001; Bjerklie et al., 2002).

Recently, the US Geological Survey has been exploring the viability of remote sensing methods based on radar and lidar for flow measurement through its Hydro21 Working Group (Hydro21 Committee, 2000). Some success has been achieved with Doppler radar techniques, although these are yet to be used on an operational basis. However, Vorosmarty et al. (1999) reported that the NASA HydraSat might offer a means of measuring the surface velocity of large continental rivers using lidar techniques in the near future. Doppler radar techniques are described further in Chapter 7.

Laser Doppler Velocimetry
Laser methods are similar in principle to Doppler radar techniques, but use signals in the visible or near-visible light range, which are reflected by small particles moving in the water column rather than at the water surface. Laser Doppler Velocimetry (LDV) is a well-established method in laboratory fluid dynamics. In LDV pulses of laser light are beamed through the water column and the light reflected back by small particles is measured using a photo-detector. The time between the pulse and the echo determines the distance, and the shift in the colour of the light determines the velocity of the particles along the laser's line of sight. The same system is also commonly referred to as Laser Doppler Anemometry (LDA) e.g. see Nezu and Rodi (1986).

Although under laboratory conditions the technique has the potential to provide highly accurate point measurements of velocity, it does however require the use of very high powered laser sources; typically, laboratories using these would be quarantined during experiments because of potential risks to health. For a system to be technically feasible in a natural open channel, it is likely that even more powerful lasers would be required and the consequences for Health and Safety and the aquatic environment are likely to be prohibitive in practice. The method is therefore not described further in this report.

3.2.5 Particle Imaging Velocimetry (PIV)
In PIV a pulsed light source sheet is used to illuminate a flow field containing tracer particles small enough to accurately follow the flow (natural sediments act in the same
The positions of the particles are recorded on either photographic film or digital cameras at each instant the light sheet is pulsed. The data processing consists of either determining the average displacement of the particles over a small interrogation region in the image or the individual particle displacements between pulses of the light sheet. Knowledge of the time interval between light sheet pulses then permits computation of the flow velocity.

PIV is usually applied on a laboratory scale, where powerful lasers are used to illuminate the water column. As with LDV the use of such lasers is prohibitive on a field scale. However, PIV techniques have recently been applied at a field scale using a natural light source in order to estimate surface stream velocities. The potential for such methods for continuous flow measurement is described in Chapter 8.

The rising air float technique (RAFT), also known as the “rising bubble technique”, is a method of measuring flows that has been previously investigated in the UK. This technique relies on measuring profiles of bubbles floating through the water column and can be considered as a particle imaging technique. It is therefore included within Chapter 8.

### 3.3 Measurement and Calibration

#### 3.3.1 Application of the velocity-area method

Non-invasive technologies determine discharge via the velocity-area method, in which the stream discharge, $Q$, is determined from the equation

$$Q = \bar{v} \cdot A_W$$

(3.1)

where $\bar{v}$ is the mean velocity, and $A_W$ is the wetted cross sectional area of the stream.

The velocity term in Equation (3.1) represents the mean velocity of water moving perpendicular to the cross section. However, both natural and artificial channels may show considerable spatial variation in velocity within the cross section, which can be due to drag effects caused by bed and bank roughness, irregularities in channel shape and turbulence. In a trapezoidal channel, for example, velocity will tend to be highest towards the upper centre of the stream where drag effects are lowest. The lateral and vertical variation means that, in practice, it is very difficult to make a single direct measurement of mean velocity. Three main variants of the velocity-area method have therefore developed:

- index velocity method,
- summation of partial discharges,
- indirect measurement of mean velocity.

#### 3.3.2 Index velocity approach

Many non-invasive methods measure only particular velocity vectors within the cross section. It is therefore necessary to calibrate measured velocities against mean velocity, over a wide range of flows using an index velocity procedure.
In this approach a single velocity vector, known as the ‘index velocity’, is measured along a particular plane, which might be oriented either horizontally ($v_x$) or vertically ($v_h$) with respect to the main direction of flow, as shown in Figure 3.2. The index velocity might also be the velocity at a fixed point on the surface ($v_s$). The index velocity is then related to the mean cross-sectional velocity by constructing a calibration relationship, which may be empirical or based on theoretical assumptions about the velocity profile.

![Figure 3.2: Typical measure velocity vectors and velocity contours in a trapezoidal channel](image)

The total discharge is then

$$ Q = f(v_{index})A_w $$

where $v_{index}$ is the measured index velocity and $f$ is a function describing the index calibration. The function $f$ needs to be determined over a range of flow conditions, as velocity distributions can vary strongly with stage, especially in channels having irregular shapes.

The index velocity approach is extremely versatile because it can be used in conjunction with a number of measurement methods. For example, single path transit time gauging stations and side-looking acoustic Doppler meters can be used to measure a horizontal index velocity vector, whilst up-looking acoustic Doppler meters are able to measure vertical velocity vectors. Doppler radar and particle imaging methods both provide a measure of the surface velocity.

However, the accuracy that might be achieved by this approach depends strongly on the cross section and on any assumptions made about the velocity profile. Melching and Meno (1998) noted a number of common assumptions, as follows:

- Primary flow direction does not change appreciably with stage,
- Substantial secondary circulation (from stream bends or expansions and contractions) and large eddies are not present,
- Channel is stable, or can be measured for cross section change,
- Shape of the channel is approximately prismatic,
- Velocity distribution conforms to a power law in the vertical.
Index velocity methods may therefore not be viable at some sites.

### 3.3.3 Summation of partial discharges

If the velocity vectors at all points in the channel were known, their integral would define the total discharge. A more practical approximation is to divide the cross section into \( n \) units and to determine an appropriate velocity for each unit. The total discharge is then determined from

\[
Q = \sum_{i=0}^{n-1} v_i a_i
\]  

(3.3)

where \( v_i \) and \( a_i \) are the velocity and cross-sectional area respectively of the \( i^{th} \) unit. The term \( v_i a_i \) represents the partial discharge for the \( i^{th} \) unit.

This approach is employed with multiple path transit time gauging stations, where partial discharges are determined for individual horizontal ‘slices’ delineated between paths, and is discussed in more detail in Section 5.2.3.

### 3.3.4 Indirect measurement of mean velocity

Here a value of the mean velocity within the cross-section is derived indirectly by measuring some other variable, i.e.

\[
Q = f(p) A_w
\]  

(3.4)

where \( p \) is the measured parameter and \( f \) is a theoretical or empirical function that relates it to the mean velocity (\( \bar{v} \)).

For example, in the full-channel width electromagnetic meter, the magnetic inductance of the channel can, in theory, be directly related to the mean velocity. Similarly, in the Rising Air Float Technique (RAFT) the bubble envelope is the measured parameter.

The accuracies of such methods can be very variable, and highly dependent on the characteristics of the stream.

### 3.4 General Advantages and Disadvantages of Non-invasive Methods

A number of issues are common to all types of non-invasive methods. These are discussed in more detail in the individual chapters, but are introduced here.

#### 3.4.1 Environmental impacts

Non-invasive techniques can be divided into contact and non-contact methods, as illustrated in Figure 3.3.
Figure 3.3: Schematic examples of (a) contact and (b) non-contact sensors

Contact methods involve some degree of physical contact between the instrumentation and the stream; sensors are typically immersed below the water surface. Most non-invasive methods, including acoustic and electromagnetic devices, fall into this category (it is also noted that traditional open channel gauging methods, such as propeller current meters, are contact methods). Despite this contact with the water, sensors may still be considered non-invasive if they do not disturb the continuity of the watercourse in physical, environmental or ecological terms. As noted previously, there is a scale issue here in that a small sensor, such as an ultrasonic transducer, may have no impact on the watercourse under most conditions, but could for example interfere with the flow at very low velocities.

Non-contact methods do not require any physical contact between the instrumentation and the water body. Sensors are instead operated from the river bank, a structure, or from a more remote platform, typically within a maximum range of tens or hundreds of meters. At present such methods are generally only able to measure surface velocities, although this is an area of ongoing research. Space-based remote sensing methods (using orbiting satellite platforms) are the most ambitious form of non-contact sensor. Remote sensing has been used to measure river stage, width and inundated areas (e.g. Smith, 1997), but cannot currently offer a means of directly determining stream velocity or discharge.

It is worth remembering that there can be some environmental impacts of using both non-invasive and non-contact techniques. There may be disturbances during the installation phase, or due to the need for continued upkeep of the gauging site. For example, maintenance procedures such as weed control might be considered as invasive in some situations. There are also potentially intrusive bank side structures such as
stilling wells, cableways, staff gauges, power and communication links and other equipment. At present no method can be considered wholly non-invasive in all these respects.

The only techniques that are known to have any direct detrimental effect on fish movement are hydroacoustic devices using low frequency ultrasound, which can deter shad from passing.

### 3.4.2 Measurement range and reliability

Non-invasive methods are generally more versatile compared with gauging structures and rated sections and can be applied under a wider range of field conditions. In particular they often enable flow measurement:

- where variable backwater conditions occur,
- where the water-surface slope is shallow,
- under reverse flow conditions (e.g. tidal streams and estuaries),
- during periods of high flows.

Often physical requirements limit the suitability of particular methods at particular sites. For example, hydroacoustic devices require a minimum velocity to operate successfully, and will not tolerate excessive weed growth in the channel. Other considerations include channel width, depth, bed stability, suspended sediment concentrations and entrained air. There may also be external sources of interference, such as electric power lines, which might restrict the applicability of particular techniques at particular sites.

### 3.4.3 Accuracy

The accuracy of flow measurements made using non-invasive technologies primarily depends on the calibration procedures employed, as most methods are able to measure velocity vectors relatively accurately. In many cases it will not be possible to fully quantify the uncertainties associated with each measurement, although the British Standard BS3680 does provide guidance on this.

### 3.4.4 Costs

Capital costs associated with non-invasive methods do vary widely, depending on the method and configuration used, the size of the channel and the accuracy to be achieved. For example, experience in the UK has shown that single path transit time stations are much cheaper to install than multiple path arrays. It is also difficult to estimate what typical operating costs for many of the research-level methods might be. Costs are discussed in further detail in Chapter 11.

### 3.4.5 Ease of installation and maintenance requirements

Ease of installation is often quoted as one of the main advantages of non-invasive methods. Some non-invasive methods e.g. acoustic Doppler meters can be installed quickly and easily, but this is not always the case. In particular cabling and power requirements are often difficult and expensive.
Similarly, maintenance requirements can vary from method to method. Some equipment can be removed from the watercourse for cleaning, but in other cases maintenance has to carried out in situ by specialist technicians. Particular problems can arise due to lack of robustness of electronic equipment that can often be irreparably damaged by debris, siltation or by foul water.

3.5 References


4 FULL CHANNEL WIDTH ELECTROMAGNETIC METER

4.1 Introduction

Water is a natural conductor. This means that a body of water moving through a magnetic field behaves according to Faraday’s Law of Magnetic Induction and generates a voltage proportional to its velocity. Electromagnetic flow gauging methods recreate this behaviour at field scale in order to estimate streamflow velocities. The magnetic field is generated by means of a large electromagnetic (EM) coil that traverses the full-channel width (this is typically located under the channel bed, but it can sometimes be suspended over the channel). The voltage induced as water flows through this field is measured using sensors on the channel banks or bed.

The EM method provides an integrated measurement of velocity over the full cross section, which is, in theory, not affected by the presence of weed growth, suspended sediment, entrained air or variable backwater. It therefore offers the potential of accurate measurement of flow at sites where other methods are impossible or impractical. However the civil works required during installation can be significant and costly, particularly for buried coils where a channel diversion is required prior to installation. EM gauges are also vulnerable to electrical interference (for example from nearby power lines) and are not suitable for channels where water conductivity varies spatially (e.g. tidal systems).

The Environment Agency and its predecessors have used full-channel width EM meters for gauging of river flows since the early 1970’s, primarily at sites having unstable rating relationships caused by weed growth, where it is impractical to maintain the frequency and accuracy of current meter gauging necessary to track the changes with adequate reliability. There are now about 35 EM gauges in continuous use in England and Wales. Figure 4.1 shows a buried coil EM meter installed at Snakeholme, Yorkshire, in 1988 in order to gauge flows in West Beck.

Figure 4.1: EM gauging station on West Beck at Snakeholme
Unfortunately, persistent problems with calibration and unreliability at certain sites have led to a general distrust of EM gauges, and a recent Environment Agency review indicated that no Region had immediate plans for the future installation of any new EM gauges. As a consequence the main supplier has recently discontinued their manufacture.

This chapter discusses the principles of operation of the full channel EM methods and outlines the factors that might constrain the accuracy of flow measurements. Other practical and financial considerations are also discussed.

A new type of magnetic device, widely known as the ‘slab-mag’, is now being marketed for use in open channels. In this method, which is best suited to smaller artificial channels having semi-regular geometry, the channel bed and banks are lined with a number of prefabricated and pre-calibrated magnetic plates. Specific considerations related to use of slab type gauges are discussed in Section 4.5.

4.2 Principles of Operation

4.2.1 Basic principles

Full channel EM meters are discussed in most UK-led textbooks on hydrometry and/or hydrology, such as Herschy, (1999) or Shaw (1994). British Standard 3680:1993 (part 3H) and its equivalent International Standard, ISO 9213:1992 describe the procedures involved in more detail. Iredale (2002) summarises the operational details of EM gauges used within the UK. Ewan Associates Ltd (1999) review the calibration procedures used.

Faraday’s Law of Magnetic Induction is the governing physical principle. It describes how a magnetic field acting upon a conductor forces the charges in the conductor to separate, in turn inducing an electric field. At equilibrium the magnetic and electric fields are balanced. However where these are not equal, for example where the field strength varies or if the conductor is moving, an electromotive force (emf) is induced within the conductor, so that a difference in electrical potential (a voltage) is generated across its ends.

Assuming that the conductor acts as a closed conducting path with zero resistance, in the case where a stationary conductor is located within a varying magnetic field, the potential difference depends on rate of change of the magnetic flux, so that the potential difference, $\varepsilon$ (in Volts), maintained between the ends of the conductor is given by

$$\varepsilon = -\frac{d\Phi_B}{dt}$$

where $\Phi_B$ is the magnetic flux in Weber per second. For a uniform field the magnetic flux is equal to the product of the field strength, $B$, and the surface area, $A$. The magnetic flux might therefore change due to variations in magnetic field strength, or if the field area changes relative to the area of the conducting circuit. Where the emf is induced as the conductor moves through a uniform magnetic field, the potential difference depends on the conductor’s velocity i.e.

$$\varepsilon = vbB$$
where \( v \) is the average (integrated) velocity of the conductor (ms\(^{-1}\)), \( b \) is the length of the conductor (m) and \( B \) is the magnetic field strength (Am\(^{-1}\)).

Figure 4.2 illustrates how the concept of Faraday’s Law applies to a full channel EM meter. The magnetic field, \( B \), is generated by an EM coil placed either above or below the flow, whilst the stream moving at velocity, \( v \), through this field acts as the conductor. The channel banks act as the ends of the conductor, so that the conductor width in the direction of movement is equivalent to the channel width, \( b \). The potential difference generated across the ends of the conductor, \( V \), is sensed by a pair of electrodes connected to a highly sensitive voltmeter.

\[
V = k \cdot \nu b B
\]  

(4.3)

where \( k \) is a shortening factor of between 0.9 and 1, and \( \nu \) and \( b \) are the velocity and width of the stream respectively. As the potential difference is representative of the integrated effects over the coil width, it is unaffected by weeds, suspended sediment, channel debris and so the velocity term in Equation (4.3) represents the mean velocity within the channel. It follows that:
and so, in a rectilinear channel the discharge through the channel for a given depth of flow, $h$, is

$$Q = vA = vbh = k\frac{V}{B}$$

(4.5)

where $A$ is the cross sectional area, $h$ is the stage (m) and the other terms are defined as before. In a non-rectilinear channel the $k$ factor also has to account for changes in the conducting area with stage.

### 4.2.2 Buried coil configuration

The buried coil is the most widely used configuration, at least in the UK. Newman (1982) and Iredale (2002) describe typical construction details for many such meters installed in the UK over the last thirty years. Buried coils are generally used in natural channels where the visual effects of a suspended coil would be undesirable.

Figure 4.3 is a schematic of the configuration of a buried coil gauge. Here the electromagnetic coil covers the base and banks of the section, up to bank full level. The coil will typically consist of insulated multi-core copper cable using between 50 and 300 turns. The strength of the field produced by the coil depends on the number of turns and the electrical current applied to it. According to the British Standard somewhere between 200 to 1000 ampere turns are required to generate a measurable voltage, which approximately translates to a 300 turn, $4\text{mm}^2$ cross section copper conductor running a maximum current of 5A. The direction of the magnetic field generated by the coil is switched at regular intervals so that the induced voltage can be differentiated from electrical interference.

![Figure 4.3: Schematic of buried coil configuration](image_url)
In addition to the EM coil, the components making up the gauge include a pair of electrodes (one located on each side of the channel), the insulating membrane and water level sensor. A control unit, typically housed in a nearby gauge hut, is used to drive the coil and amplify and process voltage measurements.

Electrodes are typically made of stainless steel and may be covered by a filter to minimise oxidation, depending on whether the electrode is likely to contact foul water when the filter is not used (these often become blocked). Electrodes are usually mounted on guides on the walls or banks on either side of the channel, positioned centrally within the magnetic field. As they need to be in contact with the water at all times they are normally designed to extend through the whole depth of flow.

The insulating membrane covers the entire cross-section from bank to bank (it is usually at least 1.5 times the channel width). Heavy duty polythene is commonly used. The membrane must be sealed properly (especially on the leading or side edge) to protect against local scour and seepage. It is normally then covered in materials such as concrete, clay bricks or rock-filled gabions (metal reinforcements cannot be used within the channel). As they must be installed under dry conditions, installation of the coil and membrane almost invariably requires channel diversion.

### 4.2.3 Suspended coil configuration

Suspended, or bridged, coils are a cheaper alternative to buried coils, and are generally used where aesthetic effects are not important or where a buried coil would be impractical, such as where the stream profile has a complex shape or consists of two or more channels. They are widely used in artificial concrete channels. Figure 4.4 illustrates a typical suspended coil configuration.

![Figure 4.4: Schematic of suspended coil configuration](image-url)
Whilst the coil is supported above the channel, the principles of operation are similar to the buried coil, and the stream still needs to be insulated from the channel bed. In many cases the insulating membrane is incorporated into preformed concrete sections that are used to line the channel and support the coil.

4.2.4 Field calibration of buried and suspended coils

Buried and suspended coils both need to be independently calibrated in the field. The need for this calibration process arises from the fact that the $k$ term in Equation (4.5) – the parameter of the relationship between the discharge and stage, probe voltage and field strength – is site-specific. However, calibration of EM gauges is not straightforward. There are several reasons for this.

Independent discharge measurements are usually obtained by current metering, although techniques such as ADCP can also be used. However, since the justification for the EM gauge is typically the difficulty of current meter gauging, it is usual to observe large bias or scatter between the EM measured discharge and the current meter discharge.

Furthermore, Equation (4.5) assumes that a uniform magnetic field is maintained across the cross-section. In reality the magnetic field tends to decrease with vertical distance from the plane of the coil. For a buried coil the magnetic flux density will thus be greater near the bed than near the water surface, whereas it will be greatest nearer the surface for a bridged (surface) coil. This creates a strong magnetic gradient through the channel, which will be especially marked where the channel is deep relative to its width. In other words, the potential difference measured is not independent of the stage, and independent calibration over a wide range of flow conditions is required. To account for the variation in magnetic field strength with depth, the guidance in BS3680:1992 (part H) suggests a calibration which involves fitting a quadratic equation similar to the following

$$Q_o = \left( K_1 + h - K_2 h^2 \right) \cdot \frac{V}{B}$$

(4.6)

where $Q_o$ is the independent observation of discharge at the gauge, $h$ is the stage (m), $V$ is the measured potential difference between electrodes located on channel banks (mV), $B$ is the average magnetic field strength (Am$^{-1}$) and $K_1$ and $K_2$ are empirically derived constants.

Additional uncertainty arises in determining the zero datum of water depth, and because devices tend to register a voltage even when the water has zero velocity. Ewan Associates Ltd (1999) describe these problems in more detail. To account for these additional problems complex calibration procedures have been carried out in the past. The calibration procedure currently employed by the Agency requires a lengthy optimisation of five constants in the relationship

$$Q = K_1 \cdot \frac{K_2 \cdot V}{C} \cdot [K_3 + (h + K_5) + K_4 (K_5 + h)^2]$$

(4.7)
where $Q$ is the discharge, $h$ is the stage above zero datum, $V$ is the measured voltage between electrodes, $C$ is the coil current (used to represent the average magnetic field strength). The parameters $K_1$ to $K_5$ are defined as follows:

- $K_1$ is a factor relating to the gauge design.
- $K_2$ is a voltage offset applied to the $V$ parameter.
- $K_3$ is a zero datum of water depth offset applied to the $h$ parameter.
- $K_4$ is a multiplier for the $h^2$ term.
- $K_5$ is an offset applied to both the $h$ and $h^2$ terms.

It can be very difficult to derive optimal values for each of the five calibration parameters, particularly as there are only three independent variables. This approach can lead to greater uncertainty due to over-parameterisation, an issue that has been noted by others (e.g. Ewan Associates Ltd., 1999). It has been general practice to leave calibration procedures to the manufacturer. It should also be emphasised that if a gauge is characterised both by an unstable hydraulic control and by a significantly non-uniform electromagnetic field density, it may be impossible to determine a unique calibration for the site.

### 4.3 Sources of Uncertainty and Technical Issues

A number of temporally and spatially varying factors can influence the uncertainty associated with each measurement of flow made using a full channel EM meter. Much of this relates to the applicability of the calibration parameters over long periods of time. In order to ensure that uncertainties are kept to a minimum, a number of technical requirements should be considered during site selection. These are discussed later in the section.

In overall terms, uncertainties associated with EM coil gauges are at best likely to be between 5 and 15%. The British Standard suggests that a much better degree of accuracy can be obtained - a figure of 2% at 95% confidence interval is quoted. This figure does not seem to be based on the field performance of EM gauges.

#### 4.3.1 Variation in magnetic field

As discussed previously, magnetic field strength decreases with distance from the coil, unless enhancement plates are used. This means, for example, that for a buried coil the magnetic field will be stronger near the bed than at the water surface, which in deep channels can lead to the development of a strong magnetic gradient within the channel. Whilst the voltage measurement is an integrated one, the presence of such a gradient means that different depth portions of the channel will contribute differently to the voltage generated over the section as a whole. This will have little effect in a uniform channel having a small stage range, but in a non-uniform channel exhibiting a large seasonal variation in stage, such effect can prove significant. These effects can be minimised by making the coils much wider than the channel depth. As a result for narrow deep channels, the coil may have to be many times wider than the channel.
The magnetic field strength can also change over time in response to power fluctuations and changes in the Earth’s magnetic field. Proximity to heavily reinforced concrete and sheet piling may also distort the magnetic field and should be avoided if possible.

### 4.3.2 Electrical interference

Interference can arise from a number of sources, including the power supply unit. Electric railways, overhead power cables, radio transmissions and lightning are other major sources of interference.

Most interference can be filtered out at commissioning stage by tuning the amplifier to the same frequency as the stimulating frequency of the coil, thus enhancing the induced signal at the expense of the non-synchronous signal, which is usually many orders of magnitude greater than the induced signal. Particular difficulties arise if the interfering signal is large or if an interfering frequency is close to that of the coil, causing electrochemical signals between water and electrodes. The greater the interfering signal, the longer the integration period required to assess mean discharge; typically for rivers it is 15 minutes. Whilst potential interference can be checked before and during commissioning, there is no guarantee that future unrelated developments (e.g. power lines) will not occur close to the gauging station, thereby affecting the performance of the station and requiring recalibration.

The Earth’s magnetic field and electrolytic effects of the electrodes in the water also cause interference. This is overcome by regularly reversing the coil field (by reversing the current direction). Measurements are taken with the field in one direction and then the other.

### 4.3.3 Membrane integrity

It is essential that the integrity of any insulating membrane is maintained. For example precautions must be taken if there is a risk that bank or bed erosion might undermine the membrane. If the membrane were to become damaged, this would usually be evident in the voltages measured.

### 4.3.4 Velocity and stage – discharge relationships

Iredale (2002) quotes a minimum operating velocity of approximately 0.03 ms⁻¹. Lower velocities are unable to generate voltages that can be clearly delineated from background noise, although in some cases this can be compensated for by increasing the strength of the magnetic field.

Whilst EM gauges are, theoretically, tolerant of conditions in the channel, a significant variable backwater can lead to serious difficulties during gauge calibration, particularly if there is a strong variation in magnetic field strength with depth.

### 4.3.5 Salinity variations

The calibration coefficients hold true only where the conductivity of the water remains constant over time and space. This means that the EM method is not well suited to channels where water quality might change over time (e.g. tidal systems, or locations downstream of a waste water discharge outlet) or that are poorly mixed (e.g. saline over freshwater stratifications).
Changes in conductivity manifest as slowly changing voltages between the electrodes. Such changes will bias the amplifier stages of the electronic system. Water conductivity must be measured constantly in order to correct for these effects. Thermal stratifications will not, in general, affect the measurement process.

4.3.6 Siltation

Although the method is said to be unaffected by siltation, build up of silt may affect the calibration – saturated silts and muds on the channel bed provide an electrical pathway that does not contribute to the effective area of flow. The impact is greatest at low flows where the depth of silt may be large relative to the depth of flow. For instance Iredale (2002) quotes check gauging results that show strong differences between the EM and spot gaugings during periods of low flow, and also indicates that stations with a sustained base flow and water depth, such as those draining chalk catchments, tend to produce more comparable results with check gaugings.

4.3.7 Weed growth

Whilst EM gauges are, theoretically, tolerant of conditions in the channel, gauge performance may decrease if there is significant weed growth in the channel. Weed can contribute to non-linear stage-discharge relationships, prevent electrodes making clear contact with the water column and reduce the accuracy of current meter check / calibration gaugings.

4.3.8 Out-of-bank flows

An EM gauge will only measure flows passing through the vertical magnetic field generated by the coil. This means that serious error in measurement will occur if, in extreme flood conditions, the water level exceeds the upper limit of the membrane. Two factors are involved:

- For flows outside the planned shape of the coil, the lines of flux are oriented in the opposite direction, giving a negative contribution to the measured flow.
- The induced flow signal may be shorted through the ground, resulting in a reduced signal.

Both these factors lead to high errors in the overall flow calculation during periods of extreme flows. This loss of extreme flow records is a serious limitation and if full range flow calculation is desired, careful selection of the site is required to ensure it is not bypassed.

4.3.9 Other uncertainties

The experience of using full channel EMs in England and Wales has highlighted a number of problems with EM gauges for which there seems to be no physical explanation. Iredale (2002) evaluated the performance of a number of EM gauges, in relation to check gauging, and observed a number of seasonal and step changes at various sites for which no explanation could be found. For example he quotes a clear repeated seasonal shift of some 20% in the EM/current meter relationship for a gauge site on the River Ryton at Blyth.
Whilst these uncertainties have been limited to a small number of EM gauges used in England and Wales, the absence of a clear explanation has proved disquieting for those managing the stations. This has led to a general, and perhaps unwarranted, distrust of EM meters in the hydrological community.

### 4.3.10 Technical requirements

In order to minimise sources of uncertainty, the measurement site should be selected carefully. The main technical requirements of a good measurement site are summarised below. A fuller discussion can be found in the British Standard for full channel width EM meters (BS 3680, part H).

- The site should be a straight reach with opposite banks parallel. The bank-to-bank profile should be near horizontal.
- The channel should ideally be straight for 5 to 10 channel widths upstream and 1 to 2 channel widths downstream of the measurement section. Newman (1982) suggests that the approach channel should be straight for at least ten times the river width, although some manufacturers suggest that a much shorter approach channel would be sufficient.
- A constant cross-sectional area and shape over the upstream and downstream extent of the measurement section is desirable. The method is better suited to rectangular or trapezoidal channels. The channel bottom should be stable or easily monitored for variations.
- There should also be suitable channel aspect ratio, as the technique is not suited to narrow, deep channels, where the magnetic field strength can change significantly over the range of stages observed.
- There should be no salinity gradients; the method is not suitable for use in estuaries or tidal systems.
- The gauge cross section should not be bypassed at high flows. If out-of-bank flows occur embankments may be needed to contain the full range of flows to be measured.
- The gauge should be sited away from potential sources of electrical interference. It needs to be at least 100m away from power cables and electrical railway lines, and several kilometres from radio transmitters.

### 4.4 Practical and Resource Considerations

As has been discussed over the previous sections EM meters are able to measure flows under a variety of channel conditions. The main sources of uncertainty include interference and calibration procedures. However a number of practical, economic and environmental constraints may preclude the use of the EM meters at some sites, even though the method might be acceptable in a technical sense. These include:

- availability of services and access,
• impact on local environment,
• capital expenditure,
• design life and data capture rate,
• data archiving and reprocessing,
• initialising, calibration and staff training,
• maintenance requirements,
• health and safety,
• availability of standards and legislation.

4.4.1 Practical constraints on site selection

Services and access
EM gauges are powered via mains electricity. The gauge site therefore needs to have connections to mains electricity or a capacity for a permanent on-site generator.

If telemetry is to be used, the site must either have connection to the landline telephone network, or be located in an area having suitable mobile network coverage.

Good site access is a vital consideration in site selection due to the engineering works required during installation. There must also be space to allow a diversion channel to be constructed.

The site must also provide a suitable environment and housing for processing units and so on.

Channel width
EM meters are an impractical choice for very wide channels. A maximum channel width of around 7m is normal for use of suspended coil systems. Although in principle buried coils could be used in very wide channels, in practice the maximum channel width is 30 to 40m.

Debris
In channels where debris is extremely problematic, extra precautions may be required to ensure that the insulation membrane is protected from damage.

Risk of vandalism or disturbance
Vandalism can be problematic where suspended coils are used. Buried coils are much less susceptible to vandalism.

Ice
Instrumentation will continue to operate correctly even where surface ice affects the site, although in very cold conditions the electronic systems may start to fail (BS 3680 quotes the operational range between –10°C and 50°C). However surface ice is likely to compromise level measurement at the site, even where a stilling well is used, and can also damage instruments physically.
4.4.2 Impact on local environment

Ecology, habitat and migrating fish
Once installed EM instrumentation has negligible detrimental effects on habitat, ecology or migrating fish.

Visual intrusion
Suspended coils can be visually intrusive. There is little visual intrusion where buried coils are used.

Disturbance during installation
Disturbance during installation can be severe. Buried and suspended coil meters invariably require channel diversion, as the membrane has to be installed ‘in the dry’ and will involve some bank reconstruction. This can lead to large amounts of engineering works, disruption to amenity and, potentially, damage to the local ecology.

4.4.3 Feasibility study

Assuring the technical feasibility of the method at the proposed site is an important, time consuming and potentially costly aspect of procuring a new site. This should focus on the channel geometry and stability, with a programme of measurement to look at variability of stream parameters. For EM meters this programme must specifically include:

- Field survey for sources of electrical and radio interference.
- Conductivity survey

The feasibility study will also look at environment issues, and in some cases a formal Environmental Impact Assessment (EIA) may be required.

4.4.4 Capital expenditure

Costs can be divided into two main groups - capital expenditure and maintenance/operations costs. Here feasibility, design, instrumentation, utilities, installation and commissioning are considered as contributing to the total capital cost. This would also include any compensation and legal costs, and land purchase or lease if required.

Total capital costs can vary substantially depending on the size of the watercourse and complexities of the site. Including installation costs, total capital expenditure for EM gauges is likely to range between £300,000 and £500,000. For example a 30m wide buried coil meter installed on the River Severn at Yoxall in 1995 cost around £350,000 whilst total capital costs for installation of buried coil on the River Devon at Cotham were more than half a million pounds.

Feasibility study cost
The initial costs associated with a feasibility study are around £2,000 to £6,000. However an EIA, if required, can add around £20,000 to the total costs. For buried coils a geotechnical site investigation is also a likely requirement. For example, at Cotham site investigation costs were of the order of £11,000.
Design cost
The design requirements will, of course, depend on the site. Typical costs are between £30,000 and £40,000.

Instrumentation cost
Instrumentation costs include the EM coil, electrodes console unit, cabling, loggers, construction of the housing (hut) for console unit and so on. The costs associated with the membrane are usually considered as part of the construction costs.

Instrumentation costs are typically small compared with construction costs for EM gauges. The cost of the Thermo EM was around £30,000, although this product is no longer available.

Utilities cost
Utilities include telemetry, electricity and back up power. Costs include installation of a new BT line, connection to the electricity grid, and cost of back-up generator and/or batteries. For sites where there are no opportunities for connecting to utilities, the site should be entirely self-sufficient, which may require solar panels and mobile phone links. Costs will typically be around £10,000 to £15,000.

Installation / construction costs
Construction costs are extremely high for EM gauges, amounting to several hundred thousand pounds in many cases - around 70% of the total costs. For example the cost of civil engineering works associated with installation of the buried coil at Cotham was around £300,000. A large proportion of such costs may arise from channel diversion, and the geomaterials used to protect the coil and membrane.

Commissioning and calibration costs
EM meters require specialist calibration, which can be costly. Detailed survey of cross section may be required for calibration purposes, if this hasn’t already been undertaken at feasibility or design stages.

4.4.5 Routine (maintenance and operational) costs
Child et al. (2001) report total maintenance costs of the order of £1500 per year. A large proportion of this cost represents fees by specialist contractors or manufacturer for maintenance of electrodes, and periodic re-calibration.

Maintenance of additional equipment, such as telemetry, might typically cost between £200 and £600 per annum.

4.4.6 Design life, data capture and data processing
Many EM gauges have been in place for a number of years, indicating that a design life of at least 20-30 years can be assumed. However a number of practical problems at EM gauging stations are now arising due to the age of the electronic technology, especially for data entry and storage of calibration constants. With the ageing 8-bit processor used, there are limited number ranges and as a result calibration constants have to be converted to a machine compatible format. Along with the complexity of deriving the K coefficients, the practice has been for Regions (with the exception of Midlands) to leave the calibration changes to the manufacturer. Whilst a modern redesigned EM gauge
would avoid such problems, there is currently no development occurring that would enable existing gauges to be altered.

Major equipment failures have been very limited. There have been no reported failures of coils or membranes. In the past data have been lost as a consequence of the failure of fuses, but this problem seems to have been eliminated. Iredale (2002) reports that data loss has been greater for EM gauges than for other types of gauging station. A data capture rate of between 95 and 98% can be expected for EM gauges compared with >99% for structures.

4.4.7 Routine maintenance, operational issues and performance checking

The electronic systems used in EM gauges require specialised maintenance. Maintenance will generally involve either repairing any faults or deterioration in the equipment that might potentially impair the operation of the gauge, or checking the device after spurious data have been collected. For example, cleaning of probes is required at least annually to prevent corrosion of electrode terminations caused by ingress of water.

It may be necessary to visit the site following vandalism or power failures, to clear known obstructions in the channel, or after periods of silt build up. For example the British Standard suggests that routine visits should be made every six months or more frequently, ideally coinciding with times of extreme conditions such as after flood events.

Performance checking (audit) usually involves taking a limited number of check gaugings throughout the year. The number of performance checks required on an annual basis will depend on the perceived performance of the device. Current guidelines for good hydrometric practice (Child et al., 2001) suggest that between one and twelve check gaugings may be required per year. A further programme of gauging may also be required if it is felt that there is a need for recalibration.

4.4.8 Staff training

The availability of properly trained staff can make all the difference in the use of the technique. This refers to staff trained in calibration techniques, technicians able to maintain the instrumentation and operate the instrument control system, staff able to operate data management software as well as staff who can interpret the measurements and appreciate factors that might affect the quality of the gauging station data.

Training issues include the availability of training from manufacturers or the possibility of in-house training, the number of staff to be trained, cost and availability of manuals and so on. Training costs can, therefore, vary considerably depending on which make and model is used.

4.4.9 Health & safety

Health and safety implications depend on site as well as method. The major health and safety risk specifically associated with EM gauges is the risk of electric shock.
4.4.10 Standards and legislation

Buried and suspended coil gauges are covered by British Standard BS3680 part 3H (this standard does not specifically cover slab sensors, although many of the issues discussed will be relevant).

4.5 Slab Type Electromagnetic Devices

4.5.1 Principles of operation

The full channel width EM meters currently used in the UK were designed in the 1970s. Since that time a wide array of technologies based upon magnetic induction have been designed for flow measurement in closed pipes. These methods have recently been adapted for use in open channels and are being used in a number of waste water applications.

ChannelMag (this is a trade name of a patented design) is one such device. This device consists of a flat bed magnetic flow sensor (this incorporates both electrodes and the EM source coil) that is fixed to the bottom of the channel. The magnetic field is produced using a pulsed AC power supply and is much stronger than might be generated with traditional DC coils (for instance coils are usually energized with between 1 to 5 Amps at a frequency of 40 Hz). The sensor sits within a cradle of steel ‘enhancement’ plates that line the side and base of the channel (these are prefabricated to the dimensions of the channel). This ensures that the magnetic field is uniform over the entire cross-sectional area, and does not vary depending on the stage.

Figure 4.5 shows a schematic of how a ChannelMag might be installed in an existing channel. In this case the channel is narrow, so that a single plate is used, but for wider channels a series of plates can be used in parallel.
The sensors stand a few inches off the channel bed, so that ramps are used to reduce any turbulence that might result. It is also possible for these sensors to be installed in a recess in the floor of the channel so that they are flush with the bed. For this particular product, the whole set-up, including sensor(s), plates and any level sensors are pre-calibrated prior to installation in a long tow tank over the required velocity range. The discharge is then calculated using Equation (4.8)

\[ Q = K \cdot V h^n \]  

(4.8)

where \( K \) is the calibration constant and the exponent \( n \) depends on the shape of the channel. As the magnetic field is extremely strong, the device claims a high signal to noise ratio and does not require any field calibration. The ChannelMag device is certified by the USA National Institute of Standards and Technology.

### 4.5.2 Practical and resource considerations

Slab type EM meters are obviously better suited to artificial concrete channels that are regular in shape, but could, potentially, be installed onto bedrock if conditions allowed, or between the wingwalls of existing weirs. In such channels slab meters offer a very accurate method of flow measurement. It is worth noting at this point that, in ideal conditions, slab meters using enhancement plates can be considered to be inherently more accurate than buried or suspended coils, and are less susceptible to many of the sources of noise that affect coil gauges. For example the manufacturers of the ChannelMag device claim that accuracy of ± 2% is achievable for stream velocities greater than 0.6 ms\(^{-1}\). However due to sedimentation, weed growth and bed movement, slab type meters are not generally appropriate for use in natural channels.

Other practical considerations include the requirement for drainage of the channel prior to installation, and power requirements (an AC power supply is generally required). In addition the ChannelMag is typically suitable only for channels up to 6 m wide and 3.6 m deep, having a minimum of seven straight channel widths upstream and two straight channel widths upstream.

Advantages of slab-type meters include the relatively low capital costs and ease of maintenance. Instrumentation costs for the ChannelMag range from £5,000 to £40,000 depending on the channel widths to be covered – this figure includes the sensor, enhancement plates and ramps.

### 4.6 References


5 ACoustic (ultrasonic) Transit Time Method

5.1 Introduction

Acoustic transit time methods involve measuring the time taken for a sound pulse to travel between ultrasonic transducers arranged on opposite banks of a watercourse. The transit time is used to calculate the streamflow velocity and hence the flow. The instrumentation operates using sound in the ultrasonic range (i.e. at frequencies of 15kHz and above) and it is often called an ‘Ultrasonic Velocity Meter’ (UVM).

In a uniform and stable cross-section the transit time method can work reasonably well using a single offset pair of transducers to estimate water velocity along a single diagonal path through the water column. Provided assumptions regarding spatial variation in velocity within the channel and cross-sectional area are valid or that the system is adequately calibrated against independent discharge measurements, path velocity can then be related to the flow rate through the watercourse. In non-uniform natural channels multiple path UVMs are generally required. These use a series of transducer pairs, arrayed in the vertical, enabling the vertical velocity profile to be better characterised and providing more accurate estimates of mean velocity (and discharge) in the cross-section. It is generally accepted that, if used appropriately, transit time methods can provide hydrometric measurements of equal or better accuracy than open channel ratings (Melching & Meno, 1998), particularly where multi-path configurations are used.

Transit time devices can be operated over a wide range of flow and channel conditions, including periods of low flows, highly unsteady flows, variable backwater and surface ice, in both natural and canalised channels, large rivers and small streams. They thus lend themselves to continuous measurement and can be readily established as permanent gauging stations. For these reasons UVMs have a relatively long history of use in the UK gauging network, starting with the trials of single path devices in the 1960’s. Installation of transit time devices has particularly increased over the last ten years and there are now more than 100 UVM gauging stations in the UK. Figure 5.1 shows a typical multi-path UVM that was recently installed in Northeast Region.

The total costs involved depend on the size and method of installation, ranging from a few thousand pounds for a single path unit, to around three hundred thousand pounds for a large multi-path array. However in some countries, such as the USA and The Netherlands for example, transit time devices are being superseded by Doppler instruments, which are generally cheaper and more versatile.

This chapter discusses factors affecting the performance of acoustic transit time instruments, drawing upon studies reported in the scientific literature, product specifications and users’ experiences. The constraints to be overcome if such instruments are to operate to British Standard (BS 3680:1993, Part 3E) are considered. Other practical and financial considerations are also discussed.
5.2 Principles of Operation

5.2.1 Basic theory

The fundamentals of the transit time method are generally covered in modern hydrology texts (e.g. Herschy, 1999). Laenen (1985) gives a definitive description of the methodology as applied to natural streams. Guidelines for best practice in use of transit time instruments in open channels are given in ISO 6416:1992 and the corresponding British Standard BS 3680:1993 (Part 3E).

The transit time method relies on accurate measurement of the time taken for an ultrasonic sound pulse to travel between two reference points diagonally transecting a watercourse. This transit time depends on the distance travelled and the propagation speed of the sound pulse. In flowing waters the orientation of the traverse relative to the direction of water movement and the stream velocity are additional factors. The total transit time is therefore shorter if the traverse is oriented downstream (i.e. pulse travels in the direction of flow), but longer where the traverse is oriented upstream (opposes the flow). Figure 5.2 illustrates how the method applies to a single transect (path), although the same principles are equally valid for a multi-path arrangement.
In Figure 5.2 the reference points, A and B, at either end of an acoustic ‘flight path’, are located on opposite banks of the watercourse. Transceivers (transducers able to both transmit and receive signals) are located at A and B. These are positioned so that the path between them creates a submerged diagonal transect across the river, at a fixed elevation in the vertical (here transducer A is the most ‘upstream’ of the pair). This path thus intersects the mean direction of flow at an angle of between 30° and 60° depending on the configuration. Stage is determined from a separate water level sensor (a down-looking ultrasonic level gauge is shown in Figure 5.2, but this could equally be a stilling well, or pressure transducer).

A sound pulse is emitted from the transceiver at A to be received by the transceiver at B, and vice versa. In each case the transit time, $t$, depends on the distance travelled along the path, $L$, and the average pulse velocity. If there was no water motion the average pulse velocity along the path between A and B would be equal to the speed of sound in water, $c_p$. However the downstream movement of water through the channel exerts an additional force on the pulse so that its average velocity along the flight path is increased. The increase in velocity is related to the directional component of the mean water velocity that acts along the flight path AB, $v_{AB}$. The corresponding transit time between transducers A and B, $t_{AB}$, is therefore given by

$$t_{AB} = \frac{L}{c_p + v_{AB}} \quad (5.1)$$

However, where the pulse direction opposes the direction of flow, such as when travelling from transducer B to transducer A, the average pulse velocity is lower, even though the path length is unchanged. The transit time, $t_{BA}$, of a sound pulse travelling between points B and A is therefore calculated as follows:

$$t_{BA} = \frac{L}{c_p - v_{AB}} \quad (5.2)$$
where $v_{AB}$ is the component of mean water velocity acting along the acoustic flight path AB, $c_p$ is the mean propagation speed of the acoustic pulse, $L$ is the length of the acoustic flight path AB, $t_{AB}$ is the transit time taken for the pulse to travel from transducer A to transducer B (not opposing the direction of flow), and $t_{BA}$ is the transit time from transducer B to transducer A (opposing the direction of flow).

Combining Equations (5.1) and (5.2) to eliminate the parameter $c_p$ gives the mean velocity along the acoustic flight path in terms of transit time and path length only:

$$
\bar{v}_{AB} = \frac{1}{2} \left( \frac{L}{t_{AB}} - \frac{L}{t_{BA}} \right)
$$

Eliminating the propagation speed, $c_p$, in Equation (5.3) avoids having to account for the effects of fluctuations in the speed of sound caused by spatial changes in water density within the cross section (the speed of sound in water can vary between about 1400 and 1500 ms$^{-1}$ depending on temperature and salinity).

5.2.2 Single path configurations

Single path

In the single path configuration (Figure 5.3) the estimate of velocity along the acoustic path, $\bar{v}_{AB}$, is resolved to provide an estimate of the velocity parallel to the mean direction of the flow in the channel, $\bar{v}_d$. This requires the angle of intersection, $\phi$, between the path and the mean direction of flow (which may not be parallel to the banks of the channel) to be known accurately.

Thus the mean velocity $\bar{v}_d$ at elevation, $d$, can be determined from

$$
\bar{v}_d = \frac{\bar{v}_{AB}}{\cos \phi}
$$

(a) (b)

Figure 5.3: Single path arrangement (a) in plan and (b) in cross-section
In a uniform channel the path angle can be calculated via trigonometry based on the path length, $L$, and channel width, $b$, according to

$$\phi = \sin^{-1} \frac{b}{L}$$  \hspace{1cm} (5.5)

where $\phi$ is the angle between the mean direction of flow and the acoustic flight path. Combining Equations (5.3) and (5.4) gives the velocity in the mean direction of flow in the channel as follows:

$$\bar{v}_d = \frac{L}{2 \cos \phi \left( \frac{1}{t_{AB}} - \frac{1}{t_{BA}} \right)}$$  \hspace{1cm} (5.6)

This means that the component of the path velocity acting in the mean direction of flow at elevation $d$ can be determined simply by measuring the travel forward ($t_{AB}$) and reverse ($t_{BA}$) transit times, provided that the distance between the two transducers and path angle are known. Sources of uncertainty in this particular include:

- Errors in measurement of the diagonal and lateral distance between transducers. These depend on the accuracy of surveying.
- Uncertainties in determining the point of arrival of the received pulse at B and measuring the transit time of the pulse between A and B. These depend on the level of signal attenuation and interference taking place in the channel. These issues are discussed further in Section 5.3.
- Uncertainties associated with the assumption that the path lengths $L_{AB}$ and $L_{BA}$ are exactly reciprocal - the distance travelled by the pulse may exceed the distance between transducers due to ray bending effects caused by density gradients in the channel. These issues are also described further in Section 5.3.
- Uncertainties in determining the angle between the mean direction of flow that may not be parallel to the banks of the channel, and the acoustic flight path. These can be minimised by using a crossed path configuration, as discussed below.

**Crossed path configuration**

Profile shape and bed geometry can influence the direction of the main current in the channel. The assumption that flow is parallel to the banks cannot always be maintained, particularly when the effects of complex channel geometry exceed the normal control of main direction from the banks. In such cases it may be difficult to determine the path angle, $\phi$, adequately. Errors in computation of the path angle may introduce large errors in computed velocities, especially where the path angle is large. For example a 1° error in path angle will result in a 3% error in velocity where the path angle is 60° but only a 1% error in velocity where the path angle is 30°. Newman (1982) quotes errors between –16 and +19 % (depending on the skew direction) where the true angle, $\beta$, is 50°, and the ‘assumed angle’, $\phi$, is 45°.

The problem may be reduced by using a ‘cross path array’. In this situation twin pathways laid out in a cross configuration are often used (Figure 5.4). This allows...
velocities for each path in the crossed pairs (i.e. AB & CD) to be compared. If cross velocities are equal it can be assumed that the assumed path angle used is correct (i.e. \( \phi = \beta \)). If the cross velocities are not equal the angles involved can be back calculated as described in BS3680.

Figure 5.4: Crossed path arrangement

Responder configuration
The single and crossed path configurations require hard-wire cross-channel links between the transducers. In cases where it is difficult to install cross-channel cables, for example where the channel is very wide, a responder adaptation may be used instead (Figure 5.5a). In this case reception of an acoustic pulse at transducer B triggers the transmission of a pulse along path DC. Pulses are then sent from each side in a continual pattern (Laenen, 1985). Responder arrays are, however, rarely used in practice. In a survey of UVM applications undertaken in 1996, Melching and Meno (1998) found that only 2% of UVMS used this type of configuration.

Figure 5.5: (a) Responder and (b) reflector configurations
Reflected path configuration
Where it is not possible to install transducers on both banks or where a responder adaptation is not desirable, a reflector design may be considered. In this case transmitting and receiving transducers (A and A’) are located on the same bank, separated by a distance, S, as shown in Figure 5.5b. The sound pulse is bounced using a passive reflector situated on the opposite bank. This system has the advantage that the main and reflected beams make different angles to the direction of flow so that errors caused by skew or cross flows are cancelled out. The mean channel velocity is then determined as follows:

\[
\bar{V}_d = \frac{L_R}{2S} \left( \frac{1}{t_{R2}} - \frac{1}{t_{R1}} \right)
\]

(5.7)

where \(L_R\) is the total length of the reflected flight path (i.e. \(L_{AR} + L_{RA'}\)), \(S\) is the separation distance between transducers A and A’, \(t_{R1}\) is the total transit time from transducer A to transducer A’ via reflector R on the opposite bank, and \(t_{R2}\) is the total transit time from transducer A’ to transducer A via reflector R on the opposite bank.

The reflector usually consists of a length of polished steel. Use of a corner (angled) reflector allows for small errors in the alignment the reflector (for flat reflectors the alignment is a critical factor in receiving a strong signal). Reflectors also may need regular cleaning to maintain their reflective properties. Unfortunately the reflector arrangement can be affected by signal scattering, and is appropriate only for narrow channels, typically less than 20m in width (Newman, 1982) and Melching and Meno (1998) found that reflectors were being used in only about 8% of cases. The British Standard (BS 3680, part 3E) gives further detail regarding reflector design and use.

5.2.3 Determination of discharge and calibration requirements for single path configuration
In common with several other non-invasive methods for gauging stream discharge, the rate of flow \(Q\), across the gauge cross section, is determined by combining the estimate of depth-averaged mean flow velocity \(\bar{v}\) with information regarding wetted cross sectional area, \(A_W\), the latter being dependent on the water depth, such that

\[Q = \bar{v} A_W.\]

(5.8)

Large uncertainties may be associated with both wetted area and mean velocity determination.

Cross sectional area estimation
The cross sectional area available for flow, \(A_W\), is usually calculated as a function of the stage, \(h\). The accuracy of this estimate depends on the accuracy of stage measurement and the uncertainty in the \(h\) to \(A_W\) rating used, the latter in turn dependent on the quality of survey of cross section geometry, the stage range covered by the calibration data, and the stability of the cross-section profile over time.

Mean velocity estimation
The single path \(\bar{v}_d\) estimate can be taken as a good approximation to the mean channel velocity (\(\bar{v}\)) in very few situations. This might occur in a uniform concrete channel.
having a minimal variation in stage over time and a constant vertical velocity distribution, where the path was located a depth known to correspond to the mean flow.

For most sites it is impossible to fix a single path height that remains representative over a wide range of stage and flow conditions, particularly where channel geometry is complex (there also has to be a minimum clearance distance from the channel bed and water surface to avoid interference effects caused by boundary reflections). Rather, the relationship between $\bar{v}_d$ and $\bar{v}$ will depend on the vertical profile of velocity during the measurement, which in turn depends on the stage. A theoretical velocity distribution, commonly a logarithmic profile, may be assumed in order to determine how an estimate of $\bar{v}_d$ might deviate from $\bar{v}$ with changing stage. In most natural watercourses conditions may depart from the assumed profile, so it is usually necessary to establish an empirical rating between $\bar{v}_d$ and $\bar{v}$. Thus a calibration of the form

$$Q = f(\bar{v}_d)$$  \hspace{1cm} (5.9)

may be applied where $f$ is an empirically derived function based on calibration gauging at the site over a period of time. Calibration gauging should normally cover a wide range of flow conditions.

**Index velocity method for calibration**

If the acoustic flight path is fixed in the vertical, current meter gaugings must be used to independently calibrate the system. This will typically involve taking a number of gaugings along the plane of the transect AB (as shown in Figure 5.6) which are manipulated in the conventional way to compute mean channel velocity. A rating can then be developed using linear regression techniques to find the best-fit equation with the instantaneous mean channel velocity as the dependent variable, and stage ($h$) and the velocity along the acoustic path AB as the independent variables. The rating is used to derive a calibration factor that is a function of stage.

![Figure 5.6: Index velocity method for calibration](image-url)
The calibration should uniformly cover the expected range of stage and discharge. Whilst this is time consuming, it does compensate for any errors in the assumed path angle and path length. A disadvantage of the method is that it is vulnerable to errors in current meter gaugings.

**Self calibration**

For sites where the path elevation, \(d\), can be adjusted (or where, for example, a multi-path system is used as described in Section 5.2.4), self-calibration methods are acceptable. Self-calibration requires that, as the stage changes, the acoustic path is moved so that its elevation is that which gives the average velocity. This elevation will preferably be determined by empirical velocity–depth curves for a range of stage values or, if these are not available, by assuming a theoretical (logarithmic) distribution where the mean velocity horizon occurs at 60% of the depth (BS 3680). In this case the ratio \(\bar{v}/\bar{v}_d\) is related to the ratio between path height and total stage \((d/h)\) and used to build up a calibration where an instantaneous value of \(\bar{v}_d\) can be up-scaled to \(\bar{v}\) providing the stage, \(h\), and path elevation, \(d\), are known. Figure 5.6 illustrates this concept and shows the vertical velocity profile over which \(\bar{v}\) is integrated.

A number of variations on this theme are reported by Melching and Meno (1998), including

- Application of an area weight to the path velocities and computation of the weighted mean (used in France and the UK).
- Application of an area weight to the path velocities and additional correction factor to the velocities measures at the upper and lower paths (used in The Netherlands and Germany).
- Velocity measurements are made to relate each path velocity to the mean cross-sectional velocity individually (used in the United States).
- Application of an index velocity method wherein the average of all paths is related to the mean cross-sectional velocity determined from independent discharge measurements (used in the United States).

### 5.2.4 Multi-path configuration

For sites where cross-sectional geometry or vertical velocity profile are complex (for example where backwater effects are influential or where there is a wide seasonal variation in stage) it is unlikely that a single or cross path configuration will provide a very accurate estimate of mean velocity in the channel. This is because, even if well calibrated, a single path cannot truly take into account the velocity profile in the vertical. Better results can, however, be gained by combining velocities from paths located at two or more different elevations, as in the multi-path configuration. Using a multi-path array also allows for a level of backup in the system in the case of failure of one or more transducers. This principle of ‘built-in redundancy’ is often used when designing multi-path gauges – it is usual to specify more paths than optimal.

A typical arrangement would use four paths as shown in Figure 5.7 and Figure 5.8. However some instruments offer up to 36 paths depending on the channel characteristics and accuracy required. Others use fewer paths but increase the number of
velocity measurements along each path by using multiphase signals (the phase change as the signal propagates along path AB can also be used to derive independent estimates of path velocity and can be measured simultaneously to the travel time). Crossed paths may be included, particularly if skewed flow is likely. These do not have to cross at the same levels as the main paths, and in fact can be interleaved equidistantly between them—this has the potential advantage of increasing the resolution with which the vertical velocity profile is known, provided that the vertical component of any velocities vectors is not great.

Note that the increase in accuracy of a multi-path system is not necessarily proportional to the number of paths used, but the more paths that are used the better the definition of the velocity profile and the less overall uncertainty. Transducers will typically be mounted in arrays as shown in Figure 5.7. Transit times along individual paths are measured in sequence, usually starting at the transducer pair nearest the bed and continuing up to the uppermost path.

Figure 5.7: Multi-path arrangement based on four vertical pathways

As stage changes, the validity of measurement along particular paths will change. Some paths will essentially ‘drop-out’ of the system as they become ‘dry’ (e.g. path AB in Figure 5.7), whilst results from others may be abandoned as their vicinity to the surface imparts high levels of interference. To gain best results may require a compromise between ‘capturing’ velocities in the upper part of the section to better measure high flows, and having a large number of redundant paths at other times when water level is lower. Velocities close to the channel bed or water surface cannot be measured because of acoustic interference caused by signal reflection. BS 3680 (part 3E) offers guidance as to the minimum elevations of the lowermost and uppermost paths. Note that the lowest path need not necessarily be parallel to the other paths, and can be angled to take account of the asymmetrical bed shape.
The measurements can be used to reconstruct the velocity profile (in the vertical), which can then be numerically integrated over the (wetted) cross-sectional area to determine the discharge through the section. Alternatively the cross section can be divided into a number of slices or panels delimited in the vertical by the acoustic paths. Discharge is then determined for each panel based on the appropriate travel time measurements and the panel discharges summed to produce an estimate of the total discharge through the section.

This procedure is illustrated in Figure 5.8. Here panels are taken as the area between two paths and each panel velocity is based on the mean of paths delineating upper and lower panel boundaries. An equivalent approach defines panels as being delineated by boundaries mid-way between two flight paths, thus a single flight path velocity is used to calculate the panel velocity. The velocity derived for the lower most path will be an overestimate, as drag effects along the channel bottom are not accounted for. Ideally an empirical weighting factor, derived by calibrating against current meter gaugings, should be used to modify the velocity estimate for the lowermost panel. In practice the weighting factor is often standardised – typically a value of around 0.8 is used in Britain.

\[ Q_{\text{panel}} \propto \frac{V_{IJ} + V_{MN}}{2} \cdot A_{\text{panel}} \]

**Figure 5.8: Determination of discharge for multi-path configuration**

### 5.2.5 Instrumentation

The instrumentation required to set up a permanent gauging station using the transit time technique will include an electronic control unit, transducers and mountings, recording device and power supply. Multi-path arrays are usually mains powered (with backup batteries), but smaller gauges are typically battery powered using a 12v system. An independent water level device will also typically be installed at the site. Telemetry equipment will be needed if the site is to provide real-time data.

**Control unit**

The electronics of the system are controlled by a computer processor housed in a console unit, which will also determine the operating sequence, process received signals and determine transit times and velocities. It will also generally perform some level of automated signal optimisation (for instance in most modern systems digital signal processing (DSP) techniques are applied). Allied with use of ‘smart-transducers’ this allows signal amplification to be controlled automatically depending on the channel...
conditions, so that optimum signal transmission is achieved with minimal manual intervention. The processor will also determine discharges, providing any ratings required have been programmed in.

**Transducers and signal measurement**
The acoustic signals are generated and detected using electro-acoustic transducers. In the transmitting transducer a voltage sent from the control unit oscillates a piezo-electric crystal, which in turn produces the pressure energy generating the ultrasonic wave. When received by the transducer on the opposite bank, the wave energy is converted back to a voltage.

Transducers are usually operated in a coherent manner, i.e. the sound is transmitted as encoded sound pulses using a carrier frequency appropriate to the distance to the receiving transducer. Usually the pulse will be damped burst, i.e. a number of periods of a sine wave (typically between 4 and 20 cycles). The pulse frequency and beam width both influence signal propagation and must be selected to suit the conditions in the watercourse and the target distance to the receiver. Typically the operating frequency will range between 200kHz and 1 MHz, and transducers designed to emit the pulse in a narrow conical beam with a beam width (half power point) of around 5° to 10° will be used.

Figure 5.9 illustrates typical transmitted and received signals, expressed as transducer voltages. The transit time is the time measured between the departure of the waveform from the transmitter (the spike) and the first point on the pulse arriving at the receiver. Whilst the time $t_{AB}$ is very small it can usually be measured fairly precisely using digital methods. An average travel time is derived on the basis of measurements taken over a few minutes (the measurement rate is typically about 50 to 100 times per minute depending on the pulse frequency) so that the influence of any fluctuations in transmission or momentary path failures are minimised.

![Figure 5.9: Travel time between transducer signals](image)

Figure 5.9 shows that the received signal has much smaller amplitude than that transmitted. This is primarily due to signal spreading effects (the signal spreads out in
cone shape), which means that transducer B intercepts only a small portion of the sound energy emitted from A, corresponding to that transmitted along the most direct route between them. This means that the signal energy is small which increases its vulnerability to noise (described further in Section 5.3).

**Transducer mountings**

The transducer mountings are an important aspect of the instrumentation. Transducers must be kept to the correct alignment and free of debris and silt or other damage. It is also important to ensure that there is no trapped air in front of a transducer. This is particularly important in the single path system, which will fail if either of the transducers becomes damaged. They must also be connected to the control unit by either overhead or submarine cabling. Typically they must be able to be lifted out of the water for maintenance.

A number of transducer mounting types are shown in Figure 5.10. Generally these are unobtrusive and cause no or little obstruction within the channel, and rarely present a Health and Safety issue. Transducers are often mounted on steel H-piles anchored parallel to the slope of the bank (a), as this approach is suitable for both single and multi-path configurations and allows for the possibility of adding further transducers at a later date. However where stream conditions are appropriate transducers may also be mounted on iron “tripods” standing on the stream bed if velocities are slow (b), or bracketed to the channel wall in fast flowing waters (c). The more recent mounting designs reflect the increased demand for instrument portability. It is also possible to mount transducers within vertical poles or tubes away from the bank as shown in a recent multi-path installation on the River Rede at Otterburn (Figure 5.11).

![Figure 5.10: Transducer mountings](image-url)
Recording and logging of data
As it is usually sufficient to log flows at a resolution of 15 minutes, there are two distinct modes of operation with regard to recording of data. Measurement can either be continuous, in which case an average of measurements made continually over a 15 minute period is taken, or periodic, in which case the system is set to power up every 15 minutes. The continuous system allows for transient loss of data (for instance if the beam is disturbed for a few seconds by a passing boat or debris) and where data accuracy is highly variable due to transient effects in the stream, but has much higher power requirements than the periodic system (and will drain batteries more quickly). In each case the data are either stored in a logging device, or if required in real-time fed into a telemetry system with a data logger as backup.

5.3 Sources of Uncertainty and Technical Issues

Much of the uncertainty associated with acoustic transit time methods relates to how the measured path velocities relate to the mean channel discharge, an issue that is generic to many non-invasive methods and which is discussed in more detail in Chapter 10. In overall terms, uncertainties associated with multi-path arrays, which measure velocities along a number of points in the vertical, are, therefore, much smaller than those associated with the single path approach. A particular difficulty associated with multi-path arrays is ensuring continuity and accuracy of low flow measurement, when only the lower most paths might operate.

The reliability of the method also depends on the accuracy by which the transit time (and hence velocity) can be measured along each path. Optimising signal transmission is a key element in this respect, as it is vital that the point of arrival of the received signal be identified correctly if transit times are to be accurate. Signal transmission can be improved by careful design of the system, for instance by setting signal characteristics such as frequency and beam width appropriately, by choosing sites where background noise is minimised, and by applying signal amplification (gain) techniques and sophisticated methods for signal processing. Where these major sources
of error are satisfactorily addressed by the system design, a high level of measurement accuracy can be achieved, typically around 5-10% where multiple paths are used.

5.3.1 Attenuation and loss of signal strength

As an acoustic signal propagates through the stream its strength gradually becomes diminished. A number of factors, including signal spreading and scattering, can contribute to signal attenuation. In extreme cases attenuation can prevent any signal from reaching the receiving transducer.

Signal attenuation may be reduced by transmitting signals at lower frequency (Laenen, 1985), but this can result in poorer resolution whilst increasing power requirements and instrument costs. Many modern systems have an ‘autogain’ facility that detects when the signal is deteriorating and temporarily boosts the signal.

Signal spreading
Signal spreading, which occurs because the signal is emitted as a conical beam, is the main influence on strength within the first 20 m or so, and causes a logarithmic loss in signal strength with distance travelled. It can be minimised by using narrow beam transducers, which concentrate the pulse into a beam width of between 5° and 20°, and siting transducers to ensure that the path angle is between 30° to 60°. If the paths intersect at an angle shallower than 30°, resulting in longer path lengths, the signal strength may become diminished. Conversely for path angles larger than 60° the difference in travel time between forward and reverse paths becomes small and difficult to measure, especially in slow moving streams.

Absorption (acoustic energy being converted into heat by friction between water molecules and sound waves) may also degrade signal strength. It primarily depends on water salinity and is lower for freshwater rivers.

Attenuation by sediment, bubbles and vegetation
Particles in the water, including bubbles, suspended matter, algae and vegetation, can also impede the signal by scattering and reflecting its acoustic energy. These scattering losses are usually the dominant cause of attenuation in natural streams, the effect being magnified where larger wave frequencies are used or where salinity is high.

Table 5.1 (taken from Laenen, 1985) gives tolerable concentrations of sediment for selected transducer frequencies and path lengths. Typical sediment concentrations in British rivers are rarely sufficient to cause significant signal loss, so long as a suitable signal frequency for given path length has been selected. Loss of signal most often occurs as a short term effect on the rising limb of a hydrograph (lasting until just after the flood peak) when suspended sediment concentrations are at their highest.
Table 5.1: Tolerable sediment concentrations (in mg/l) for transit time ultrasonic devices

<table>
<thead>
<tr>
<th>Transducer Frequency (kHz)</th>
<th>5</th>
<th>20</th>
<th>50</th>
<th>100</th>
<th>200</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>6300</td>
<td>1200</td>
<td>400</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>500</td>
<td>--</td>
<td>3500</td>
<td>1200</td>
<td>530</td>
<td>230</td>
</tr>
<tr>
<td>300</td>
<td>--</td>
<td>7900</td>
<td>2800</td>
<td>1300</td>
<td>560</td>
</tr>
<tr>
<td>200</td>
<td>--</td>
<td>11000</td>
<td>4000</td>
<td>1800</td>
<td>830</td>
</tr>
</tbody>
</table>

Aeration can have significant effects on signal strength. Bubbles cause much more attenuation than sediment particles of the same size, and ultrasound cannot propagate with even a small amount of bubbles in the water. For example Kasuga et al. (2003) showed that the noise from bubbles generated by three and a half minutes of heavy rainfall prevented propagation of an ultrasonic pulse for over two minutes. Similar effects occur in turbid conditions, e.g. in upland streams, downstream of spillways or storm overflows outlets, or during flood flows. Bubble resonance, which occurs if the diameter is the same as the wavelength, results in much increased attenuation, although the mechanisms for this are poorly understood at present.

Excessive weed growth can also cause attenuation of the signal and can ultimately lead to failure due not only to the weed itself but also to the air, which is integral to the plant structure or trapped in the foliage.

5.3.2 Signal noise

Background noise may be a major source of error in transit time measurement, as it may obscure the arrival of the ultrasonic signal at the receiving transducer. Signal interference and signal reflection are the main causes of background noise, although noise may also arise from electrical interference (e.g. from power lines or radio transmission). It is important to achieve a balance between signal strength and noise by keeping such effects to a minimum.

Interference

Boundary interference occurs when signal reflections (echoes) at the stream boundaries, such as the water surface or streambed, reach the receiver coincidently with the direct transmission causing it to be obscured, as shown in Error! Reference source not found. This situation is more likely the closer the transducer is to the reflective boundary and where the beam width is wider, and can cause gross inaccuracies in the measurement of transit time.
Reflections from the water surface are the primary cause of interference, particularly during calm conditions when a smooth surface enables a greater degree of reflection. Interference from the bed is usually a lesser problem as the rough bed surface favours absorption and dispersion of the signal, rather than reflection. Sandy sediments generally have the strongest reflective qualities; stoney beds tend to scatter the beam, whilst silty sediments or muds promote absorption of the beam.

In the case shown in Error! Reference source not found. the reflected signals are sufficiently displaced in time that they do not coincide with the signal along the direct path between A and B. This is because the distances between transducers and reflecting surfaces exceed a minimum clearance distance required to ensure a time difference equivalent to at least one wavelength. As a ‘rule-of-thumb, the clearance distance for a signal with carrier frequency of 500kHz should exceed $0.0274\sqrt{L}$. In practice a greater distance is often required to allow for obstructions on the streambed or temperature stratification. In shallow streams, or during low flow conditions in deeper rivers, the clearance distance for the lower most path is less likely to be achieved and boundary interference is likely to be higher, particularly where there is little turbulence and the water surface is smooth. For single path systems, siting of the path in the vertical is therefore critical if interference effects are to be avoided. Multi-path configurations are more flexible with respect to clearance distance, as where paths ‘drop-out’ of the system, transit time can usually be measured along the others.

### Signal refraction

Refraction occurs when the path of an acoustic pulse encounters a change in density, which causes a change in pulse velocity and direction as shown in Figure 5.13. This reduces the proportion of the emitted beam that is able to reach the receiving transducer and in extreme cases may prevent any signal from being received (i.e. failure).

Refraction effects also cause ‘ray bending’, that is they cause the acoustic path to deviate from a straight line. The transit times of signals affected by ray bending are extended, leading to an underestimation of velocity and bias in calculated discharge.

Signal refraction can occur where the water column is stratified, i.e. where there are strong temperature, salinity and suspended sediments gradients within the channel. It is therefore usually a problem in poorly mixed streams and in wide streams where even a very small beam deflection near to the transmitter can lead to signal failure.
Thermal stratification is a problem at some sites in the UK due to heating of the near surface layers of a cold water body. This can result in ray bending effects, and also lead to the development of spurious vertical velocity changes, both of which can cause measurement errors. Laenen (1985) represents the relationships between beam deflection, path length and temperature gradient in a useful graphical format. If a system using 5° beam width transducers were used, for example, a 0.1 °C/m temperature gradient occurring within in a 50 m wide channel would cause the centre of the beam to deflect by 0.3 m, whilst in a 200 m wide channel the same gradient would give a deflection of 5 m. In both cases some of the beam would still reach the transmitter, but for the wider channel the signal strength would be much reduced. In contrast a 1 °C/m gradient would cause the beam to deflect by 2 m in a 50 m wide channel and by several metres in a 200 m wide channel. As illustrated in Figure 5.13, such deflections would mean that the receiver would receive little, if any, of the transmitted signal.

Salinity gradients have a more pronounced effect on signal refraction, and in estuarine conditions are often large enough to prevent any reception of the pulse signal. Again useful graphs showing the relation between beam deflection, path length and salinity gradient are given in Laenen (1985). For example for a 50 m wide channel a salinity gradient exceeding 200 micromhos/m would produce a beam deflection outside the primary beam width.

5.3.3 Errors associated with triggers for transit time measurement

The most straightforward trigger for the transit time method is the point where the voltage of the received signal exceeds a threshold. Problems arise in this approach as the threshold must be set low enough to be surpassed by the arriving pulse but high enough to avoid being triggered by background noise. In some cases, for example where wave amplitude is reduced through attenuation, the measurement may trigger from the second rather than first pulse, which can cause serious errors if it affects, say, only the downstream ($t_{AB}$) but not the upstream leg ($t_{BA}$) of the measurement.

A number of checks can be used to identify if such problems occur; pulses must arrive within the expected time window (as judged from typical speeds of sound or from measurement along other paths), there must not be an excessive time difference between

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**Figure 5.13: Signal refraction at a density gradient**

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forward and reverse paths, and so on. Variable threshold methods, where the threshold is aligned to the intensity of the waveform (peak value) are commonly used, especially in systems using digital signal processing. Barshan (2000) and Andria et al. (2001) describe some of the recent advances in these methods.

A number of other signal processing techniques are beginning to be used, such as curve fitting and cross correlation techniques which are based on a match and filter approach between the received signal and a template signal. Where there is heavy interference via surface reflections cross-correlation processes are more difficult to apply, and the latest methods use auto-covariance models to account for the effects of interference on the received waveforms (e.g. van der Heijen et al., 2003). Lengricht and Frey (2002) describe processing techniques based on zero-up crossing algorithms that are better able to determine the start of the returning signal than threshold methods. In the case of signal attenuation, or where travel times are small such methods can significantly reduce the error, $E_t$, associated with travel time measurement, as illustrated in Figure 5.14.

![Figure 5.14: Signal processing methods: (a) minimal attenuation b) large attenuation](image)

5.3.4 Flow and velocity ranges

Ultrasonic transit time gauges are generally perceived to work well over a wide range of velocities. Particular problems may arise at extreme flows; for instance at high flows increased levels of entrained air, debris and sediment can lead to loss of data, but this is not a direct function of the velocity being measured. Similarly it may be difficult to ensure continuity and accuracy of flow measurement at low flows, where depths may fall to very low levels such that it is impractical to secure the required minimum clearance distance between the lower most path and the bed. This is particularly true in irregular channels with mobile beds where bed level may alter frequently. Deposited boulders may intercept the lowest flight path causing a loss of signal.

For out of bank flows index relationships, if applied, are unlikely to remain valid, and for multi-path arrays there will be difficulties in estimating both mean velocity and
cross sectional area for the upper most panel, as this will no longer be confined within the limits of the transducers. It is possible to make empirical adjustments to the measurements to take account of flow beyond the limits of the transducers by making assumptions on the velocity profile on the floodplain in relation to that occurring in the river. It is generally thought that the overall error in assessed total flow arising from such assumptions is likely to be less than 10%.

Transit time devices have been used at a limited number of locations in deliberate attempts to measure out-of-bank flows on the floodplain (e.g. Pinning Lock on the River Soar), though with limited success. Installations have been made to measure flow on floodplain widths of greater than 50 metres, but as these generally have to be low to the ground, a number of practical problems have resulted, such as vegetation and damage by livestock and vehicles.

5.3.5 Technical requirements

In order to minimise the sources of uncertainty discussed in the previous sections, the measurement site should be selected carefully. The characteristics of a good measurement site are summarised in the British Standard, by Newman (1982) and in the USBR Water Measurement Manual (US Bureau of Reclamation, 2001). The main points are summarised below. Note that practical and resource considerations in site selection are discussed in the next section.

- The site should be a straight reach with opposite banks parallel. The bank-to-bank profile should be near horizontal.
- The velocity distribution should be uniform, the channel confined and areas with eddies or turbulence avoided. The relationship between water depth and velocity should be stable and well understood.
- Sites where the mean direction of flow is skewed should be avoided. The channel should ideally be straight for 5 to 10 channel widths upstream and 1 to 2 channel widths downstream of the measurement section. Newman (1982) suggests that the approach channel should be straight for at least ten times the river width, although some manufacturers suggest that a distance between 3 and 5 times the width should be sufficient.
- A constant cross-sectional area and shape over the upstream and downstream extent of the measurement section is desirable. The channel bottom should be stable or easily monitored for variations.
- There should also be suitable channel aspect ratio, as the technique is not suited to wide, shallow channels, where the width-depth ratio results in large amount of secondary reflections. Channel depth should range between 0.1 to 20 m depending on width (the method can be applied to channels between 2 and 200m in width).

The transit time method works best where physical properties of the water are homogeneous. In particular the following points should be considered if optimal data quality is to be achieved.
- Weed growth should be minimal (weed can attenuate the acoustic signal, due to air in the plant structure). Selection of sites in well shaded bridge sections or shaded by bankside vegetation may help to reduce weed incidence. Weed and bankside vegetation may need to be cut back during the summer.

- There should be no water temperature or salinity gradients. UVMs should not be sited downstream of confluences or waste water discharge points, in estuarine or deep slow moving channels.

- High sediment loads, as typically might be observed during flood conditions, cause reflection and scatter resulting in high levels of signal attenuation. The British Standard suggests that the method is not appropriate where suspended sediment concentration exceeds 1500 mg/l, whilst some manufacturers suggest that UVMs can perform well up to concentrations of 2000 mg/l. However the combination of path length and transducer size usually determines whether adequate measurements can be made when sediment and entrained air concentrations are high. A bigger (lower frequency) transducer will work with much higher concentrations than a smaller transducer operating at a higher frequency.

- Entrained air bubbles may similarly result in high levels of attenuation (due to dispersal of the beam), particularly in flood conditions when sediment concentrations may already be elevated. Waterfalls, weirs, dams, reservoirs and mill tail-races all increase the level of entrained air, and may persist several kilometres downstream of the source.

In practice it may be difficult to identify a reach meeting all these requirements and often it might be necessary to apply transit time methods at sub-optimal sites. In such cases the system must be configured and operated in the best possible way to overcome such deficiencies.

5.4 Practical and Resource Considerations

A number of practical, economic and environmental constraints may preclude the use of the transit time methods at some sites, even though the method might be acceptable in a technical sense. These include:

- availability of services and access,
- impact on local environment,
- design life and data capture,
- initialising, calibration and staff training,
- capital and operational costs,
- routine maintenance requirements,
- health and safety,
• availability of standards and legislation.

5.4.1 Practical constraints on site selection

Amenity and navigation
Transit time instruments do not generally pose a problem for navigation or to other users of river amenities. Provided that river traffic is allowed for in the transducer mounting design, risk of damage by passing boats is minimal. Signal transmissions may be momentarily disturbed by passage of boats, however this should have little effect when data are processed to provide 15-minute data.

Bank topography and access
Bank topography can affect access to the site, and may determine equipment requirements. A variety of transducer mountings can be used to suit different bank conditions - transducers are typically positioned to prevent any flow behind the transducers, but this might not always prove practical. Piles are suitable if the banks are irregular or in fast moving or deep water (as shown in Figure 5.15). In artificial channels transducers can be fitted to wall mounted brackets. In slow moving streams transducers may be mounted on tripods fixed to the streambed.

![Figure 5.15: Pile mounted transducers (River Nidd at Skip Bridge).](image)

All types of transducer require access for maintenance. In the past it has been common to install steps in the bank (Figure 5.16) to improve access to transducers (although this may encourage unwanted interest from members of the public) or to use a sliding rack that can be withdrawn from the river for maintenance.
Cables
The need for cross-channel cables may preclude the use of the transit time method at sites where dredging or dragging anchors disturb the channel bed. Buried cables are also at risk of exposure and damage from sediment movement. Responder or reflector arrays may provide an alternative approach in this situation, however it is worth bearing in mind that responder arrays still require cables for power supply and that reflector arrays are not generally appropriate for channels where signal attenuation is high. Many sites in the Agency utilise existing overhead structures such as bridges and cableways to attach cables for safety. Alternatively thrust boring is used to duct cables deep under river beds, although this is relatively expensive (it can cost more than £20,000 for larger rivers).

Bridges
Bridges, especially modern single span concrete bridges, and culverts with vertical abutments can potentially provide good ultrasonic gauging sites, as they can be expected to contain flood flows, crossings are frequently in a straight reach of channel with limited channel mobility and bank erosion, and the shading provided by bridges limits weed growth. As has already been mentioned, the bridge may provide a ready route for cable crossing.

Ultrasonic measurement at arch bridges including multiple arched sections (up to four channels) is also possible, but often such bridges have other undesirable characteristics of channel configuration in the approach, or through the bridge opening, which make measurement difficult or impractical. In additional there may be amenity reasons for not fixing transducers to historic structures.

Debris
Debris can influence data capture rate and data accuracy by blocking or reducing signal strength, or by causing skew flows. Build up of waterborne debris on transducer faces is a common problem particularly during the autumn and winter months (e.g. fallen leaves and so on). Ultrasonic gauging stations also require regular maintenance in the growing season (grass cutting and vegetation clearance) which may be time consuming and costly. In channels where debris is extremely problematic, extra precautions may be required so that the transducer arrays are protected from damage.
Risk of vandalism or disturbance
Vandalism can be very problematic, especially where the site is located in an urban area, or where there is easy access to the instrumentation. The transducers are especially vulnerable. One solution is to mount transducers inside a protective enclosure (glass reinforced polyester moulds have been used in the past). However this can increase the level of signal attenuation.

Electrical interference
Ambient electrical noise can be significant at some sites, especially where close to powerful radio transmitters. These effects can be minimised by using sub channel cables. An example is at Alston in Northumbria. At this site, cables were initially on a pylon, but suffered from interference. They were then re-routed, bringing significant improvement. The issue of getting cables across the river can be significant. Problems include cables or mountings being washed out if not in a fixed tunnel or pipe. Access will also be required for maintenance (for example, to cure water ingress into the cable).

Ice
Instrumentation will continue to operate correctly even where surface ice affects the site, although in very cold conditions the electronic systems may start to fail (BS 3680 quotes the operational range between –10°C and 50°C). However surface ice is likely to compromise level measurement at the site, even where a stilling well is used, or if flow became pressurised invalidate the index velocity calibration used at the site. Ice push can also have the potential to destroy or damage transducer mountings unless they are properly protected. Transit time devices are used in Nordic countries where they are often mounted within a recess in a concrete abutment so that they receive some protection from floating ice.

Services and access
Hydroacoustic instruments are generally designed to be powered from an external source, although battery driven units have been shown to work well. The site would ideally have connections to mains electricity or a permanent on-site capacity for generation. If telemetry is to be used, the site must either have connection to the landline telephone network, or be located in an area having suitable mobile network coverage.

Good access is required, and due to the nature of the equipment there may be some engineering works required. The site must also provide a suitable environment and housing for processing units and so on.

5.4.2 Impact on local environment

The impacts of flow gauging technologies on the aquatic environment have been considered in Chapter 2. Key specific points of relevance to transit time ultrasonics are noted below.

Ecology, habitat and migrating fish
The instrumentation has negligible detrimental effects on habitat, ecology or migrating fish. However, some fish species, particularly shad and roach, are able to hear low frequency sound and can be alarmed by ultrasonic signals in the frequency range 200 to 400 kHz. In order to prevent these species from being deterred from passing ultrasonic
gauging stations it is generally suggested that signals exceeding 420 kHz should be used.

**Visual intrusion**

The visual intrusion from the instrumentation is usually minimal, although transducer mountings may seem to protrude when levels are low.

**Disturbance during installation**

During the installation phase there may be some disturbance laying cross channel cables and putting in transducer mountings. This may require the temporary clearance of vegetation on the channel banks. River diversion would not generally be required.

### 5.4.3 Feasibility study requirements

- Assuring the feasibility of the method at the proposed site is an important, time consuming and, potentially, costly aspect of procuring a new site. This should focus on the channel geometry and stability, with a programme of measurement to look at variability of stream parameters, with reference to specifications such as required flow range and accuracy. This programme must include:
  - Water temperature survey.
  - Suspended sediment and dissolved solids survey – for many sites in the UK typical ranges of suspended sediment are reasonably well known, so that a field survey may not be necessary.
  - Survey for possible upstream sources of air entrainment (spillways etc.). Often the extent of aeration is not apparent in normal flows and it is essential therefore to make an effort to visit the station during the planning phase at high flows).
  - Survey of possible obstructions.
  - Detailed cross-section survey - stability over time.
  - Stage variation survey (this needs to include enough data so that the probable maximum stage can be estimated).
  - Determination of the relationship between mean velocity in the direction of flow, channel discharge and stage (understanding the relationship between mean velocity, channel discharge and stage is a fundamental problem associated with many types of flow measurement).
  - Survey for electrical and radio noise and interference.

The feasibility study should also consider the suitability of different path configurations and attempt to find the optimum number of paths and path elevations required to assure the system accuracy. Within this study there is also a need to consider hypothetical flows greater than the maximum expected. Laenen (1985) and the British Standard both give guidance on how to proceed. The procedures will involve:
• Computation of clearance distance required between the lowermost path and the channel bed.

• Determination of the ‘best’ distribution of paths in the vertical and so on, allowing for redundancy, need for crossed paths, power availability and so on.

• Signal propagation surveys should be carried out. Further detail is given in the British Standard.

• Hypothetical ray bending analysis, based on typical temperature and salinity gradients observed.

• Hypothetical attenuation analysis based on sediment concentrations and aeration levels likely to be observed at the site.

5.4.4 Capital expenditure

Here feasibility, design, instrumentation, utilities, installation and commissioning are considered as contributing to the total capital cost. This would also include any compensation and legal costs, and land purchase or lease if required. Total capital costs can vary substantially depending on the size of the watercourse and complexities of the site. Typically a four or five path array might cost in the region of £300,000 to £500,000.

Feasibility study costs
Costs of a full feasibility study range between £2,000 and £20,000 depending on the complexities of the proposed site. For example a recently commissioned gauge at Bow Green on Birkin Brook involved a feasibility study lasting 6 months and costing £20,000.

Design costs
Typical design costs are around £10,000 to £40,000 depending on the number of paths and complexities of the site.

Instrumentation costs
Instrumentation costs are likely to include the transducers and mountings, cabling, console unit, loggers and batteries. Recent Environment Agency Science Report W6-055/TR on Good Practices for Hydrometry (Child et al., 2001) quoted indicative capital costs for transit time instrumentation ranging from £50,000 for a narrow section (~5m width) with four cross paths to £100,000 for a 20m wide transducer array using 8 crossed paths. Recent examples include the Irwell at Kearsley, near Manchester, (a 5-path array costing £55,000), the Birkin Brook at Bow Green (a 4-path array costing £26,000) and the Till at Clifton Hall near Manchester (a crossed multi-path array costing £27,000).

Utilities costs
Utilities include telemetry, electricity and back up power. Costs include installation of a new BT line, connection to the electricity grid if arrays are mains powered (and cost of back-up generator and/or batteries), and battery costs for battery powered units. For sites where there are no opportunities for connecting to utilities, the site should be
entirely self-sufficient, may require solar panels and mobile phone links. Costs will typically be around £10,000 to £15,000.

**Installation costs**
Installation costs can vary considerably depending on the size of the arrays and the type of transducer mounting and cabling options to be employed, and often exceed instrumentation costs. The installation costs for the new gauge at Kearsley were about £180,000 whilst costs at Bow Green were about £230,000.

A large proportion of the total installation costs may arise from installation of cross channel cables, which require additional works and channel clearance, and for transducer mountings. Transducer alignment is critical and divers may be required. If installed on pilings, consideration must be given for cost and logistics of moving pile-driving equipment. Land purchase and compensation payments to landowners can be quite large and are generally increasing.

**Calibration and commissioning costs**
Single path UVMs require an index velocity rating to be developed. Index calibration of newly commissioned UVMs can be done using current meter measurements, other velocity-area methods such as ADCP or using computations based on theoretical velocity profiles. Transit time instruments therefore do not necessarily require specialist calibration and may be performed in house, providing appropriately trained staff are available. An index velocity rating may take up to a year to develop, which means that it may take a year before flow data can be generated. Assuming that around 20 gaugings at a cost of £250 per gauging are required, the total cost of index calibration is likely to be of the order of £5000. Calibration costs are therefore usually minor in comparison to instrumentation and installation costs.

5.4.5 **Design life and data capture**

The design life can be assumed to be in the 10-20 years bracket. However the technology is likely to be outdated before the instrument would need to be replaced. Transducers are most at risk of damage or breakage and may need to be replaced several times during the lifetime of the gauging station.

Transit time devices are generally considered to be relatively reliable with the average time between failures on the order of two or more years at most sites. Of course at some sites, failures have been much more common. However, it is often possible to develop a stage-discharge rating from the observed data record, which can be used to fill in missing records where the device has failed. The reliability may also improve over time, as staff become familiar with the maintenance requirements of the site and calibrations are improved.

5.4.6 **Routine maintenance, operational issues and performance checking**

UVMs are advanced electronic systems that require specialised maintenance. Maintenance will generally involve either repairing any faults or deterioration in the equipment which might potentially impair the operation of the gauge, or checking the device after spurious data have been collected (for instance if a path malfunctions regularly). The major manufactures of these gauges have maintenance contracts with the Agency, with time targets to respond by and criteria for the need to be called out in
terms of percentage inaccuracy compared to current meter gauging, or gauge failure in terms of percentage loss in paths. A regular maintenance regime is necessary in achieving minimal downtime.

It may also be necessary to visit the site following vandalism or power failures, to clear known obstructions in the channel, or after periods of silt build up. For example the British Standard suggests that routine visits should be made every six months or more frequently, ideally coinciding with times of extreme conditions such as after flood events, or when there is excessive weed growth. Clearance of weed and algae and overhanging vegetation will also need to be addressed during routine maintenance visits.

Multi-path transit time gauges are normally assumed to represent absolute measures of flow and therefore do not require calibration. However it is necessary to undertake performance gaugings. Performance checking (audit) usually involves taking a limited number of check gaugings throughout the year. The number of performance checks required on an annual basis will depend on the perceived performance of the device. Current guidelines for good hydrometric practice (Child et al., 2001) suggest that two annual gaugings will be sufficient for multipath devices, but that between four and six annual gaugings are advisable if a single path is used, or if there are other uncertainties regarding the performance of the site. There may be more frequent (weekly) checks to ensure correct operation of instruments. In some cases where there are strong and consistent differences between check gaugings and the measurements, these are translated into an algorithm that is used to modify the ultrasonic calculated flow value.

Where a multiple path configuration is used it is prudent to monitor any variations in the channel bed level to ensure that weighting factors applied to the lower most velocity panel are appropriate. Bed level should be monitored regularly (i.e. monthly) during the first year of operation, although this can be reduced if the bed is shown to be stable, and annually thereafter. Bed level should also be resurveyed following flood events.

5.4.7 Cost of routine maintenance and operation

Child et al. (2001) report total maintenance costs of the order of £1500 per year. This compares poorly with typical costs of maintaining weirs (typically between £600 to £800 per year). A large proportion of this cost represents fees by specialist contractors or manufacturer for maintenance and minor repairs. Major repairs may not be economic and may exceed the purchase cost of the instrument.

Additional equipment such as telemetry and generators may also require regular maintenance. Maintenance of telemetry might typically cost between £200 and £600 per annum.

5.4.8 Staff training

The availability of properly trained staff can make all the difference in the use of the technique. This refers to staff trained in calibration techniques, technicians able to maintain the instrumentation and operate the instrument control system, staff able to operate data management software as well as staff who can interpret the measurements and appreciate factors that might affect the quality of the gauging station data. Staff also need to be able to use remote-access software.
Training issues include the availability of training from manufacturers or the possibility of in-house training, the number of staff to be trained, cost and availability of manuals and so on. Training costs can therefore vary considerably depending on which make and model is used.

5.4.9 Health & safety

Health and safety implications depend on site as well as method. Transit time devices do not generally pose a major threat to public safety, as the instrumentation is unobtrusive. As discussed previously safety for routine maintenance may vary depending on the type of transducer mounting used and the access available. Stairwells can facilitate access to the instrumentation. There is a minor risk of electric shock.

5.4.10 Standards and legislation

The transit time method is covered by British Standard BS3680 part E.

5.5 References


6  FIXED ACOUSTIC DOPPLER METHODS

6.1  Introduction

Acoustic Doppler velocity meters (ADVMs) measure the change in frequency that occurs when acoustic waves are reflected from suspended particles, such as sediment, air and gas bubbles (called ‘scatterers’) moving with the water column. This change, known as the Doppler shift, is directly proportional to the particle velocities and, provided the particles are transported with the flow, to the stream velocity. Therefore, in contrast to travel-time devices, Doppler methods work well in watercourses where suspended sediment concentrations are high.

All acoustic Doppler meters sample particle velocities within one or more signal beams transmitted into the flow, generally at ultrasonic frequencies. As they measure the velocity along an index path or volume, the accuracy that can be achieved primarily depends on the sampling regime used and its relationship to the true mean velocity. However, there are a variety of different makes and models, using a range of sampling regimes from the simple (e.g. a single continuous beam) to the complex (e.g. three or more pulsed beams).

Instruments emitting a continuous acoustic signal are typically mounted at a fixed point on the channel bed, with the beam pointing into the direction of flow. As reflections from scatterers everywhere along the beam path are then resolved to determine the mean Doppler shift, these devices provide only an approximate measurement of the velocity vector acting along the signal path. As such, flow measurement errors can be fairly high, typically between 15-20%, and an index velocity calibration is essential.

Pulsed beam instruments measure a profile of velocity along the beam path. They are therefore able to determine velocity vectors with much better accuracy (within 10%). Fixed (in situ) Doppler profilers are suitable for continuous flow measurement and are usually operated either in an up-looking (mounted on the channel bed) or side-looking (mounted on the channel flanks) configuration. These may use a single beam, in which case an index velocity calibration is required, or two or more beams, where measurement of velocity profiles along multiple vectors leads to more accurate determination of mean velocity. Figure 6.1 shows a pulsed beam device, installed in an up-looking configuration for gauging flows in a small irrigation channel.

Acoustic Doppler current profilers (ADCPs) are specialised profiling devices that are deployed from moving boats, rafts or cableways (Yorke and Oberg, 2002) to determine the velocity profile throughout a section. They are designed for portability between sites rather than continuous gauging at a single cross section (and are therefore beyond the scope of this report).

Factors that may compromise the accuracy achieved by acoustic Doppler instruments include high sensitivity to changes in density and temperature within the section, and distribution of reflectors through the water column. Bed mounted instruments are also particularly vulnerable to blockage by debris or silt, and do not work well where the depth is low.
Side-looking ADVMs have proved particularly popular in the USA, largely because they are relatively easy to install and maintain as cross channel cables are not generally needed. This also means that capital expenditure is much lower than for an equivalent transit time array, where cross channel cabling is often a costly necessity. Morlock et al. (2002) have examined the performance of ADVMs as permanent gauging stations at a number sites in the USA. This study gave favourable results, both in terms of accuracy and reliability. However, ADVMs are relatively new products to the British market and are not yet being used within the gauging station network in England and Wales, although they are being employed on a trial basis at a number of test sites, as reported by King et al. (2002).

This chapter discusses the general factors affecting the performance of acoustic Doppler instruments, drawing upon best practice guidelines as discussed in the ISO technical standard 15769:2000(E), experience in the USA and elsewhere and instrument manufacturers’ technical literature.

6.2 Principles of Operation

6.2.1 Basic theory

The Doppler effect is a well-known wave phenomenon, which describes how motion of a wave source or observer can result in ‘stretching’ or ‘compressing’ of the waveform. For instance, suppose an observer is moving with velocity $v$ towards a fixed wave source, which is emitting sound waves of wavelength $\lambda_s$ at a frequency $f_s$. The sound waves propagate at the speed of sound in the medium, $c$. For each complete wave emitted, the observer moves an additional distance $vT$ toward the source (where $T = 1/f_s$ is the period of the wave), so that the wave fronts arriving at the observer are closer together. Hence the observed wavelength $\lambda_o$ is shortened by an amount $vT$ such that:
\[
\lambda_o = \lambda_s - v T \\
= \lambda_s - \frac{v}{c} \lambda_s 
\]

(6.1)

where \( \lambda_o \) appears on the right hand side because the observed wavelength now depends on the time period between wavefronts experienced by the moving observer. Equation (6.1) can be re-arranged using the relationship \( f = c/\lambda \) to determine the frequency,

\[
f_o = f_s + \frac{v}{\lambda_s} = f_s + f_s \left( \frac{v}{c} \right),
\]

(6.2)

with which the wave fronts are actually observed.

The frequency apparent to the observer therefore differs from the propagation frequency by an amount depending on the observer’s velocity. The magnitude of this change is known as the Doppler shift. The Doppler shift, \( f_D \), can also be determined by comparing the wave frequencies at the source and observation point, as follows:

\[
f_D = f_o - f_s = f_s \frac{v}{c}
\]

(6.3)

From Equation (6.3) it can be seen that the component of velocity in the line-of-sight of an approaching wave source or observer can be directly determined from the Doppler shift.

In Doppler flow meters, stream velocities are estimated by measuring the Doppler shift of sound waves scattered by suspended particles and air or gas bubbles moving with the water column. This involves transmitting one or more acoustic signals into the flow from a sensor located on either the channel bed or channel banks and using a receiver (usually incorporated into the same device) to detect any backscatter along the signal path. As with acoustic transit time methods, the frequency of the signal is usually in the ultrasonic range (i.e. 20 kHz and above). Figure 6.2 illustrates this approach for a single up-looking beam, but the same principles apply where side-looking beams are used.

![Figure 6.2: Application of the Doppler principle for flow measurement](image-url)
In Figure 6.2 an acoustic signal of carrier frequency $f$ is transmitted against the direction of flow, at an angle $\theta$ and with beam width $w$. A particle, $i$, intercepts the signal at an angle $\phi$ to its direction of flow (if flow in the channel is uniform then $\theta = \phi$). As the particle moves with a velocity, $v$, the wavefront is ‘experienced’ by the particle with a Doppler frequency shift. Some of the signal scatter is reflected back along the beam path towards the sensor. A second Doppler shift then occurs as the backscattered wavefront arrives at the receiving transducer. As the transmitting and receiving transducers are located at the same place, the two Doppler shifts are equal in size, in which case the total Doppler shift becomes

$$f_{D,i} = 2\frac{v_{i,P}}{c_p}f$$

where

- $f_{D,i}$ is the total Doppler shift measured as the reflection from particle $i$ is detected,
- $v_{i,P}$ is the component of the velocity of the reflecting particle acting along the beam path,
- $c_p$ is the mean velocity of the carrier pulse (equivalent to the speed of sound in water) along the beam path, and
- $f$ is the emission frequency of the beam.

Assuming an interception angle of $\phi$, the velocity can be resolved to give the component of the particle velocity in the mean direction of flow as follows:

$$v_i = \frac{c_p}{2\cos \phi} \left( \frac{f_{D,i}}{f} \right).$$

Of course an acoustic signal emitted into a watercourse is likely to encounter a multitude of reflective particles along its path, each travelling at a velocity appropriate to its position in the flow profile and producing backscatter with a unique Doppler shift. Each of these contributes to the received signal. To produce an operational flow measurement, signal backscatter has to be measured, processed and related to the mean channel velocity in some way. It is not possible to differentiate the influence of individual particles on the cumulative backscatter from the measurement volume over a particular time interval (likewise the velocity $v_i$ of particle $i$ cannot in practice be determined). However, it is possible to control both measurement volume and sampling interval, and to do this a range of different signal types, sampling regimes and configurations are employed. The main variations include:

- single CW up-looking device,
- multiple beam side- looking pulsed Doppler,
• multiple beam up-looking pulsed Doppler.

6.2.2 Continuous wave ADVMs

Principles of operation
Continuous wave (CW) Dopplers emit a single continuous ultrasonic signal through the water column, with any backscatter along the beam path being detected simultaneously by a receiver housed in the same sensor. In this case, all particles passing within the width of the signal beam contribute to the backscatter, and therefore the signal is an additive one, being composed of all phases and amplitudes from all scatterers encountered, regardless of their positions in the water column. The returning signals measured at the sensor will therefore include the cumulative effect of velocities of all particles in the measurement volume, but not any information about their direction of movement or spatial distribution within the water column.

The Doppler shift derived from this signal is taken as an average value for the beam path, and can be resolved directly to determine the average velocity, \( \bar{v}_b \), along the beam path, such that

\[
\bar{v}_b = \frac{c}{2} \left( \frac{\bar{f}_D}{f} \right)
\]

where \( \bar{f}_D \) is the average Doppler shift. The path velocity is then taken as an index that is related to the mean velocity within the channel cross-section by calibration.

Signal processing
A number of different processing methods can be used to estimate the mean velocity along the beam path. The simpler include analogue methods, where higher weighting is given to stronger signals made by those particles nearest the sensor. More complex processing techniques include the use of Fourier transform methods to compensate for variations in signal strength.

Main issues
To ensure that the average Doppler shift in the received signal is representative of the mean velocity along the beam path, the received signal must have a negligible range bias in the sampling regime. This means that the particles contributing to the received backscatter must be numerous, randomly distributed in the water column and have velocities equivalent to those of the water. CW devices are therefore generally configured so the transmitted signal points upward and is able to propagate across the entire channel cross-section depth, from the transducer to the water surface.

6.2.3 Pulsed ADVMs

The key feature of the pulsed Doppler device is its ability to estimate the spatial variation in velocity along the beam path. This profile can then be integrated to provide a relatively accurate estimate of the mean velocity vector acting along the beam axis. A pulsed Doppler system is therefore generally preferable to a continuous wave device.

Principles of operation
In pulsed ADVMs, the signal is transmitted in a coherent manner, i.e. as a series of encoded pulses (pings), rather than as a continuous wave signal. Between two pulse
emissions the transducer serves as a receiver for signals reflected from particles in the water column. This allows range-gating (also called time-gating) techniques to be applied, in which backscatter from different sections or bins along the beam is separated out, and processed independently.

Figure 6.3 illustrates the range-gating technique employed with an up-looking pulsed Doppler flow meter, and shows how the signal backscatter obtained from ‘Gate x’ (between times \(t_1\) and \(t_2\)) corresponds to that from a particular portion, or ‘cell’, of the cross section.

Successive range gates correspond to reflected signals from increasingly distant portions of the beam. Thus for each pulse the velocity profile can be sampled almost instantaneously by sampling a number of gates in sequence. However the echo from the maximum range of interest must return before the next pulse is emitted for the method to work well. By using a narrow beam width and shorter gates it is possible to keep the cell size relatively small so that any range bias is small.

![Diagram of pulsed Doppler method](after ISO, 2000)

**Signal processing**

A variety of signal processing methods can be used to determine the Doppler shift of the echo returns in each gate including phase lock loops, fast Fourier transforms and autocovariance techniques. For example, many instruments use spectral analysis to extract the most appropriate Doppler shift frequency for each cell. Many modern pulsed Doppler systems use broadband processing in which a train of short pulses is emitted in each ping (a short pulse length generates a wide bandwidth). This allows pulsed-pair methods to be used, in which the movement of particles between two consecutive pulses...
is analysed by applying an auto covariance algorithm to the phase modulation of gated signals.

**Configurations**
Many pulsed Doppler devices are designed as side-looking instruments, that is, they look into the flow at a fixed elevation. Many side-looking instruments are adaptations of ADCP devices and typically use two or more horizontal beams (or one moveable beam), allowing the cross channel velocity vector to be reconstructed with fairly good accuracy. Typically the sensor would be mounted on the channel wings, wall or, if appropriate, from the side of bridge piers (Section 6.2.4). It should be noted, however, that the performance of a side-looking device is very much dependent on it being mounted appropriately.

A number of pulsed Dopplers are also designed specifically for use in an up-looking configuration, where they are mounted on the channel bed. Designs using single and multiple beams have both been used. This method can produce very accurate measurement of the vertical velocity profile in the cross section, which can then be integrated to determine the mean velocity in the vertical. Figure 6.4 shows two widely used pulsed ADVM devices, the SonTek Argonaut SL and the Nivus OCM Pro, which operate as side-looking and up-looking instruments respectively.

6.2.4 Side-looking configuration

Figure 6.5 illustrates a typical side-looking device using two beams emitted into the flow at a fixed elevation. Velocity vectors along the beam paths are resolved to provide an index velocity, which would then usually be used in conjunction with an index velocity calibration to determine the mean channel velocity.

Side-looking devices have a number of advantages over up-lookers. For example, installing the device on the channel sides avoids problems with build up of silt around the transmitter, which can completely block any emitted signal if an up-looking device is used. More importantly, using a side-looking configuration removes the need for cross-channel cables, which are both costly to install and vulnerable to damage. The position of the device can, however, be important with regard to the accuracy that can
be achieved. These and other technical considerations are discussed in more detail in Section 6.3.

Figure 6.5: Side-looking sensor arrangement in artificial channel

Figure 6.6: Up-looking Doppler device
6.2.5 Up-looking configuration

In the up-looking configuration, as illustrated in Figure 6.6, the sensor is mounted on the channel bed typically near the centre of the cross section or just off-centre, and the beam faces into the direction of flow so that drag affects are minimised. In a small channel, especially a shallow one, the sensor can act as an obstruction to both flow and sediment, and can result in turbulence. To minimise drag effects the sensor housings are designed to be streamline in shape, often resembling a ‘mouse’, although this varies between makes and models.

If the flow is uniform over the cross section or if an appropriate representative point across the cross section has been selected for the up-looking device, the mean velocity along the signal path may be assumed to be equivalent to the mean in the vertical. Some manufacturers have quoted figures of approximately 1% uncertainty for discharge measurements calculated in this way. Such conditions may be achieved in artificial channels having uniform shape and linear flow patterns. However, in natural streams it will nearly always be necessary to use an index velocity calibration in order to determine discharge accurately.

6.2.6 Calibration requirements

ADVMs generally require calibration by the index velocity method (Section 3.3.1). This means that the measured estimate $\bar{v}_b$ has to be independently calibrated against mean channel velocity ($\bar{v}$) to develop an index rating. Therefore, given a particular stage and beam velocity, a calibration of the form

$$Q = K_{vb} \bar{v}_b A_W$$

(6.7)

may be applied where $K_{vb}$ is an empirically derived function based on calibration gauging at the site over a period of time. Calibration gauging should normally cover a wide range of flow conditions, and will be particularly important for sites with a large range of stage. The index-velocity rating and depth-area ratings derived for the site are generally programmed into operating software so that discharge can be calculated in real time. Development and use of index velocity ratings for CW Dopplers are discussed in more detail in ISO (2000) and in manufacturers’ operating handbooks.

6.3 Sources of Uncertainty and Technical Issues

6.3.1 Overall accuracy

As the acoustic Doppler method is not yet in common use in British Rivers, it is difficult to make definitive statements regarding sources of uncertainty and accuracies that might generally be attained. Manufacturers generally claim excellent accuracy for Doppler ultrasonics. Table 6.1 illustrates some typical specifications for CW and pulsed Doppler instruments.
Table 6.1: Manufacturers specifications for Doppler devices

<table>
<thead>
<tr>
<th>Resolution - Velocity</th>
<th>CW Doppler</th>
<th>Pulsed Doppler</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth</td>
<td>1-2mm</td>
<td>1mm</td>
</tr>
<tr>
<td>Accuracy - Velocity</td>
<td>2% of measured ±0.25%</td>
<td>1% of measured or ±5mm/s ±2mm</td>
</tr>
<tr>
<td>Depth</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

CW Dopplers generally perform less well than pulsed Dopplers, particularly with increased velocity and/or depth. The manufacturers’ specifications however do not generally take into account factors such as specific site conditions, installation and operational procedures. A number of studies have compared the performance of different Doppler instruments under both laboratory and field conditions, including Lemmin and Rolland (1997), Vermeyen (1999), Davies (2003) and Vidmar (2002). In general these studies have suggested that CW Dopplers typically tend to overestimate velocities, in some cases resulting in discharges between 25% and 50% greater than actual (Vermeyen, 1999; King et al., 2002). It should be noted that some of this error is due to incorrect stage-area calibration at field sites. Pulsed Dopplers, particularly those using cross-correlation techniques, have typically been found to perform more reliably. Davies (2003) reports discharges to within 7% using a cross-correlation pulse Doppler. A number of other studies are currently considering the performance of pulsed ADVMs under a range of field conditions including those reported by Schroevers (2002), Gamaro (2002) and Dunker (2002).

6.3.2 Blanking distance

Despite the many advantages of the pulsed Doppler approach, there are some drawbacks including the need for a blanking distance to the first range of about 15cm. This is so that the resonance that occurs within the transmitter and receiver when a pulse is emitted has time to decay before the returning signal arrives. Also if the pulsed method is to be used effectively, at least three or four range cells (at least 5 cm in width) are required, which gives a minimum operational depth of about 30 cm (for an up-looker).

6.3.3 Signal characteristics

Beam width, range and intensity

Transmission losses due to signal spreading and attenuation cause the transmitted signal to lose its intensity along its path and may reduce the signal range. Both of these factors can bias particle sampling and estimation of the average velocity. For example as signal intensity is higher nearer the transmitter, scatterers near the sensor’s face, which are likely to be travelling slowly due to drag effects near the channel bed, will contribute more backscatter to the received signal than scatterers farther away.

Selecting the beam width and transmission frequency carefully may reduce transmission losses. A narrow beam width, which is a function of the frequency and diameter of the transmitter, will reduce spreading effects and keep intensity higher, whereas in deep channels, wide beams may not penetrate to the surface. A narrow beam reduces the range of angles at which particles are able to intercept the beam, so that the uncertainty associated with the path angle used in Equation (6.5) is minimised. However a narrow
beam will also reduce the volume of particles that can be sampled, so there is a trade-off between beam width and sampling coverage.

ADVM devices are typically operated at frequencies between 500 kHz and 1 MHz. However a lower frequency signal has greater range, and is able to penetrate further through the water column. To generate a lower frequency wave, a larger transducer is required for a given beam width, which is typically more costly.

**Angle of projection**
The angle, as well as the range, of the signal beam determines the total volume of the water column sampled. For best coverage the angle between the beam and the mean flow direction should be between about 30 and 50 degrees (ISO, 2000), depending on the channel dimensions. Where the channel is shallow relative to its width, better coverage can be obtained using a shallow beam angle, as shown in Figure 6.7. If too steep an angle is used, particles in the lower part of the channel can be poorly sampled. On the other hand, in deeper channels, it is generally better to use a steeper angle, as shown in Figure 6.8, otherwise the signal can be attenuated before reaching the water surface.

![Figure 6.7: Effect of projection angle $\theta$ in shallow water (after ISO, 2000)](image-url)
Speed of sound
In normal conditions the ‘textbook’ value of the speed of sound in water can be used (around 1450 ms\(^{-1}\)). In many situations, however, particularly where both temperature and salinity gradients exist within the water column, the actual propagation speed may vary. In such cases it is important to either measure the actual velocity of sound, or, provided temperature and salinity variations are known, to apply some kind of retrospective correction to recorded velocities. Some instruments include a temperature sensor and have a dynamic adjustment to correct for temperature effects.

6.3.4 Channel characteristics

Particle distribution
Scatterers such as solid particles, air bubbles, plankton and so on must be present in sufficient numbers for Doppler ultrasonic methods to work well. ISO (2000) suggest that a concentration of about 100 mg l\(^{-1}\) will produce best results. This will generally not be a problem except for example for streams in chalk catchments, or where flow rates are low. However if the concentration of suspended solids and air bubbles is too great, the beam range may become severely restricted.

Ideally scatterers should be distributed uniformly through the cross section. This will rarely be the case. For example air bubbles are generally found toward the surface of the channel, and may not move with the average flow. Scatterers also tend to move in ‘clouds’. Scatter also occurs at density differences created locally by dissolved salts, or thermal gradients. However, information about water velocity can only be obtained from these if they follow the water movement. Where the scatterers are not uniformly distributed within the cross section, it is important to make the sampled volume as large as possible.

The nature and size of reflectors may be important. Larger particles dominate the signal (Davies, 2003), yet these may not travel with the water column (and may in fact be travelling more slowly). During periods of lower flows particle settling may occur.

Figure 6.8: Effect of projection angle \(\theta\) in deeper water (after ISO, 2000)
Channel dimensions
To ensure a regular flow pattern along the sampling reach and encourage uniform flow conditions, a long and straight reach with a uniform cross-section is required. This length is often longer than that required by transit time methods, particularly if the beam angle is small. A general rule is that the sampling length should be five to ten times the width of the channel.

Assumptions about sampling do not necessarily hold true in channels that are complex in shape, or that have, for example, deep channels on their base. CW Dopplers therefore work best in circular, U- or V-shaped channels. Similarly, in wide channels the sampled velocity will only relate to part of the channel. The effect of this on the accuracy of the mean velocity estimate will depend on the uniformity of the particle distribution.

Deep channels can challenge the beam range, especially where the beam angle is acute (as discussed previously). Similarly a shallow but wide channel results in a small surface area being measured. The depth to width ratio should be, at a minimum, about 1 to 5. A large depth range is also inappropriate for side-looking instruments, unless this is accounted for in the index velocity calibration.

Flow rate
The size of the Doppler shift is proportional to the velocity of flow in the channel. CW Dopplers, in particularly, do not perform well in slow moving channels, as interference effects due to signals being simultaneously transmitted and received prevent near zero Doppler shifts being measured accurately. This means that there is a minimum theoretical operating velocity of around 0.001 ms\(^{-1}\) for CW Dopplers. For pulsed Doppler devices, it is possible to detect Doppler shifts of zero, so that there is no minimum operating velocity.

Weed, debris and silt
Weed and debris can cause turbulence within the channel, and, at worst, block the signal completely. Obstructions other than silt can interfere with the beam. In particular, weed, containing carbon dioxide, can block the signal (sound cannot pass through carbon dioxide at the frequencies used). A build up of silt around the sensor can also block the signal. Such effects may be reduced by using a side-looking configuration, as shown in Figure 6.9.

![Figure 6.9: Effect of silt build up on up-looking and side-looking devices (after ISO, 2003)](image-url)
6.3.5 Requirements to ensure good performance

System requirements for ADVMs are similar to those of transit time methods, the main exception being the need for an adequate concentration of scatterers for the Doppler method, whilst the opposite condition is required for transit times. In general the continuous wave method makes more assumptions about the velocity profile in the channel, and so works better in more homogeneous conditions where the channel is well characterised, whereas pulsed Doppler devices are more adaptable. Ideal site requirements include the following:

- The site should be a straight reach with opposite banks parallel. The bank-to-bank profile should be near horizontal.

- The velocity distribution should be uniform, the channel confined and areas with eddies or turbulence avoided (to ensure that the index velocity relationship remains stable over time).

- The channel should ideally be straight for 5 to 10 channel widths upstream and one to two channel widths downstream of the measurement section.

- A constant cross-sectional area and shape over the upstream and downstream extent of the measurement section is desirable. The channel bottom should be stable or easily monitored for variations. A stable bed can also minimize build-up of sediment on top of the sensor.

The following additional points should be considered if optimal data quality is to be achieved.

- Weed growth should be minimal (weed can attenuate the acoustic signal, due to air in the plant structure).

- The technique is not well suited to sites with strong temperature or salinity gradients, such as might occur in poorly mixed channels.

- There should also be a suitable channel aspect ratio. Ideally the depth to width ratio should be around 1:5.

- If up-looking devices are used in channels with widths in excess of 2m, multiple devices will be required to produce accurate velocity measurements. There is an elevated potential for serious sampling errors to occur when the ratio between water depth and width is low (ISO/TS 15769). Up-looking Doppler devices typically have a minimum operational depth of approximately 10-20 cm. They are usually able to measure in channels up to a couple of metres deep. The exact upper limit of the depth range is dictated by the penetration capacity, angle and frequency of the ultrasonic beam transmitted from an ultrasonic device.

- Side-looking devices can usually be used in channels up to 100 m wide, and flow depths of 8 to 10 m.

- We believe that ongoing Agency R&D is likely to recommend a suspended solid concentration in excess of 3 mg/l for efficient operation of Doppler ultrasonics.
This means that for accurate measurements in very clean water, seeding or artificial aeration may be needed.

6.4 Practical and Resource Considerations

As with other flow gauging techniques a number of practical, economic and environmental constraints may preclude the use of acoustic Doppler instruments at some sites, even though the technical performance might be adequate. These constraints include:

- availability of services and access,
- impact on local environment,
- design life and data capture,
- initialising, calibration and staff training,
- capital and operational costs,
- routine maintenance requirements,
- health and safety,
- availability of standards and legislation.

6.4.1 Practical constraints on site selection

Amenity and navigation
Acoustic Doppler devices do not generally pose a problem for navigation or to other users of river amenities. However, instruments must be positioned carefully to avoid damage by passing boats.

Dredging
The need for cross-channel cables may preclude the use of the bed-mounted devices at sites where dredging or dragging anchors disturb the channel bed. Side-looking devices may provide an alternative approach in this situation.

Debris
In channels where debris is problematic, extra precautions may be required so that the transducers are protected, and able to be regularly cleaned. Debris can also influence data capture rate and data accuracy by blocking or reducing signal strength, or by causing skew flows. As discussed previously, where debris/ragging problems are severe an up-looking sensor may be turned so that it faces downstream, protected by a glass fibre barrier or can be side-mounted.

Temperature
Provided that variations in propagation speed can be accounted for, the Doppler method can, theoretically, be used within a wide range of temperatures (-20 to 60°C). However, there may be a wider range of practical constraints if the method is used in extreme conditions. This can include damage to the transducers during extreme cold, damage to
Bank topography and access
Bank topography can affect access to the site, and may constrain equipment requirements, particular if side-looking devices are to be used. It may be advantageous to mount side-looking transducers on bridge piers.

Vandalism or disturbance
The potential for vandalism must be considered. This may depend on the ease of access to the instrumentation, and whether the site is located in an urban area. Cables can be buried or housed out of sight or reach of vandals, but may need to be exposed when entering equipment boxes. Loggers and power supply can be located in a strong, locked box or hut. Side-looking devices are more vulnerable to vandalism.

Services and access
Most ultrasonic Doppler devices are battery powered, although different instruments vary in voltage required and energy consumption. The selected site therefore does not necessarily have to have connections to mains electricity or a permanent on-site capacity for generation.

If telemetry is to be used, the site must either have connection to the landline telephone network, or be located in an area having suitable mobile network coverage. Good access is required, and the site must also provide a suitable environment and housing for processing units.

6.4.2 Impact on local environment
The impacts of flow gauging technologies on the aquatic environment have been considered in Chapter 2. Key specific points of relevance to Doppler ultrasonics are noted below.

Ecology, habitat & migrating fish
The instrumentation has negligible detrimental effects on habitat, ecology or migrating fish. However devices having operational frequencies in the range 200 to 400 kHz should be avoided as fish species such as shad can be disturbed by low frequency ultrasound.

Visual intrusion
The visual intrusion from the instrumentation is usually minimal, although a gauging hut is required.

Disturbance during installation
Doppler methods are often favoured over transit time methods for their ease of installation. However, there may be some disturbance laying cables and putting in mountings for both side-looking and up-looking devices. This may require the temporary clearance of vegetation on the channel banks. River diversion is not a requirement for Doppler methods.
6.4.3 Feasibility study requirements

Assuring the feasibility of the method at the proposed site is an important, time consuming and potentially costly aspect of procuring a new site. This should focus on the channel geometry and stability, with a programme of measurement to look at variability of stream parameters. This programme must include:

- water temperature survey,
- suspended sediment and dissolved solids survey (this can typically be achieved by desk study),
- survey of possible obstructions and debris,
- detailed cross-section survey, and assessment of its stability over time,
- stage variation survey,
- determination of relationship between mean velocity in the direction of flow, channel discharge and stage.

6.4.4 Capital expenditure

Capital expenditure will include the cost of feasibility, design, instrumentation, utilities, installation and commissioning. Any compensation and legal costs, and land purchase or lease if required.

Dopplers promise to be cost effective, compared with other gauging methods, in that installation costs are likely to be relatively low. Feasibility and design of Doppler gauges should be no more difficult or costly than for transit time ultrasonic gauges and may even be considerably less.

Feasibility costs

Feasibility assessment costs for an acoustic Doppler system are likely to be similar to those for transit time devices. A figure of between £5000 and £15000 seems appropriate.

Design costs

Design costs are likely to be between £5000 and £15000.

Instrumentation costs

Instrument costs vary significantly between devices. Current market prices are approximately £1,500 for CW and £6,000 to £8,000 for pulsed Doppler devices. Other costs include the transducers and mountings, cabling, console unit, loggers (memory) and batteries. The instrument housing needs to be safe and easy to access, protected against flooding, human or animal interference, and weather (e.g. in a secure building).

Utilities cost

Utilities include telemetry, electricity and back up power. Costs include installation of a new BT line, connection to the electricity grid (if mains power is required) and the cost of a back-up generator. For sites where there are no opportunities for connecting to
utilities, the site should be entirely self-sufficient, and may require solar panels and mobile phone links.

**Installation costs**
As discussed earlier, Doppler instruments are often favoured over transit time methods for their ease of installation, particularly as cross channel cables are not often required. In general installation costs are lower than for transit time ultrasonics but do often exceed instrumentation cost. Consideration must be given for the cost and logistics of installing device underwater and for mounting on bridge piers. A figure of between £50,000 to £100,000 seems appropriate for permanent installation on a substantial river.

**Calibration costs**
Index calibration of newly commissioned Doppler instruments can be done using current meter measurements, other velocity-area methods such as ADCP or using computations based on theoretical velocity profiles. An index velocity rating may take up to a year to develop to get winter and summer levels. This means that it may take a year before flow data can be generated. Assuming that around 20 gaugings at a cost of £250 per gauging are required, the total cost of index calibration is likely to be of the order of £5000.

**6.4.5 Design life and data capture**

The design life can be assumed to be in the 10-20 years bracket. However the technology is likely to be outdated before the instrument would need to be replaced. Transducers are most at risk of damage or breakage and may need to be replaced several times during the lifetime of the gauging station. Ensuring transducers are kept clean will be of primary importance in maintaining adequate reliability.

Some units undertake ‘on-board’ calculation of flow. In other cases, the data has to be processed offsite. The preferred method of flow calculation used in USGS (for side-lookers) is to download the raw data (level and velocity) to its computer archive. The level and flow records are then post processed off site using look-up tables that relate level to area and measured velocity to mean velocity to produce flow. This system allows the user to quality control the raw data before it is processed and validated. It is likely that an off-site processing system will be used in the UK, until the method becomes widely established.

**6.4.6 Routine maintenance and operational issues & costs**

Maintenance costs for acoustic Doppler installations are not yet well known, but it can be inferred that maintenance should be no more difficult or costly than for transit time ultrasonic gauges and probably considerably less. However major repairs may not be economical and may exceed the purchase cost of the instrument.

Doppler transducers will probably require specialised maintenance, and a large proportion of the maintenance costs will be contractors’ fees. A regular maintenance regime is necessary in achieving minimal downtime. There may also be the need to visit the site following vandalism or power failures, to clear known obstructions in the channel, or after periods of silt build up. For example, ISO 15769 suggests that routine visits should be made every six months, or more frequently, ideally coinciding with times of extreme conditions such as after flood events, or when there is excessive weed.
growth. Clearance of weed and algae and overhanging vegetation will also need to be addressed during routine maintenance visits.

Performance checking (audit) usually involves taking a limited number of check gaugings throughout the year. Current guidelines for the number of performance checks required on an annual basis (Child et al., 2001) do not cover Doppler devices, but around six or so check gaugings are likely to be required, at a total cost of £1500 per year.

6.4.7 Staff training

It is essential that staff using, calibrating or maintaining Doppler instruments are properly trained. Staff involved in data management and interpretation should also be properly trained. Training issues include the availability of training from manufacturers or the possibility of in-house training, the number of staff to be trained, cost and availability of manuals. Training costs can therefore vary considerably depending on which make and model is used. The Agency is currently developing an index velocity training course for its staff.

6.4.8 Health & safety

Health and safety implications depend on the site as well as the method. Acoustic Doppler devices do not generally pose a major threat to public safety, as the instrumentation is unobtrusive. As discussed previously, safety for routine maintenance may vary depending on the type of transducer mounting used and the access available. There is a minor risk of electric shock. Access to river for installation and maintenance is a health and safety issue.

6.5 References


7 MICROWAVE DOPPLER RADAR

7.1 Introduction

Doppler radar has emerged as a means of measuring open channel flows within the last five years, although similar methods have been used for measuring coastal currents for some time (e.g. Paduan and Graber, 1997). Doppler radar techniques involve transmitting high frequency radio signals (microwaves) onto the stream surface. Waves at the water surface scatter these signals, and by doing so induce a Doppler frequency shift proportional to their mean velocity. The frequency of the signal backscatter can therefore be used to estimate the surface water velocity, although the surface must be sufficiently reflective (i.e. rough) for the method to work well.

As radar is a true non-contact measurement, it offers a number of advantages over other gauging methods. For example, many of the maintenance problems associated with submerged sensors (such as damage by debris or foul water) are avoided. More importantly, however, Doppler radar offers an opportunity to measure flows during flood conditions when either in-stream conditions or health and safety issues preclude the use of many other flow measurement techniques. As the measurement is of surface velocity, assumptions regarding the relationship between surface and mean velocity must be applied. However this relationship is relatively robust (Plant et al., 2003) and is typically independent of stage.

A number of different groups have been actively researching Doppler radar methods over the last few years with varying degrees of success. Two main approaches have been taken (although the same basic principles apply in both);

- Mobile antennae devices, which might be deployed for spot measurements of discharge during high flow conditions in much the same way as ADCPs are presently used. A number of ‘proof of concept’ experiments, in which the radar antennae have been mounted on cableways (Costa et al., 2000), helicopters (Melcher et al., 2002) or from channel banks (Yamaguchi and Niizato, 1994) have illustrated the versatility of this approach.

- Development of fixed sensors suitable for continuous flow measurement at a single site. Fixed sensors are of most interest here as they offer continuous flow gauging, if suitably calibrated. Such devices, including both monostatic (where the transmitter and receiver are at the same location) and bistatic (i.e. separate transmitter and receiver) configurations are currently being researched (e.g. Barrick et al., 2003; Plant et al., 2003; Leu et al., 2001). Some examples are shown in Figure 7.1.

Monostatic radar designs are now manufactured as commercial products by a number of companies. To date, there is limited published data on which the performance of these commercial devices can be evaluated. However, a monostatic radar device is presently being tested in the UK on a canalised section of the River Leen in Nottingham, as a joint venture between OTT Hydrometry Ltd. and the Environment Agency.

This chapter evaluates the potential for wider use of Doppler radar methods within the UK hydrometric network.
Figure 7.1: Examples of a) monostatic Doppler radar device being tested on the River Leen at Nottingham and b) bistatic radar device (receiving antennae shown) set up for experimental use by the USGS

Notes: photo (a) also shows a level measuring device pointing downwards, photo (b) is taken from the US Geological Survey website.

7.2 Principles of Operation

7.2.1 Basic theory

Radar (RAdio Detection and Ranging) techniques use reflected radio signals (echoes) to locate and characterise distant objects. Doppler radar is often used where the target object is moving, in which case the frequencies of reflected signals are of primary interest, as they can be used to determine the target’s velocity. Flow meters based on Doppler radar technology depend on measuring the frequency shift in radio reflections from the river surface. The same Doppler equations as described in Section 6.2 apply.

When a radio signal is incident on a water surface, a number of mechanisms occur. Depending on the frequency and angle of incidence of the signal, and on the character of the water surface, the signal may be refracted, scattered, reflected, or absorbed. For example, high frequency radio signals are absorbed within a few millimetres of the water surface, whilst low frequency radio signals are generally able to pass freely through water. The roughness of the water surface and the angle of signal incidence determine if and how incident radio waves are reflected. For example, if the water surface were smooth, signal energy would be scattered randomly. However, small waves are often present at the water surface due to turbulence. Where the wavelength of the surface waves is about half that of the signal wavelength a phenomenon called resonant Bragg scattering occurs (Plant and Keller, 1990). Bragg scattering dominates microwave backscatter from rough water surfaces under many wind speed and incidence angle conditions.
In Bragg scattering, the radar wave and the water wave are in phase so that constructive interference occurs. As a result more backscatter occurs along the angle of incidence. This is illustrated in Figure 7.2, which shows a stream moving with mean velocity, $v$, and surface velocity, $u$. Waves of length $\lambda_s$ appear at the surface due to channel turbulence.

![Diagram showing Bragg scattering of surface waves](image)

**Figure 7.2: Bragg scattering of surface waves**

A radar beam of wavelength $\lambda_t$ and frequency $f_t$, transmitted to the surface at an angle $\theta$ will result in Bragg resonance if:

$$\lambda_s = \frac{\lambda_t}{2\cos \theta}$$

(7.1)

where $\lambda_t$ and $\theta$ are the wavelength and incidence angle of the radar beam respectively, and $\lambda_s$ is the wavelength of the surface wave.

When the transmitted radar signal is scattered at the water surface, Doppler frequency shifts occur due to ‘random’ surface movements of the Bragg waves. The backscatter from the surface when Bragg scattering occurs has two peaks in the Doppler frequency spectrum corresponding to the advancing and receding surface waves. ($-f_b$ and $+f_b$). A simplified example of this is illustrated in Figure 7.3. However, the surface waves also move congruently with the underlying flow, which imparts an added Doppler shift ($f_c$) that is directly related to the surface velocity.
The midpoint between the Bragg peaks is therefore shifted away from zero frequency by the surface current of the river. It can be shown that the Doppler shift \( f_d \) at the midpoint between these two peaks (e.g. see Plant et al., 2003) can be directly related to the surface velocity as follows:

\[
    f_d = \frac{2 V \sin \theta \sin \phi}{\lambda_i}
\]  

(7.2)

The reflection of wavelength, \( \lambda_i \), occurs in the direction of incidence. As the frequency spectra of the Bragg scatter can be very complex modern spectral analysis techniques are usually required to separate these two components so that the mean velocity can be estimated.

In some cases, wind shear, working either with or against the current, can bias the direction of movement of the Bragg waves. It is usually possible to identify and remove the effects of wind on surface velocity in the radar spectra (if data on wind speeds are available), but in some situations it is likely wind effects will be so great as to preclude the use of radar to measure surface velocity.

**Monostatic radar**

Monostatic Doppler radar flow meters, where transmitting and receiving transducers are housed in the same unit, are configured so as to maximise the amount of reflection, or backscatter, along the angle of incidence of the radar beam. This means that by using an incident signal frequency able to resonate the surface waves, maximum backscatter can be achieved. In open-channels of moderate size, surface waves are usually of the order of a few millimetres to centimetres in size - sufficient to backscatter high frequency (microwave) radio signals (Melcher et al., 2002).

**Bistatic radar**

Bistatic radar devices, where the transmit and receive antennas are on opposite sides of the river, generate elliptical patterns of scatter, and because they use shallower incident
angles much larger waves (~0.4 to 0.5 m) contribute to the back scattered energy (Barrick et al. 2002). This system is used to measure the velocity component perpendicular to the ellipses (i.e. provides a measure of the integrated lateral profile) but is more appropriate for wider water bodies.

### 7.2.2 Continuous wave monostatic Doppler radar

Monostatic Doppler radar can use either continuous or pulsed signals. The continuous signal approach is more straightforward and is used in some of the commercial Doppler radar devices. Here a radar signal is continuously transmitted to the surface, at an angle of approximately $45^\circ$, as shown in Figure 7.4. The beam must align with the mean direction of flow.

![Doppler radar device](image)

Figure 7.4: Commercial Doppler radar device using continuous signal

This means that the beam intersects only a small area on the surface of the river, i.e. its ‘footprint’. The size of the ‘footprint’ will depend on the beam width of the signal, the incidence angle and the distance between the antenna and the water surface (the analogy to shining a torch beam on a water surface is often made to illustrate this point) but is likely to be no larger than a couple of square meters. The Doppler shift in the returning backscatter therefore only gives the component of surface velocity acting in the antenna direction, $u_x$, averaged over the surface footprint of the beam. The antenna can be pointed up or downstream, although the latter seems to give best results (Wills, pers. comm.).

Depending on the beam alignment and channel conditions, $u_x$ may or may not be considered representative of the mean surface velocity $\bar{u}$. A number of assumptions regarding the horizontal distribution of surface velocities in the channel may be
required, and where the channel is wide an array of continuous wave sensors will probably be required if lateral variations in velocity are to be accounted for (as illustrated in Figure 7.5).

![Figure 7.5: Array of CW Doppler radar units at a site in Germany (shown with kind permission of OTT Hydrometry Ltd.)](image)

7.2.3 Pulsed Doppler radar

Pulsed Doppler radar uses a range-gating system similar to that used in acoustic Doppler instruments (see Section 6.2.3). The device transmits short pulses of radar and then receives the backscattered signal over a number of timed intervals called gates, allowing the spatial variation in surface velocity to be characterised. This process is illustrated in Figure 7.6. As the angle of incidence is shallow, the surface ‘footprint’ of each beam is elongated. In each case, the backscatter from bins (i.e. sections of the footprint) nearer to the antenna correspond to the signal received during the earlier gates.
The preferred configuration for pulsed Doppler devices is to use two side-looking beams directed at slight angles from the perpendicular toward the upstream and downstream directions. This allows the measured surface velocity for each bin to be separated into downstream and lateral components and a two dimensional picture of the surface velocity distribution to be developed.

![Pulsed Doppler geometry](image)

**Figure 7.6: Pulsed Doppler geometry a) side view and b) plan view**

### 7.2.4 Determination of discharge and calibration requirements

The key problem with use of Doppler radar methods is the difficulty in accurately relating the surface velocity $u$ to the mean channel velocity, $v$. A calibration of the form

$$Q = k \, \bar{u} \, A_w$$

(7.3)

is often used, where $k$ is a coefficient relating surface and mean velocity and $A_w$ is the cross sectional area of the wetted part of the channel. The form of this coefficient will depend on the vertical velocity profile within the channel, which in most cases, will in turn depend on the channel profile, roughness and water depth.
Ideally the coefficient $k$, would be derived by calibrating, against mean velocity derived by spot gauging methods. However, more often than not, a simple logarithmic or power law profile of velocity is assumed so that

$$\bar{v} = 0.85 \bar{u}$$  \hspace{1cm} (7.4)

As with other non-invasive methods, $A_W$ is usually calculated as a function of the stage, $h$. However, in experimental applications of Doppler radar some effort has to be made to sense the wetted cross section remotely. This has mainly been attempted using low frequency radar techniques to map the bed profile and water surface (e.g. Costa et al., 2000, Melcher et al., 2002). This has been readily achieved using commercial ground penetrating radar (GPR) devices, provided that they can be adequately suspended above the river, as described in Spicer (1997). More recently, Lee et al. (2002) used a combination of slope-area and surface velocity methods to determine wetted depth remotely.

7.3 Sources of Uncertainty and Technical Issues

Doppler radar devices are just starting to come on to the market in the USA, UK and Europe. This means that there is little practical experience on which to draw with regard to typical operating uncertainties. The main drawback of the radar-based approach is that surface velocity is the measured variable, which can be affected by wind shear. This must either be calibrated against mean velocity using index methods or assumptions regarding vertical velocity distributions. In the latter case, gauging sites need to exhibit very uniform flow conditions with a stable relationship between surface velocity and true mean velocity.

The Doppler radar system depends on a number of assumptions regarding the relationship between surface and mean velocity in the channel. As with many other non-invasive methods, the more homogeneous a channel is, the better the results will be. Ideal site requirements include the following:

- The site should be a straight reach with opposite banks parallel. The bank-to-bank profile should be near horizontal.

- The velocity distribution should be uniform, the channel confined and areas with eddies or turbulence avoided. The relationship between water depth and velocity should be stable and well understood.

- Sites where the mean direction of flow is skewed should be avoided. The channel should ideally be straight for several channel widths upstream of the measurement site.

- A constant cross-sectional area and shape over the upstream and downstream extent of the measurement section is desirable so that any index calibration remains valid over time.

The following additional points should be considered if optimal data quality is to be achieved.
• The technique is not well suited to highly vegetated sites, especially where vegetation growth is on the surface. Sites with overhanging vegetation are also best avoided.

• Doppler devices typically have a minimum operational velocity of about 0.5 m/s. The exact lower limit is determined by the roughness of the water surface.

• The beam range will be approximately 1.5 to 30 m depending on the site. The optimal beam angle is $45^\circ$ for continuous monostatic beam radar, but much lower angles can be achieved using pulsed Doppler methods. Bistatic radar devices usually have a much longer range, and are more suitable for wider rivers.

  o Where the channel is wide, an array of continuous wave sensors will probably be required if lateral variations in velocity are to be accounted for.

7.4 Practical and Resource Considerations

As radar methods represent a form of ‘non-contact’ measurement they appears to offer a number of practical advantages, including ease of installation and maintenance.

Unlike some of the other methods discussed in this report, Doppler radar offers opportunities for deployment from road and rail bridges and from overhanging gantries. Purchase and installation costs are also likely to be lower than for acoustic devices. Maintenance costs for long term installations are not yet well known, but are likely to be less than hydrometric instruments having submerged components that are more vulnerable to damage. Some of the more specific points are covered below:

7.4.1 Practical constraints on site selection

Amenity and navigation
If positioned appropriately radar devices should not generally pose a problem for navigation or to other users of river amenities.

Sediments and Debris
Sediment and debris do not generally pose a problem when using Doppler radar methods, so long as there is no change in the relationship between stage and wetted cross sectional area.

Temperature
Theoretically there are no temperature constraints on the method. However the method is not appropriate for sites where ice cover can be problematic.

Bank topography and access
Bank topography can affect access to the site, and may constrain equipment requirements. If device are mounted on bridge piers or gantries, there must also be adequate access.

Vandalism or disturbance
Vandalism is an important risk as the device is likely to be sited in an open area. Some method of camouflage may be required at vulnerable sites. Loggers and power supply can be located in a hut.
Services and access
The commercial devices available require a 12V power supply and have low power consumption, allowing them to be used in remote areas without connections to mains electricity or a permanent on-site capacity for generation.

If telemetry is to be used, the site must either have connection to the landline telephone network, or be located in an area having suitable mobile network coverage.

7.4.2 Impact on local environment
As visual intrusion and disturbance during installation are minimal, there will be negligible impact on the local environment.

7.4.3 Feasibility study
Assuring the feasibility of the method at the proposed site is an important, time consuming and potentially costly aspect of procuring a new site. However as the chemical and physical characteristics of the water are not relevant (as surface velocity is measured) in this case, the feasibility study should be less involved than, say for acoustic instruments. In the case of radar methods the focus should be on ensuring the site is suitable for use of index velocity methods. Specific requirements are:

- detailed cross-section survey,
- stage variation survey,
- determination of relationship between mean velocity in the direction of flow, channel discharge and stage,
- survey of sources of radio interference,

7.4.4 Capital expenditure
Feasibility, design, instrumentation, utilities, installation and commissioning are considered as contributing to the total capital cost of installing a gauging station based on Doppler radar methods. Capital costs would also include any compensation and legal costs, and land purchase or lease if required. As no radar gauging stations have been installed, to date, it is difficult to estimate what total capital costs are likely to be.

Feasibility and design costs
Feasibility and design costs are likely to be lower than for, say, acoustic methods. A figure of between £5000 and £15,000 seems appropriate.

Instrumentation
Current market prices are approximately £3,000 to £5,000. Other costs include the mountings, cabling, console unit, loggers (memory) and batteries.

Installation costs
Installation costs will typically be low. Little construction work is required, with the exception of the mountings.
Calibration costs
Calibration of newly commissioned Doppler radar devices will need to follow the index velocity method. This can be done using current meter measurements, other velocity-area methods such as ADCP or using computations based on theoretical velocity profiles. The effort required and cost involved will depend on which of these methods is used but is likely to involve check gaugings taken over the year at a cost of approximately £6000. On going check gauging is likely to cost about £2500 per annum.

7.4.5 Design life and data capture
The design life can be assumed to be in the 10 to 20 years bracket. However the technology is likely to be outdated before the instrument would need to be replaced.

7.4.6 Staff training
It is essential that staff using Doppler radar instruments are properly trained. Staff involved in data management and interpretation should also be properly trained. Training issues include the availability of training from manufacturers or the possibility of in-house training, the number of staff to be trained, cost per head and availability of manuals. Training costs can therefore vary considerably depending on which make and model is used.

7.4.7 Routine maintenance, operational issues
Doppler radar devices will typically require specialised maintenance. Maintenance will generally involve repair of faults and checking the device after spurious data have been collected. Maintenance costs are likely to be of the order of £1000 per year. A large proportion of this cost represents fees by specialist contractors or manufacturers for maintenance and minor repairs. Major repairs may not be economical and may exceed the purchase cost of the instrument.

Clearance of overhanging vegetation will also need to be addressed during routine maintenance visits.

Additional equipment such as telemetry and generations may also require regular maintenance. Maintenance of telemetry might typically cost between £200 and £600 per annum.

7.4.8 Health & safety
Health and safety implications depend on how, and where the device is mounted. Except during calibration, health and safety issues associated with gauging are minimal. There is a minor risk of electric shock. It is anticipated that any radar sensor used in hydrometry will conform to appropriate safety standards.

7.5 References


8 PARTICLE IMAGING VELOCIMETRY

8.1 Introduction

The term Particle Imaging Velocimetry (PIV) is used to describe instruments that remotely sense flow velocity using an imaging system. The basic principles of operation of all PIV systems (except the rising float technique, see below) are essentially the same, and from a fundamental perspective, very straightforward: a camera is simply used to track the motion of discrete particles in the flow through time. It is assumed that these particles closely follow the path of the flow. Therefore, by knowing the time between images recorded, and the dimensions of the camera field of view, it is possible to determine the velocity and trajectory of the flow.

In practice PIV systems are more complex and only a little has been done to develop PIV systems for measuring flow in natural open channels (called natural-flow PIV systems hereafter). In fact, there are no long-term PIV monitoring gauges in operation in the UK or elsewhere. Like most new velocimetry technology, early development efforts in PIV have focussed primarily on laboratory-based systems designed to measure flow in hydraulic flumes and wind tunnels rather than natural river channels. However, as laboratory-based PIV systems become more reliable and versatile, and the technology more robust, it is expected that the development of natural-flow PIV systems will follow.

The Rising Air Float Technique (RAFT) is a particle tracking method that has been applied on an experimental basis in the UK for a number of years. In many respects RAFT is similar to PIV, but is based on imaging the movement of air bubbles that have risen through the water column. The bubbles are displaced downstream as they rise, with the rate of displacement proportional to the velocity of the flow. To date, only simple image processing has been possible, but the method could be adapted for use with the more sophisticated imaging processing techniques used in many PIV systems.

This chapter evaluates the potential use of PIV and RAFT systems for stream gauging in the UK, drawing on published reports, instrument manufacturers’ technical literature and user expertise. Constraints to be overcome if such instruments are to operate effectively are also considered and development issues are proposed and discussed. Given that such methods have not yet been used for continuous stream gauging in the UK, this chapter is more speculative than some of the previous chapters.

8.2 Principles of Operation of PIV Systems

8.2.1 Laboratory-based systems

Although the focus of this study is on stream gauging in natural channels, a discussion of laboratory-based instruments will provide insight into how PIV systems operate under ideal circumstances, and as such, will help to elucidate some of the likely problems associated with the practical use and development of natural-flow PIV systems.

Advanced PIV systems are now used regularly in both hydraulic flumes and wind tunnels. A schematic illustration of the main components of a typical flume-based PIV system is shown in Figure 8.1. To obtain velocity measurements in a flume with PIV,
The flow is first seeded with neutrally buoyant tracer particles, called ‘seeding’, which closely follow the path of the flow. Although very simple types of seeding, such as milk, can be used, manufactured seeding is generally preferred because it has been developed to disperse evenly in the flow and to have high reflective properties, which make it easier to detect. One of the most common forms of manufactured seeding is hollow glass beads coated in a reflective element such as silver or titanium.

**Figure 8.1: Schematic illustration of the components of a flume-based PIV system**

Once the flow has been seeded, a test section is illuminated with some form of light source so that the seeding material is visible as it moves with the flow. Rather than lighting the entire channel, most laboratory-based PIV systems now use a laser that creates a 2-dimensional sheet of light that slices through the flow, illuminating the seeding particles in a particular plane. This allows for the measurement of velocities at very precise locations in the flow, such as along the centre of the channel, where vertical velocity profiles can be obtained (as shown in Figure 8.1). When the laser sheet slices through the flow, the light is scattered by the seeding material, and each particle is illuminated as it moves. A digital camera, positioned perpendicular to the laser sheet, is then used to record the motion of the seeding material through the glass sidewalls of the flume channel. A schematic illustration of the image collection process is shown in Figure 8.2. The first image pair is captured at time $t=1$ (Image A) and $t=1+x$ (Image B), where $x$ is the time between image recordings.

**Figure 8.2: Schematic illustration of the process of image capture in PIV.**
The camera first records two consecutive images, which are separated by a very short period of time. This image pair is then used to determine the displacement of the particles between the first and second image, from which velocity is determined (velocity derivation is discussed below). Once the first image pair has been recorded, the system pauses before a second image pair is recorded. This second image pair is then used to determine the velocity of the flow at the second time step. The time between the recording of image pairs determines the time resolution of the velocity measurement. For instance, if an image pair is recorded every second (i.e. 1 Hz), a velocity measurement will be derived every second.

8.2.2 Data processing

The process of deriving velocities from an image pair is shown in Figure 8.3. Step 1 represents the image capture phase. In step 2, a digital mesh is superimposed over the image pair in an image processing package. The purpose of this mesh is to subdivide the main images into many smaller sub images, called interrogation regions. By deriving a separate velocity vector for each interrogation region, the spatial distribution of velocity across the entire field of view can be derived.

![Figure 8.3: Flowchart illustrating the steps involved in deriving velocity vectors from image pairs.](image)

In step 3, interrogation region ij is sub sampled for velocity calculation. To determine the velocity in this region, the average spatial shift, or displacement, of seeding particles from sub Image A to sub Image B is determined. This image displacement is illustrated by the following linear signal-processing model:

\[
\begin{align*}
F(m,n) & \quad \text{Input Image (i.e. sub Image A)} \\
S(m,n) & \quad \text{Image transfer function (i.e. Spatial Shift)} \\
D(m,n) & \quad \text{Additive noise function} \\
G(m,n) & \quad \text{Output Image (i.e. sub Image B)}
\end{align*}
\]

where the function \( F(m,n) \) describes the recorded light intensity of the interrogation region at time \( t \) (i.e. sub image A) and function \( G(m,n) \) describes the light intensity of the same region at \( t+\Delta t \) (i.e. sub image B). These two terms essentially represent the input \( (F) \) and the output \( (G) \) of an image shift function \( S \), which is directly related to the velocity of the flow. Function \( D(m,n) \) represents the addition of noise to the signal.
The primary task of PIV is to use sub Image A and sub Image B to estimate the shifting function. There are various ways in which this can be done. However, modern PIV systems tend to use the statistical technique of spatial cross-correlation (Step 4). Spatial cross correlation is essentially a similarity test, which compares the recorded light intensity of each pixel in sub Image A with each pixel in sub Image B. By doing so, the cross-correlation procedure identifies a signal peak, which represents the average displacement of seeding particles between the two sub images. The location of the peak is determined with a Gaussian 2-dimensional curve-fit. This fit describes the light signal surrounding the peak and can be used to interpolate its location to sub-pixel accuracy (Huang et al., 1997).

Once the location of the peak is determined, the average spatial shift of particles between sub Image A and sub Image B is known. At this point, the conversion to velocity is simply a function of the time interval between the two sub images. Once a velocity has been estimated for interrogation region ij, Steps 2 and 3 are performed for interrogation region i+1, j+1, then for i+2, j+2 and so on until the vector map is complete. When the vector map for the first time step is complete, processing of the vector maps for subsequent time steps continues until all vector maps are complete. Further details on the principles of operation for PIV systems can be found in Huang et al. (1997), Westerweel (1997), and Ohni and Li (1997).

8.3 Natural-flow PIV Systems

Natural-flow PIV systems are those designed to measure flow in natural river channels. Currently, there are no long-term gauging stations operating PIV systems in the UK or elsewhere. However, several attempts to estimate velocity and discharge in natural channels with PIV for very short, discrete, periods of time have demonstrated a ‘proof of concept’ (e.g. Fujito and Nakashima, 1997; Fuita et al., 1997, 1998; Bradley et al., 2002; Creutin et al., 2002; Fujito and Tsubaki, 2002; Miyamoto and Kanda, 2002; Creutin et al., 2003). Despite operating in different environments, these natural-flow PIV systems have the same general principles of operation as laboratory-based PIV systems: i.e., they measure the displacement of particles in the flow from one camera image to the next and convert that displacement into a velocity using spatial cross correlation and subpixel interpolation.

There are, on the other hand, significant differences, and additional difficulties, associated with implementing PIV systems in natural channels, especially if the end goal is to estimate the discharge of the river. In the following sections, natural-flow PIV systems are discussed in the context of stream gauging. Developmental issues and possible solutions are also discussed. However, given the limited information available on natural-flow PIV systems, many of the concepts addressed are largely theoretical.

8.3.1 Measuring velocity in natural rivers with PIV

In laboratory-based PIV systems, a laser is typically submerged in the water and used to illuminate seeding particles in a plane that dissects the flow. Clearly, similar types of measurements would be ideal for river discharge estimates as they would provide an indication of the distribution of velocity throughout the water column and therefore negate the need for velocity indexing. Although theoretically possible, obtaining this type of data with a natural-flow PIV system would be impractical for a variety of reasons. Firstly, it would not be safe to submerge lasers in natural rivers. Secondly,
natural rivers do not have glass side walls like flumes, and thus it would be necessary to submerge the camera in the flow, perpendicular to the laser sheet. Thirdly, laser illumination systems and submersible cameras are extremely expensive and difficult to maintain.

In reality, it is probably only feasible to use PIV to measure the motion of particles floating on, or very near, the surface of a natural river channel. In this type of set up a laser system is not required, assuming there is enough natural light for the camera to detect the particles. Furthermore, the camera could be mounted on a bank or bridge looking down on the water surface, and thus would not need to be submerged. Monitoring flow velocity in this manner has been attempted over short periods of time by several research institutions.

Creutin et al., (2003) used the PIV system illustrated in Figure 8.4 to measure surface velocities on the Iowa River (USA) for periods of ten minutes at different times of the year (discharges ranged from 50 to 300 m$^3$s$^{-1}$). Their system comprised of a camera mounted on a building, which recorded the motion of natural foam on the river surface. This motion was then used to determine the velocity of the surface flow using spatial cross correlation. However, because the camera was positioned at an oblique angle to the surface, it was necessary to first correct for image skew. This involves a geometric transformation process related to the camera angle and the distance to the surface (see Fujita et al., 1997).

Bradley et al., (2002) used a similar set up to measure surface velocities for 30 seconds on Clear Creek near Oxford Iowa (USA), a much smaller stream (discharge 0.192 m$^3$s$^{-1}$). In their study, there was an insufficient supply of natural seeding material on the surface of the river and it was necessary to artificially seed the flow with fallen leaves gathered from the banks of the river. Fujita and Nakashima (1997) measured the flow around groins under low flow conditions on the Nagara River (Japan), where there was also an insufficient supply of seeding. To compensate, they seeded the flow with small pieces of cornstarch, a non-toxic substance normally used in the packing industry.

![Figure 8.4: A natural-flow PIV system setup with a camera mounted on the bank, at an oblique angle to the river surface](image-url)
As with Microwave Doppler Radar (Chapter 7), one of the key problems associated with the above PIV set up is the difficulty in accurately relating surface velocity $u$ to mean channel velocity $\bar{v}$ for the purpose of discharge estimates. A calibration of the form

$$Q = k \bar{u} A_w$$

is often used, where $Q$ is discharge, $A_w$ is the wetted crossed sectional area and $k$ is a coefficient relating surface velocity $u$ to mean velocity $\bar{v}$. The value of $k$ depends on the vertical velocity profile within the flow, which in turn is closely related to the channel profile, boundary roughness conditions, turbulence characteristics, and water depth. Ideally, the coefficient $k$ should be derived empirically by index velocity calibration over a wide range of flow conditions. However, more often than not, a simple logarithmic or power law profile of velocity is assumed, so that

$$\bar{v} = 0.85 \bar{u}$$

Creutin et al., (2003) used this technique to convert the surface velocity measurements they obtained with PIV to discharge estimates. A comparison of their discharge estimates with a gauging station located on site showed that the index method underestimated the discharge by approximately 4%. Recent research has shown that velocity profiles in natural rivers are not always logarithmic, particularly if the river bed is composed of coarse-grained material and occupied by bed forms (e.g. Lawless and Robert, 2001). Thus, assuming a single value for $k$, for all flows and all locations, may misrepresent the velocity column, and lead to uncertainly in discharge estimates. To overcome this problem, index velocity calibration should be carried out.

### 8.3.2 Developmental challenges

The three studies highlighted in Section 8.3.1 demonstrate a ‘proof of concept’ in terms of the ability to use natural-flow PIV systems to measure discharge in natural rivers. However, in each study the flow was only measured for discrete, short periods of time, under closely monitored conditions. If PIV systems are to be used for continuous, unmonitored stream gauging, a number of significant developmental challenges must first be overcome. This section outlines some of these challenges and proposes possible solutions.

**Source of seeding**

A prerequisite to obtaining accurate surface velocity measurements using PIV is a consistently high density of seeding material floating on, or near, the surface of the river at all times. Several studies have shown that if this seeding density is less than five particles per interrogation region, the flow velocities derived will be significantly underestimated. Furthermore, if no seeding is detected, no velocity measurement can be derived. Natural sources of seeding such as surface foam, bubbles and leaves may not be of a sufficiently high density or consistency to result in accurate flow measurements at all times of the year, particularly during periods of low flow when fewer particles are in suspension. Thus, a reliable natural-flow PIV system will probably need to rely on an artificial source of seeding.

This seeding could involve the continuous release of air bubble, which would involve the installation of an electric pump. If the PIV system was installed downstream of a
waterfall, or some other structure that produces bubbles naturally, artificial seeding of the flow might be avoided. However, this would only be practical if the density and distribution of the bubbles was relatively constant throughout all flows, at all times of the year. It is expected that an artificial aeration systems may provide greater control than natural sources and will thus be more practical in terms of stream gauging using PIV. This would, on the other hand, be an additional expense in terms of both installation and running costs (electricity and maintenance), and would need to be acceptable in environmental terms.

Source of light
Another important factor that will affect the accuracy of flow measurements derived using PIV is the distribution of light on the water surface. PIV requires a consistent source of light so that the motion of seeding particles can be detected and recorded at all times. Any variation in the light source, even minor, may lead to erroneous results.

Clearly an artificial source of light, such as a spot light or floodlight, would be required at night or during periods of low light. However, lighting the river may attract unwanted attention and could increase the likelihood of vandalism and theft, especially if the system is located in an urban area. Lighting the river will also be an additional expense, both in terms of installation and running costs. Nevertheless, lighting the surface of the river will be a necessary component of any natural-flow PIV system if accurate night time measurements are to be obtained. Lighting the river surface during daylight hours may also be beneficial because the artificial light source would reduce the influence of shadows (i.e. from trees, buildings, clouds) and daily variations in light on the velocity measurements derived.

Installation location
Installing the PIV system at an appropriate location will also influence the accuracy of the measurements derived. In the studies highlighted in section 8.3.1, the PIV camera was mounted on a bank of the river at an oblique angle to the flow. This set up requires a geometric transformation of the images before the processing of velocity can begin, because the images are skewed. The transformation factor required to correct the skew is a function of stage, because variations in stage effectively alter the camera angle. Thus, capturing images on a continuous basis in this manner will require complicated image processing techniques that will increase the uncertainly of the measurements derived. For continuous gauging using PIV, it may be more beneficial to mount the camera directly above the river surface, perpendicular to the flow. This could be accomplished by mounting the camera to the underside of a bridge, as shown in Figure 8.5.

In this set up, the camera would be perpendicular to the flow during all stages, thus eliminating the need to geometrically transform the images. There may also be other advantages to mounting the camera to the soffit of the bridge. For instance, the limited natural light under the bridge would be advantageous because it would reduce the influence of daily variations in light and shadowing effects on the images captured. An artificial source of light could then be used to provide a more uniform distribution at all times of the day and night. The opening of the bridge will also have a regular geometry. Thus, the relationship between stage and cross-sectional area will be well known and constant through time, leading to more reliable estimates of discharge. Attaching the PIV system to the soffit of the bridge may also provide a margin of protection against
vandalism and theft, although it will make maintenance more difficult than if the system was installed in an open area.

The major disadvantage associated with attaching the PIV system to the underside of a bridge is that the bridge may overtop during extreme flood events, thus rendering the system useless and vulnerable to damage by water and floating debris. Clearly, the system would therefore be best suited to bridges with high soffit levels and low probability of overtopping and special measures would be required to protect the system during an overtop situation.

![Figure 8.5: Schematic illustration of a natural-flow PIV system attached to the underside of a bridge](image)

**Camera**

Accurate surface flow measurements require a properly focussed camera. It is essential that individual seeding particles are distinct from the surrounding flow in each image recorded and that they each occupy at least three pixels. This requires a precise and continuous focusing procedure because the distance between the camera and the surface changes as stage changes. This could be accommodated for by an automatically focusing camera, or alternatively, there could be a feedback mechanism whereby the camera moves with the stage: i.e. a motorised carriage holding the camera could be linked via telemetry to a depth sensor, and could move with the stage. This would maintain a constant distance between the camera and the water surface and would thus negate the need for refocusing. This technique would be particularly useful if the camera was mounted on the river bank at an oblique angle to the surface, because the angle (and thus the transformation factor) would be maintained at all times. If the camera was to be mounted to the underside of a bridge, an automatically focussing camera would be sufficient.
Weather conditions
Weather conditions may also affect the accuracy of the flow measurements derived using PIV. For instance, clouds create variations in light, and unless compensated for by an artificial light source, may affect the flow estimates. Rainfall may also have an affect on the system, however, the nature of its influence is unknown. Presumably, raindrops will function similar to an aeration system and may actually increase the density of traceable seeding on the surface of the river, thereby improving the reliability of the measurements. However, rainfall may have the opposite effect if it alters the properties of the seeding particles normally detected by the camera. As with microwave Doppler radar, ice cover will render a PIV system useless because it will mask the flow.

Image processing
PIV is essentially an image processing system, and thus requires a PC to derive flow measurements. Theft and damage will be significant concerns if the PC is installed on site. However, if the images collected could be transferred via a landline or mobile network, the PC required could be located at an Environment Agency office.

Data storage
In terms of data storage, it would be impractical to save the image files collected using PIV on a continuous basis. For instance, if velocity measurements were required at 15 minute intervals, this would necessitate the collection of 720 images a day. If each image was 1 megabyte in size, 263 gigabytes of storage would be required every year. The more practical solution would be to process the image files in real time and only to store the derived velocities, which could be saved in binary format (low storage requirements). However, disposing of the images themselves would eliminate the ability to reprocess velocity measurements at a later date (i.e. in the case of recalibration).

8.3.3 Summary of system requirements
Although some of the system requirements for natural-flow PIV systems are similar to those required for the techniques described in previous chapters, some of the more specific requirements of a PIV gauging station, which should be considered if optimal data quality is to be achieved, include the following:

- The velocity distribution should be uniform, the channel confined and areas with eddies or turbulence avoided. The relationship between water depth and velocity should be stable and well understood, or else an index calibration undertaken. For PIV, this could be achieved by installing the system to the underside of a bridge opening.

- If the PIV camera is installed at an oblique angle to the flow, the images will need to be geometrically transformed before velocity is processed. The associated transformation factors will also change with stage, leading to a complicated pre-processing procedure. Image transformation could be avoided if the PIV system is housed on the underside of a bridge perpendicular to the flow. In this set up no geometric transformation would be required. However, an auto focus camera would need to be installed.

- An artificial light source will be required to provide light in times of darkness and to help reduce the influence of shadowing (i.e. from trees, buildings and clouds) and daily variations in natural light.
• An artificial aeration system, or some other form of seeding, will be required to ensure that the camera can detect a high density (at least 3 particles per interrogation region) of particles at all times of the year.

Following from these points, natural-flow PIV systems require particular conditions to operate reliably and accurately. Provided these conditions can be met, a high level of measurement accuracy can theoretically be achieved. However, because the quality of the estimates is a function of a variety of interrelated factors, and because few natural-flow systems have been tested thoroughly, it is difficult to assess the exact accuracy of the method. Nevertheless, for their studies, Creutin et al. (2003) indicate a standard error in discharge estimates of approximately 4%, whilst Bradley et al. (2002) suggest a standard error in discharge estimates of 6.4%.

8.4 Rising Air Float Technique (RAFT)

8.4.1 Principles of operation

Like the natural flow PIV systems discussed above, the Rising Air Float Technique (RAFT) is a type of particle that relies on the release of buoyant tracer particles (usually air bubbles) from the bed of a stream. The methodology used to derive discharge with RAFT is different to PIV, and has the potential to take better account of velocity variations within a cross section. As shown below, the calculation of velocity is implicit within the RAFT technique. However, since the approach relies on particle imaging of some sort, and integrates velocity over the cross sectional area, it has therefore been grouped with PIV for this report.

Bubbles rising to the surface will be subject to forces that cause movement both in the vertical and horizontal (downstream) planes. The vertical motion of bubbles rising to the surface can be expressed as

$$\frac{dz}{dt} = u_{term} \quad (8.3)$$

where $u_{term}$ is the terminal rise velocity of a bubble, $z$ is the vertical dimension and $t$ is time. Horizontal motion in the downstream direction is described by the equation

$$\frac{dx}{dt} = v(z) \quad (8.4)$$

where $x$ is the horizontal dimension and $v(z)$ is the downstream component of bubble velocity at a vertical position $z$. It is assumed that the bubbles travel horizontally at the same velocity as the water that conveys them. Combining the equations of motion and integrating results in the following expression,

$$\int_0^d v(z)dz = \int_0^L u_{term}dx \quad (8.5)$$

where $d$ is the local depth of flow and $L$ is the distance downstream at which bubbles emerge at the surface. The left hand side of Equation (8.5) is the depth-integrated downstream velocity, $v(z)$, which is equivalent to the discharge per unit channel width.
Note that Equation (8.5) is written in terms of depth and downstream distance \( x \) only. To calculate the discharge in a channel of width \( B \), it is necessary to integrate Equation (8.5) over the lateral dimension, \( y \). The resulting expression for the channel discharge is

\[
Q = \int_0^B \int_0^d v(y,z)dzdy = \int_0^B u_{\text{term}} L(y)dy. \tag{8.6}
\]

The application of the theory behind RAFT is very simple. Bubbles of a given diameter are released through a perforated pipe laid across the bed of a channel. The bubbles rise to the surface and emerge downstream, creating what is known as a bubble envelope (Figure 8.6).

![Figure 8.6: Schematic illustration of a RAFT system (plan view)](image)

If the terminal rise velocity of the bubbles is assumed to be constant through the water column, then it is possible to simply the right hand term in Equation (8.6) to give

\[
Q = u_{\text{term}} \int_0^B L(y)dy \tag{8.7}
\]

The integral in Equation (8.7) is the area of the bubble envelope at the surface. If the rise velocity of the bubbles is known, it is therefore possible to estimate discharge from the envelope area using the simple formula

\[
Q = u_{\text{term}} \times A_b \tag{8.8}
\]

where \( A_b \) is the envelope area. The terminal rise velocity depends primarily on the size of the air bubbles and can be calculated using the relationship

\[
u_{\text{term}} = \frac{8R_b g}{3C_D} \tag{8.9}
\]
where \( R_b \) is the radius of a bubble, \( g \) is acceleration due to gravity, and \( C_D \) is a drag coefficient (assumed to be 2.72 for fully turbulent flow).

Several attempts to use RAFT for both spot (Viol and Semenov, 1964; Liu and Martin, 1968; Sargent, 1981, 1982; Yorkshire Water, 1986) and continuous (Toop et al., 1997) stream gauging have demonstrated that the technique can provide highly accurate discharge estimates. For instance, Viol and Semenov (1964) demonstrated that the RAFT technique was accurate to within 2% of spot estimates obtained with current meters, whilst Sargent (1981, 1982) found an average discrepancy between RAFT and current meter gaugings of 1.3% (range of -6% to +10%). Despite these promising results, as yet no continuously monitoring RAFT system is operating in the UK.

### 8.4.2 Developmental Issues

The developmental issues that will preclude the use of RAFT for continuous gauging are similar in nature to PIV and will generally involve the development of a system that can operate with little or no intervention; all previous applications of RAFT have been under highly controlled conditions. Some of the specific developmental issues expected are as follows:

**Determination of the bubble envelop area**

Previous attempts to use RAFT have generally involved directly measuring the bubble envelope area on site. If RAFT is to be used for continuous monitoring, an automatic and continuous system of measuring \( A_b \) would be required. Although attempts have been made to measure the envelope area indirectly using photographic images obtained on site, difficulties in lighting and perspective have resulted in limited success (Toop et al., 1997; Yorkshire Water, 1986). However, it is expected that an automated digital imaging system, similar to that described for PIV, using newly developed image processing software and appropriate lighting, may provide the necessary tools to implement continuous monitoring with RAFT. The authors are not aware of any such developments at present. However, many of the components suggested for the natural flow PIV system would also benefit an automated RAFT system.

**Estimation of Terminal Rise Velocity**

If velocity measurements obtained using RAFT are to be accurate, the terminal rise velocity of the bubbles should be uniform and constant through the water column. Any deviation from the terminal rise velocity assumed in Equation 8.9 and the actual terminal rise velocity at a specific time will result in error. There are various parameters that affect the terminal rise velocity of the bubbles (see Toop et al., 1997); perhaps most important is the pressure in the air supply pipe which determines the size and shape of the bubbles. Because this pressure will change as a function of depth, it will be necessary to develop either an automated feedback system that maintains a constant pressure in the pipe or a self calibration function, based on pressure sensors, which will adjust the estimates of \( u_{term} \) accordingly. Previous studies using RAFT techniques have generally been conducted under steady flow conditions and so these stage variation issues have not been addressed.

**Camera**

As for PIV, accurate discharge measurements using RAFT will require a properly focussed camera. It is essential that bubbles are distinct from the surrounding flow in order to determine the bubble envelope area. This will likely require a precise and
continuous focusing procedure because the distance between the camera and the surface changes as stage changes. This could be accommodated by an automatically focusing camera, or alternatively, there could be a feedback mechanism whereby the camera moves with the stage, as suggested for the natural flow PIV system.

**Installation Location**
For continuous gauging using RAFT it may be beneficial to mount the camera directly above the river surface, perpendicular to the flow. This could be accomplished by mounting the camera to the underside of a bridge, where the camera would be perpendicular to the flow during all stages, thus eliminating the need to geometrically transform the images. This type of system could also benefit from artificial lighting, which would provide a uniform distribution of light at all times of the day and night.

**Weather Conditions**
Weather conditions may also affect the accuracy of the flow measurements derived using RAFT. For instance, clouds create variations in light, and unless compensated for by an artificial light source, may affect the flow estimates. Rainfall may also adversely affect the system if the raindrops disturb the water surface and mask the boundary of the bubble envelope area. As with Microwave Doppler Radar and PIV, ice cover will render a RAFT system useless.

**Other considerations**
The system requirements and practical and resource considerations that might be expected if a continuously monitoring RAFT system is to be developed and employed in the UK would probably be identical to those outlined for natural flow PIV systems and are discussed in Section 8.5.

**8.5 Practical and Resource Considerations**

There are a number of technical, environmental or economic issues that might constrain the use of PIV or RAFT methods at a particular site. These issues are addressed in the following sections.

**8.5.1 Practical constraints on site selection**

**Service and Access**
Imaging systems are generally designed to be powered by an external source. Battery powered systems would not be practical given the considerable energy consumption required to light the surface of the river and to run the aeration system. If telemetry is to be used, the site must have either connection to the landline telephone network, or be located in an area having suitable mobile network coverage.

**Amenity and navigation**
A natural-flow PIV system would not generally pose a problem for navigation or to other users of river amenities. However, sites with high levels of river traffic are not ideal locations because the images recorded might be interrupted by passing boats.

**Cabling requirements**
Although none of the main components of the PIV system would require cross-channel cables or bed mounted devices, a pipe would need to be laid if an aeration system is installed (RAFT). This may create a constraint associated with dredging.
**Ice and Temperature**
Theoretically, there are no temperature constraints associated with particle imaging systems. However, PIV is unable to operate if the surface of the river is covered with ice. Thus, the technique may not be suited to northern regions, where sub-zero temperatures are expected for prolonged periods of time.

**Debris**
Moderate levels of debris would not adversely affect an imaging system. However, in channels where debris is extremely problematic, floating material may interfere with seeding particles or bubbles and thus influence the quality of the measurements derived.

**Vandalism or disturbance**
The potential for vandalism at a PIV gauging station is significant because the artificial light source required may attract unwanted attention. Furthermore, the main component of the system is a digital camera, which may be a target for theft. Attaching the system to the underside of a bridge would make access to the equipment more difficult and thus reduce the risk of vandalism and theft. However, this will make regular maintenance and repair more difficult than if the system was installed on the banks of the river.

8.5.2 **Impact on local environment**
The impacts of flow gauging technologies on the aquatic environment have been considered in Chapter 2. Key specific points of relevance to PIV and RAFT are discussed below.

**Ecology, habitat & migrating fish**
The main components of the system are not submerged within the channel and thus will not affect local habitats, ecology or migrating fish. However, if an artificial mechanism for seeding is installed, such as an aeration system, there may be some minor effects on local habitats. Aeration

**Visual intrusion**
The only significant visual intrusion associated with PIV is the artificial light source required to illuminate the surface of the river and the bubbles produced by the aeration system (if one is installed). These issues are considered to be minimal as long as the light does not affect local properties.

**Disturbance during installation**
During the installation phase there may be some disturbance laying cross channel cables for the aeration system. This may require the temporary clearance of vegetation on the channel banks. River diversion would not generally be required.

8.5.3 **Feasibility study requirements**
Assuring the feasibility of a PIV gauging station at a particular site will be an important, time consuming, and potentially costly procedure. This procedure should focus on the following issues:

- The suitability of the site for the index velocity method. This will require a detailed cross section survey of the site, a stage validation survey, and
determination of the relationship between mean surface velocity $\bar{u}$, mean velocity $\bar{v}$, stage and channel discharge.

- The availability of natural seeding sources. This will require a survey of the density and consistency of naturally occurring particulate matter (e.g. surface foam, bubbles, vegetation debris) in the flow at different discharges and times of the year. If there is an insufficient supply of natural material, the feasibility of an aeration system must be addressed.

- The number of days, if any, the river is likely to be covered with ice.

- The effects of shadows (from trees and buildings) and daily variations in light on the surface of the river.

In addition the feasibility of a RAFT gauging station will depend specifically on:

- Feasibility of installing an aeration system at the site.

- The amount of debris, weed or foam etc. that might obscure the site.

### 8.5.4 Capital Expenditure

It is difficult to estimate what the required expenditure might be for a natural PIV or RAFT system. The figures quoted here are broad estimates based on experience of lab-based methods.

#### Cost of feasibility study and design costs

Costs of feasibility and design elements are likely to be comparable to other methods; in total around £30,000 to £50,000 depending on the site.

#### Instrumentation costs

Instrumentation costs will include a digital camera, a PC for image processing, a light source, an aeration system, mountings, cabling, and loggers. Depending on sophistication of the equipment used, costs are likely to be in the order of between £10,000 and £20,000.

#### Utilities cost

Utility costs will mainly include electricity and back up power. Electricity costs are expected to be relatively expensive if an aeration system and artificial light source are installed. Consideration should also be given to the costs associated with transferring the images collected onsite to an offsite facility via telemetry on a continuous basis; for this a BT line or mobile phone link would be required.

#### Installation costs

In some situations it is likely that installation costs might exceed instrumentation costs. A large proportion of this will arise from the installation of cross channel pipes/diffusers for the aeration system if one is required. Additional costs include mounting the camera and light source to the banks of the river or to the underside of a bridge.

#### Calibration and commissioning costs

Calibration of newly commissioned PIV systems will need to follow the index velocity method. This can be done using current meter measurements, other velocity-area
methods such as ADCP, using computations based on theoretical velocity profiles, or using self-calibration techniques. It is expected that the calibration of a new PIV system will require specialist knowledge. However, the effort required and cost involved will depend on the methodology chosen, the complexity of the flow-stage relationship, and channel stability.

8.5.5 Design life and data capture

The design life of the site is likely to depend on the electrical equipment. Cameras are most at risk of damage or theft and may need to be replaced several times during the lifetime of the gauging station.

8.5.6 Routine maintenance, operational issues and performance checking

PIV systems typically require specialised maintenance, which will generally involve repairing faults and checking the components of the system after spurious data have been collected. As natural-flow PIV systems have not been yet been used for long-term gauging, it is difficult to anticipate exact maintenance costs. However, a large proportion of these costs will probably represent the fees of specialist contractors or manufacturers.

Less specialised maintenance requirements will include: checking that the camera lens is free of debris; removing any vegetation that may disrupt the aeration system; and regularly checking bulbs in the lighting system.

Additional equipment such as telemetry and generations may also require regular maintenance. Maintenance of telemetry might typically cost between £200 and £600 per annum.

Performance checking (audit) usually involves taking a limited number of check gaugings throughout the year. The number of performance checks required on an annual basis will depend on the perceived performance of the device. There are currently no guidelines for good hydrometric practice using natural-flow PIV systems or the RAFT technique. However, given the complexity of the system it is expected that at least several annual gaugings will be required, particularly in the first few years of operation. It will also be necessary to monitor any variations in the channel bed topography to ensure that the indexing coefficients used are appropriate.

8.5.7 Staff training

The availability of properly trained staff is essential for PIV given the complicated nature of its operation. This refers to staff trained in calibration techniques, technicians able to maintain the instrumentation and operate the instrument control system, staff able to operate data management and image processing software and staff that can interpret the measurements and appreciate factors that might affect the quality of the gauging station data. Training issues include the availability of training from manufacturers, the possibility of in-house training, the number of staff to be trained, and the cost and availability of manuals.
8.5.8 Health & safety

Health and safety implications depend on how and where the device is mounted. Health and safety concerns are negligible in terms of regular gauging procedures. However, there may be safety issues during the calibration phase and during maintenance of the camera and lighting source if they are mounted to the underside of a bridge. There is a minor risk of electric shock associated with the aeration system if one is installed.

8.6 References


9 SEISMIC INDUCTION

9.1 Introduction

The seismic flow meter is an experimental device that is currently being tested at a number of upland sites in Wales (Newman & Bennell, 2002). It is based on a novel method that is very different to other flow measurement techniques considered in this report - inferring streamflow rates from seismic vibrations in the earth around a watercourse.

The advantage of this technique is that it is well suited to streams that are steep and fast-flowing – where the turbulent conditions impart measurable vibrations in the ground. Other gauging methods, including weirs and ultrasonic gauges, do not perform well in these high-energy environments, and few permanent gauging stations have been established in small upland catchments. Also it seems likely that the method will have lower costs than some other gauging techniques.

This potential method is still in the early stages of development and requires further investigation under controlled conditions before it can be fully proven. Unlike PIV (Chapter 8), which has a track record in the laboratory, or Doppler Radar (Chapter 7), which is also an established technology with commercial developers, seismic induction is currently a small-scale development. To date the development has been funded by a mixture of private investment and small grants (including input from Snowdonia National Park and the University of Wales, Bangor) and a more secure source of funding is required for future work to continue.

This chapter briefly summarises the principles of operation of the seismic noise method, and its future potential for continuous flow gauging in England and Wales.

9.2 Principles of Operation

9.2.1 Basic theory

Water flowing in a stream imparts an energy that is proportional to both its rate of flow and the bed slope. The faster the flow and steeper the slope, the higher the energy. This energy is lost in a number of forms, mostly as heat loss through turbulent mixing and friction along the bed and banks, but also as pressure waves at the stream boundaries. Pressure waves radiating from the stream are manifest as sound energy in the air (the characteristic noise of flowing water we are all familiar with) and seismic vibrations in the ground. The fraction of energy converted to pressure waves is small – for example Hawkins (1975) estimated that only about 0.0001% of stream energy is converted to sound – but is still measurable in highly turbulent streams.

The schematic shown in Figure 9.1 illustrates how seismic waves radiating from a mountain stream are detected using a geophone placed near the stream edge. In practice a three-component geophone is used to detect the vibrations (vibration signals are detected in one vertical and two orthogonal components). Detected vibrations are output as signal voltages. To maximise signal detection, the geophone is cemented directly to the bedrock. The geophone is also sensitive to air-borne vibrations (such as from passing aircraft and vehicles), but these effects are dampened by housing the geophone in a brick lined box filled with dry sand as shown in Figure 9.2. Interference can also be
caused by localised ground vibration, such as footsteps for example. Detected vibrations are output as signal voltages. The instrumentation is configured to amplify these signals, and feed them into a logging device.

Figure 9.1: Detection of seismic waves produced around high-energy streams.

Figure 9.2: Geophone housing, Afon Mynach
9.2.2 Signal processing techniques

The measurement interval used in the technique is around three to five minutes. This allows most fluctuations to be smoothed out, whilst preserving enough temporal resolution to reflect changes in flow.

Spectral analysis techniques are used to separate the signal into its various frequency components. Any sources of interference, which are mostly outside the spectral range of the vibrations used for assessing flow, are screened out at this stage. Figure 9.3 illustrates how the power spectrum of the processed signal closely reflects the behaviour of the hydrograph over time, capturing both rising and falling limbs (both vertical and horizontal components of the vibration signal are shown). In this example signals were recorded by the side of an upland stream in Wales (the Afon Mynach) using the geophone shown in Figure 9.2.

![Figure 9.3](image.png)

*Figure 9.3: Variation in seismic vibration for the Afon Mynach compared with flow measurement at the site*

*Reproduced with kind permission of the University of Wales at Bangor.*

9.2.3 Calibration

At present the meter has to be manually calibrated on a site-by-site basis, by establishing a rating between observed flow and observed power. The research so far has shown that this relation is represented by a power law (Bennell, pers. comm.). Regression parameters might be applicable regionally (i.e. for streams with similar slope and bed roughness), although at present there is insufficient data to determine whether this would work reliably.
The disadvantage with calibrating in this way is the inherent inaccuracies associated with current metering in mountain steams, where it can be difficult to measure level and velocities accurately, especially when flows are high. Better calibration might be obtained if flow could be measured by a flume or weir for example. Recent work at a site where controlled releases have been made from reservoirs is likely to give better insight into the relationship between flow and power in the near future.

9.3 Potential for Future Use

Whilst this technique is in its infancy it shows good potential as a practical method of determining flow in mountain streams. It has a number of advantages over other methods that can be used in upland streams, such as dilution gauging (the amounts of salt needed can be prohibitive) and slope-area methods (can be highly inaccurate), and is wholly non-contact. Furthermore the instrumentation required is inexpensive and is battery powered. There would be little problem installing the equipment at a remote site, for example. Data processing is also relatively straightforward (it can be carried out on a standard PC).

At present the accuracy and benefit of the method are limited due to the need to calibrate against flow measured by current metering. Current metering in mountain streams is time consuming, and if a stable, accurate stage-discharge relationship could be generated, there would be little need to bother with seismic measurements. A further disadvantage is the range of flows over which the power-discharge relationship holds. This relationship is unlikely to hold when flows are low, as the stream would have insufficient energy to impart measurable seismic vibrations to the surrounding ground. A hybrid approach, where stage-discharge and power-discharge relationships are used in conjunction might be useful at many sites.

Although the method shows promise, further research is needed to:

- improve understanding of the physical processes inducing the measured signal
- explore signal processing methods for its operational use
- quantify the accuracy and reliability of the method.

This research would be suitable for academic projects, perhaps supported in part by Environment Agency sponsorship.

9.4 References


10 SLOPE – AREA METHOD

10.1 Introduction

There are a number of ‘indirect’ hydraulic techniques for flow measurement in which discharges are inferred based on measurements of stage and channel geometry. An approach occasionally used in hydrometry is the slope-area method (Dalrymple and Benson, 1968, ISO 1070:1992, Rantz, 1982, Herschey, 1995). The slope-area method depends on upstream and downstream measurements of water level in a river reach. It is therefore physically non-invasive and is included briefly in this review.

The slope-area principle is often introduced as a method for estimating peak flows from high water marks, but can also be used for continuous flow measurement or to extend rating curves (Ramsbottom and Whitlow, 2003).

10.2 Principles

The basic principle of the slope-area method is that the water surface slope \( S \) is determined for the measuring reach using two level gauges and the discharge calculated using Manning’s equation. The variations in wetted perimeter \( P \) and cross section area \( A_w \) as functions of stage must also be known. A basic configuration is illustrated in Figure 10.1 where two level gauges are used to measure upstream and downstream water levels \( Y_u \) and \( Y_d \) over a reach of length \( L \).

\[
Q = \frac{1}{n} A_w R^{\frac{2}{3}} S^{\frac{1}{2}}
\]

Figure 10.1: Definition of terms for the slope-area method: (a) long section under uniform flow conditions; (b) cross section representative of the measurement reach used for application of Manning’s equation.
The slope-area method is relevant for steady flow in channels of low slope (less than about 0.1). Manning’s equation is given as:

\[ Q = \frac{1}{n} A_w R^{2/3} S^{1/2} \] (10.1)

where \( n \) is a roughness coefficient, \( R \) is the hydraulic radius of the channel (equal to \( A_w/P \)) and \( S \) is the energy slope. For uniform flow conditions, \( S \) can be estimated from the water surface slope using the upstream and downstream level gauges.

A more general development uses gradually varied flow theory to allow for departure from uniform conditions, which may occur if a gradual change in bed slope, or some other factor, causes velocity to change longitudinally through the measurement reach. A schematic example of one such situation is shown in Figure 10.2. Using the principle of energy conservation, the energy slope becomes the gradient between the upstream and downstream values of water level plus velocity head, and can be written

\[ S = \frac{1}{L} \left( \frac{Y_u + \alpha_u v_u^2}{2g} \right) - \left( \frac{Y_d + \alpha_d v_d^2}{2g} \right) \] (10.2)

where \( L \) is the reach length, \( Y \) is the water level, \((\alpha v^2/2g)\) is the velocity head and subscripts \( u \) and \( d \) indicate upstream and downstream, respectively.

![Figure 10.2: Definition of terms for the slope-area method: gradually-varying flow.](image)

The coefficient \( \alpha \) is a kinetic energy correction factor for the velocity distribution across a river section; it is equal to unity for uniform flows. Calculation typically proceeds by forming an initial estimate of discharge based only on water levels (neglecting the velocity head), then making an iterative adjustment for the velocity head until the computed discharge converges.
10.3 Opportunities to use the Slope-area Method

The slope-area method has the advantage that it only requires two water level sensors, provided the cross sectional areas, hydraulic radius and roughness are reasonably uniform. It requires computer processing to calculate discharge, but this need not be done in real time.

There are a number of limitations of the method, as outlined below. These limitations essentially stem from differences between the physical world and the simplified hydraulic model described by Equations (10.1) and (10.2). An important consequence is that some form of calibration using flow gaugings is likely to be needed in establishing and maintaining a site. In this case, the slope-area method is essentially little different from an open channel rating. However, it has the advantage of coping with variable backwater (using the gradually varied flow approximation), or other conditions that make a unique stage-discharge relationship untenable.

From a practical point of view, the use of a pair of level gauges means the slope-area method can potentially be applied to a reach for low capital cost, especially if at one level station already exists. The ‘hidden’ costs of calibration gaugings and establishing data processing procedures should not be overlooked, however.

10.4 Limitations

The method relies on the steady flow assumption at low slopes, and assumes that the slope, channel area and streambed material change minimally along the gauging reach. It will be less accurate where the channel is highly irregular, such as when floodplain flow occurs, and $\alpha \neq 1$. Furthermore, the accuracy deteriorates for any flow condition where additional energy losses due to flow expansion, contraction, direction change and obstruction occur. At low flows, a single channel definition for braided streams is inappropriate, and thus the method becomes inapplicable.

There will inevitably be some uncertainty in measurement of upstream and downstream water levels. This could be important if the water surface slope is so small that the difference between $Y_u$ and $Y_d$ approaches the accuracy of level measurement. The issue can be addressed by ensuring that the measurement reach length is sufficiently long, although this increases the chances of inaccuracies arising from channel irregularities.

The greatest single source of uncertainty with the method is the accurate estimation of the roughness coefficient $n$. Herschey (1995) noted that “… at the present state of knowledge, the selection of the roughness coefficient… remains something of an art”. The roughness is often treated as a fixed, uniform property of the channel vegetation and substrate material. In reality, roughness varies with depth of flow. It will generally increase with decreased flow depth because of the increased influence of bed roughness elements. Figure 10.3 shows data from 25 river sites discussed in a recent review of roughness for the Environment Agency (Fisher and Dawson, 2003). A two-component power law, shown as a solid curve in Figure 10.3, was proposed to summarise the roughness-depth relationship.
The effects of variation in roughness with depth can be significant. Figure 10.4 shows rating curves for a simple river reach, calculated under uniform flow conditions using a 1D hydraulic model (HEC-RAS). The solid curve (labelled ‘uniform roughness’) was modelled by assuming Manning’s $n$ to be constant with depth. The broken curve (labelled ‘roughness profile’) assumes that Manning’s $n$ varies with depth according to the power law relationship fitted to the data of Fisher and Dawson (2003). The effect of allowing roughness to increase at low stage can clearly be seen in the difference between the two curves.
Roughness may also vary with time (independently of flow depth) because of seasonal vegetation growth and weed cutting. It is probable that calibration gaugings could be used to help optimise the roughness, but this would need to cover the full range of flow rates and also account for seasonal variation.

10.5 Slope, Stage and Conveyance at a Rated Section

The traditional presentation of the slope-area method uses the Manning equation to compute flow. It is based on a roughness parameter, channel cross sectional geometry and an estimate of the energy slope. It is also possible to make a more general conceptual separation between the channel conveyance, $K$, and the slope by writing

$$Q(t) = K(Y,t)\sqrt{S(t)}$$

(10.3)

where the conveyance varies according to water level and time, and the slope and discharge vary with time. Here, $S$ is again the energy slope. Assuming uniform flow conditions, the variation of $K$ with stage alone can be represented by a typical resistance law, such as Manning or Chezy, or derived empirically from gauging, using Equation (10.3).

The result is in effect a stage-conveyance curve. Equation (10.3) may then be used to calculate flow under differing slopes, for example in the presence of variable backwater.

The approach outlined above assumes uniform flow conditions. This may be reasonable in situations where backwater precludes use of a conventional rating curve and the flow is close to uniform over the measurement reach at any time. Where flow conditions are unsteady or varied, the energy slope can differ from the measured water surface slope. This type of behaviour can occur, for example, during the passage of a flood wave, and can lead to a looped stage-discharge rating curve. A kinematic correction for the unsteady flow case is given in Annex E of BS 3680:Part 3C (ISO 1100/2). The kinematic correction assumes that gravity and frictional forces are in balance, but it neglects diffusive forces. Further adjustments to correct for diffusive processes are discussed in text books such as Henderson (1966).

The main principle of the approach described above is to formulate a rating curve for conveyance, using flow gauging, and to account explicitly for slope. Alternative possibilities to allow for non-uniform flow include gauging at both ends of the measurement reach to enable the direct estimation of velocity heads, if conditions allow this to be done safely, or solving the energy Equation (10.2) for each gauging to estimate the energy slope, and hence derive the conveyance.

Where there is no gauging, or insufficient data to derive an empirical stage-conveyance curve, there are other methods available that provide a physically detailed description of the conveyance. In this context, it is worth noting research project W5A-057 Reducing uncertainty in river flood conveyance, commissioned under the Engineering Theme of the joint Defra/Environment Agency Flood Management Science Programme.

Project W5A-057 has delivered a new system for estimating channel conveyance. It includes a ‘roughness advisor’ that uses a database of vegetation types to build up an integrated measure of flow resistance. The resistance is calculated over a number of roughness zones, which can include the main channel, river banks and floodplain. The
roughness advisor also incorporates typical seasonal growth curves and can be programmed with vegetation cutting dates, which gives a time-varying estimate of conveyance.

10.6 References


11 COMPARISON OF METHODS

11.1 Introduction

This chapter sets out a comparison of the non-invasive measurement methods that have been reviewed in this report. It considers the following criteria:

- accuracy,
- suitability,
- costs.

For the relatively new non-invasive technologies, there is not a wide experience base. Anecdotal evidence from our consultation suggests that hydrometric agencies often rely on the manufacturer or manufacturer’s agents to design, install and provide maintenance for the instrumentation. In some cases this even extends to operating the instruments, once commissioned. Experienced field hydrologists are then used to quality check the data and monitor the systems. Where agencies do install equipment themselves, they often rely on manufacturer guidance to help install and configure the systems.

For these reasons it can be difficult to obtain independent data by which to appraise the performance of the methods, especially the newer technologies. Some devices have been widely tested in laboratory conditions using tow tanks and flumes. However, tow tank tests and other lab experiments may not necessarily reflect conditions in the field (e.g. Davies, 2003; Veymeyen, 1999).

11.2 Components of Accuracy

11.2.1 Error and uncertainty

There can be differing interpretations of concepts of accuracy, error and uncertainty in statistics, physical sciences and engineering. Here, accuracy is considered for practical purposes as being a combination of two elements: measurement error and measurement uncertainty. We interpret measurement error as comprising largely (but not necessarily) of systematic effects that would need to be corrected in order to achieve accurate measurement. We interpret uncertainty as a measure of the lack of exact knowledge about the value of a quantity being measured.

This interpretation is based on the concepts set out in the ISO Guide to The Expression of Uncertainty in Measurement (GUM). The two aspects of accuracy can be translated into meaningful terms for hydrometry by considering the uncertainty of measurement as being a measure of precision under circumstances that are tolerable for a particular technology and the error in measurement as arising from deviation from these circumstances.

For continuous flow measurement, the balance between the two aspects of accuracy may change over time. For example one might consider accuracy of local velocity measurement under good conditions to be equivalent to instrument uncertainty, but under adverse conditions the errors arising from a partial failure of the measurement methods will dominate the achievable accuracy.
For discharge measurement, as discussed below, there is typically a combination of variables that must be measured. Consequently there are several factors that will govern the accuracy of the final measured flow. The relative contribution of each source may vary according to water depth or flow rate.

11.2.2 Uncertainties in discharge determination by the velocity-area method

The technologies that rely on the velocity-area method are acoustic ‘transit-time’ (Chapter 5), acoustic Doppler (Chapter 6), microwave Doppler radar (Chapter 7), electromagnetic full channel gauges (Chapter 4) and particle imaging velocimetry (Chapter 8). Discharge estimates using velocity-area methods are made by multiplying the mean velocity of flow with the wetted cross sectional area of the stream. Discharge is not measured directly, but is determined from other quantities. Because the value of each of these quantities must be measured, or estimated, the total error or uncertainty in a discharge estimate is a combination of the uncertainty of its component parts. In general, the components of uncertainty in a discharge estimate using a velocity-area method can broadly be classified as the following:

- uncertainty in the accuracy of the velocity measurements,
- uncertainty in the estimates of cross sectional area,
- uncertainty in the methods used to calculate a cross-sectional average velocity from local velocity measurements.

This section attempts to compare the different velocity-area methods discussed in the previous chapters in terms of these three components of uncertainty. However, as will be shown, it is difficult to put a numerical value to each of the above sources of error. Thus, the analysis of uncertainty in this section is first approached largely from a qualitative perspective. A second approach is to compute measures of accuracy by comparing data from a gauging station with ‘independent’ reference data, usually check gaugings. Values derived from this type of comparison are discussed in Section 11.3.

11.2.3 Uncertainty in local velocity measurements

The velocity-area method requires some measurement of local stream velocity that can be related to the mean velocity of the channel, or the mean velocity of a segment of the channel. Uncertainty in the context of these velocity measurements refers to the degree to which there is doubt that the measure of velocity provided by a given instrument accurately represents the real local velocity at the point, or plane, of interest.

Whilst manufacturers do quote figures for measurement accuracy, these rarely give a detailed breakdown of the constituent figures for local velocity, mean velocity (if an index velocity calibration is programmed into a packaged flow measurement system) and discharge. It is also rare for manufacturers’ literature to state the coverage probability for their accuracy or uncertainty claims (i.e. whether the figure quoted represents one or two standard deviations, a 90% confidence interval or some other interval width) or the exact method of derivation. Quantitative accuracy statements are therefore best regarded as rather generalised figures, but can be summarised as follows:
• When operating under suitable conditions, manufacturers’ data and independent tests in tow tanks (Morlock et al., 2002) suggest local velocity measurements by Doppler ultrasonic instruments can be accurate to within 5% or better of the measured value, though minimum measurable velocities are of the order of 10 mms$^{-1}$ to 50 mms$^{-1}$.

• There are reports of uncertainty up to 50% of the measured velocity for acoustic Doppler sensors (Vermeyen, 1999), but these values were obtained with instruments that have elsewhere been found to be within 5% accuracy.

• Transit time ultrasonics have manufacturers’ quoted accuracies for velocity along a single path as low as 1%, with high accuracy being maintained even for low velocities of the order of 1 mms$^{-1}$ to 10 mms$^{-1}$, owing to the integrating nature of the measurement.

• For Doppler radar, there are even fewer data sources on measurement accuracy. One system used in pipes claims to achieve ±0.5% accuracy for surface velocity measurement. Lee et al. (2002) reported Radar surface velocity measurements accurate to within 12% on an 890 m wide river under flood conditions (this figure was based on comparison with velocities estimated by tracking floating debris which may not represent the measurement scale of the Radar device).

• Laboratory Particle Image Velocimetry (PIV) is used to make highly accurate small-scale (~ 1 cm) measurements. Given that application to larger flows is only beginning to emerge, there is little information on what accuracy would be achievable in practice for rivers. A recent PIV application in a 1.8 x 20 m flume reported an accuracy for surface mean velocity of less than 0.6 mm displacement per image cycle of 85 seconds (Weitbrecht et al., 2002). Bradley et al. (1999), working in a natural stream, reported a root mean square error of 32 mms$^{-1}$ for depth-averaged velocity using PIV, compared with current meter gaugings.

In most circumstances, local velocity accuracy is not considered to be the most useful means of comparing different velocity-area methods. What is more important in the context of the velocity-area method is the location at which a specific instrument can measure velocity, and the number of instruments, because these factors determine the averaging method that will be used.

### 11.2.4 Uncertainty in the estimate of cross-sectional area of flow

Along with some estimate of velocity, the velocity-area method requires an estimate of the cross-sectional area of the flow at every point in time that a discharge estimate is to be determined. This is usually estimated as a function of the stage and the cross sectional geometry of the channel. Thus, the uncertainty depends on both the accuracy of the stage measurement and the quality of data on cross sectional geometry. The uncertainty is also dependent on the stability of the cross-section profile over time and any calibrations used.

Although estimates of cross-sectional area have large components of uncertainty, this uncertainty is completely unrelated to the velocimetry instrument used. Thus, it is assumed that each of the velocity-area methods discussed in this study will, in principle, have a similar degree of uncertainty associated with estimation of cross sectional area.
11.2.5 Calculation of average velocity or discharge integration

The greatest uncertainty with any velocity-area technique is associated with the method used to extrapolate channel discharge from the measurements of velocity. There are a variety of methods that can be used, within three broad categories:

- theoretical index velocity methods that assume a theoretical profile of velocity,
- calibrated index velocity methods that use measured velocity profile data,
- velocity or discharge integration methods.

Each of these methods, which are discussed below, has different sources and degrees of uncertainty.

**Index velocity method (theoretical or calibrated profile)**

The index velocity method is generally used with instruments that measure velocity at one point, or over one plane, and thus do not provide any information on the distribution of velocity throughout the vertical water column. If that velocity measurement is taken at exactly 40% of the total depth, then it may represent a relatively good indication of the average velocity of the channel and can thus be used to estimate discharge with relative confidence.

Single point (or single plane) velocimeters are generally fixed in the vertical (i.e. to the bed or bank), and thus their relative position in the water column is stage dependent. It is necessary, therefore, to estimate the relationship between the velocity measurement obtained at a given relative depth and the average velocity of the channel before a meaningful estimate of discharge can be derived. This can generally be done in one of two ways, as follows.

In some situations, assumptions are made concerning the distribution of velocity throughout the water column. These assumptions are based on the theory that velocity increases from the bed to the surface in a log-linear manner, and that the gradient of velocity is related to the roughness of the bed. Thus, according to this assumption, if the roughness of the bed is known, and the velocity of the flow at any point in the water column is known, the entire distribution of velocity can be estimated. As such, a velocity measurement at any depth in the flow can be related to the average velocity.

Although this method provides an easy way of estimating mean channel velocity, there are significant uncertainties associated with the assumptions made. Firstly, only under very rare conditions are velocity profiles in natural channels log-linear. In coarse-grained channels, for instance, it has been shown that vertical velocity profiles tend to be segmented with three or more log-linear regions that each have a different gradient of velocity (Lawless and Robert, 2001). Thus, the relationship between the velocity at any given location, and the average velocity, becomes very complex and uncertain. Secondly, channel roughness may change through time due to variations in sediment transport and deposition and seasonal changes in vegetation. Thus, one estimate of roughness for all times of the year will not always represent true roughness conditions.

More accurate results using single point or plane velocity measurements can be obtained by using a calibrated index velocity method. This will typically involve
measuring vertical profiles of velocity by another means, such as ADCP, so that the distribution of velocity from the bed to the surface at the point of interest is measured rather than estimated. A rating can then be developed using regression techniques to derive an equation that fits the velocity distribution more accurately than a logarithmic profile. This rating can then be used to derive a calibration factor that is a function of stage. Determining different calibration factors for different times of the year will help to compensate for seasonal changes in roughness. Generally speaking, each of the single point, or plane, velocity-area techniques discussed in this study can be used with either a theoretical index or a calibrated method.

**Velocity or discharge integration methods**

The velocity integration method is used with instruments that measure velocity at multiple points in the flow, and thus provide direct information on the distribution of velocity throughout the vertical water column (at the time of measurement). These measurements can then be used to reconstruct a vertical velocity profile, which can be numerically integrated over the wetted cross-sectional area to determine the discharge through the section.

Alternatively, the cross section can be divided into a number of slices or panels delimited in the vertical by the measurements obtained. Discharge is then determined for each panel based on the appropriate velocity measurements and the panel discharges summed to produce an estimate of the total discharge through the section.

**Calculation methods used with non-invasive sensors**

Most non-invasive technologies can be applied using more than one of the methods for calculating a depth-averaged velocity (or a discharge integration). The methods used will depend as much on the configuration of the gauging site (such as the number and position of sensors and the stage range) as on the technology itself. Assuming all other conditions are held constant, and each instrument is operating under suitable conditions, velocity or discharge integration in principle provides the most accurate discharge measurement.

The gauging station configurations that can take advantage of velocity integration are multi-path acoustic transit-time (UVM) systems, pulsed acoustic Doppler systems and multi-beam acoustic Doppler systems, provided there are sufficient paths or beams in use to sample the velocity profile. The rising float (RAFT) technique involves implicit velocity integration. All other systems require either a theoretical, or better, a calibrated, index velocity relationship. The full channel electromagnetic gauging station is a special case; although it is an integrating measurement (both in the vertical and horizontal planes), it does also depend on a complex calibration that accounts, among other things, for variations in the relationship between induced voltage and mean velocity as stage varies. Seismic induction is also dependent on a calibration relationship inferred from gaugings.

**11.3 Accuracy of Discharge Determination**

**11.3.1 Assessment of accuracy of total discharge**

More accurate local velocity measurement will not always equate to more accurate discharge estimates. The discrepancy between the accuracy of different velocimetry instruments under good operating conditions is generally small in comparison to the
differences between the different methods for calculating an average velocity. From this perspective, the dominant factors that determine the overall accuracy of discharge estimates are:

- the suitability of operating conditions for a particular sensor or system,
- the average velocity (or discharge integration) method, and its suitability for the gauging site/flow conditions,
- the accuracy of measurement of cross-sectional flow area.

The GUM provides a method for integrating these (and their component) sources of uncertainty to calculate a combined uncertainty. To meet our requirement for a measure of accuracy, the uncertainties would also have to include pure error. The only practical way to assess both ‘lack of knowledge’ uncertainty and pure error is to compare a specific discharge measurement to some reference value, usually obtained by a more detailed measurement of the flow using some other technique.

11.3.2 Reported data on accuracy

Quantitative data sources
The methods generally used to determine reference data are current meter gauging, ADCP data or weir flows. Each of these methods is subject to its own accuracy limitations and may well be impractical under some conditions. However, bearing these caveats in mind, Table 11.1 summarises reported statements of overall discharge accuracy for various flow measurement methods.

The upper portion of the table reports on gauging stations where the Environment Agency has recently compared local discharge estimates to check gaugings as part of the Gauging Station Data Quality (GSDQ) project (Science W6-058; Lamb et al., 2004). The lower portion of the table reports on the accuracy of techniques not yet in routine operational use in the UK. For Radar and PIV, the additional information has been drawn from experimental ‘proof of concept’ studies conducted by academic researchers.

For Doppler acoustics, there is greater operational experience. Morlock et al. (2002) deployed side-looking Dopplers at three USGS sites in Indiana and published the deviations between flows measured using the Dopplers and current meter or ADCP gauging. The summary figures in Table 11.1 have been derived from the published field data. The devices in this study were operated successfully for continuous flow measurement for up to 17 months. Index velocity calibration was carried out at the sites. A recent Environment Agency Science project W6-008 (King et al., 2002) has tested three Doppler devices in low head loss conditions in Britain. Both up-looking and side-looking devices were investigated and compared with current meter gauging. The figures in Table 11.1 have been derived from the raw data for deviations from the gauged flows, kindly made available by Hydro-Logic Ltd. with permission of the Environment Agency.

Bias and variability
The data indicate that for ultrasonic transit time gauging stations, the average bias is within ±10%, with deviations having a standard error of about 10%. Electromagnetic
stations exhibit bias within the range ±15%, with deviations having a standard error of around 15% or more. These figures would appear to be in line with general industry experience. For Doppler acoustics, the data sources are far more limited. This is perhaps reflected in the greater variation in reported accuracy. The remaining techniques have only been applied in research or ‘proof-of-concept’ studies, and data on accuracy is therefore limited (and also rather specific to design of the experimental study).

As a general comparison, weirs and flumes are often considered able to determine flow with an accuracy of 5% or less, depending on the design and condition of the structure. For rated sections, similar accuracy can be achieved for some sites and flow ranges, although it is to be expected that greater deviations will be encountered where the stage-discharge relationship becomes unstable (for example during the passage of a flood wave).
Table 11.1: Reported data on total accuracy (percentage deviations) of open channel discharge measurements for non-invasive methods.

<table>
<thead>
<tr>
<th>Technique</th>
<th>Configuration at site</th>
<th>Range of deviations (%)</th>
<th>Mean (%)</th>
<th>Std. error (%)</th>
<th>No. obs.</th>
<th>Source, comparison data, notes.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ultrasonic transit time</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multi-path, crossed</td>
<td>-17 to 33</td>
<td>4.5</td>
<td>9.9</td>
<td>143</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multi-path, crossed</td>
<td>-28 to 18</td>
<td>4.1</td>
<td>7.3</td>
<td>51</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multi-path</td>
<td>-1 to 4</td>
<td>8.5</td>
<td>6.6</td>
<td>9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Multi-path with reflector</td>
<td>-13 to 89</td>
<td>8.2</td>
<td>26.0</td>
<td>21</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Mean</strong></td>
<td>-15.2 to 37.2</td>
<td>3.9</td>
<td>10.5</td>
<td>50</td>
<td></td>
<td>Melching and Meno (1998)</td>
</tr>
<tr>
<td>Various systems</td>
<td>-</td>
<td>2 to 5</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Electromagnetic</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Buried Coil</td>
<td>-31 to 50</td>
<td>2.0</td>
<td>15.0</td>
<td>188</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Buried Coil</td>
<td>-23 to 24</td>
<td>-0.7</td>
<td>10.3</td>
<td>69</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Buried Coil</td>
<td>-10 to 52</td>
<td>8.5</td>
<td>17.8</td>
<td>21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Buried Coil</td>
<td>-30 to 63</td>
<td>0.2</td>
<td>14.5</td>
<td>163</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Buried Coil</td>
<td>-28 to 24</td>
<td>-1.7</td>
<td>9.1</td>
<td>52</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Buried Coil</td>
<td>-39 to 11</td>
<td>-8.3</td>
<td>10.9</td>
<td>29</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Buried Coil</td>
<td>-7 to 41</td>
<td>9.1</td>
<td>9.9</td>
<td>32</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Buried Coil</td>
<td>-54 to 0.1</td>
<td>-14.4</td>
<td>21.3</td>
<td>6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Buried Coil</td>
<td>-22 to 85</td>
<td>13.2</td>
<td>21.2</td>
<td>43</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Mean</strong></td>
<td>-27.1 to 38.9</td>
<td>0.9</td>
<td>14.4</td>
<td>67</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Acoustic Doppler</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pulsed, side-looking</td>
<td>-8 to 6</td>
<td>0.2</td>
<td>3.8</td>
<td>10</td>
<td></td>
<td>†Morlock <em>et al.</em>, 2002. Current meter or ADCP gaugings. Index velocity ratings applied.</td>
</tr>
<tr>
<td>Pulsed, side-looking</td>
<td>-5 to 6</td>
<td>0.1</td>
<td>3.2</td>
<td>8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pulsed, side-looking</td>
<td>-13 to 15</td>
<td>-0.7</td>
<td>6.2</td>
<td>18</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Pulsed, up-looking</strong></td>
<td>“within roughly 10%”</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
<td>†Metcalfe <em>et al.</em>, 1997. Gauging.</td>
</tr>
<tr>
<td>Pulsed, up-looking</td>
<td>3 to 10</td>
<td>6.7</td>
<td>1.6</td>
<td>24</td>
<td></td>
<td>Davies, 2003. Flume with orifice plate.</td>
</tr>
<tr>
<td>Continuous wave, up-looking</td>
<td>-77 to 76</td>
<td>-4.3</td>
<td>67.2</td>
<td>5</td>
<td></td>
<td>Comparison with current meter gaugings, EA R&amp;D (W6-008/TR1, King <em>et al.</em>, 2002.)</td>
</tr>
<tr>
<td>Pulsed, side-looking</td>
<td>-1 to 28</td>
<td>17.2</td>
<td>10.2</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Continuous wave, up-looking</td>
<td>22 to 52</td>
<td>35.7</td>
<td>10.3</td>
<td>9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pulsed, up-looking</td>
<td>-23 to 254</td>
<td>110.4</td>
<td>117.1</td>
<td>9</td>
<td></td>
<td>†High flows and stage range experienced</td>
</tr>
<tr>
<td>Pulsed, up-looking</td>
<td>101 to 143</td>
<td>116.8</td>
<td>23.1</td>
<td>3</td>
<td></td>
<td>†Site has mobile bed and velocity variations</td>
</tr>
<tr>
<td>Pulsed, side-looking</td>
<td>2 to 30</td>
<td>19.3</td>
<td>15.3</td>
<td>3</td>
<td></td>
<td>*Site has skew flow and eddies</td>
</tr>
<tr>
<td><strong>Radar</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Microwave pulse</td>
<td>-</td>
<td>0.5</td>
<td>-</td>
<td>1</td>
<td></td>
<td>Costa <em>et al.</em>, 2000. Gauging.</td>
</tr>
<tr>
<td>X-band pulse</td>
<td>1.9 to 2.7</td>
<td>2.0</td>
<td>0.6</td>
<td>4</td>
<td></td>
<td>Lee <em>et al.</em>, 2002b. Times floating debris.</td>
</tr>
<tr>
<td>UHF</td>
<td>0.3 to 10</td>
<td>-</td>
<td>-</td>
<td>3</td>
<td></td>
<td>Teague <em>et al.</em>, 2001. Gauging.</td>
</tr>
<tr>
<td>UHF</td>
<td>0.3 to 1.6</td>
<td>0.9</td>
<td>-</td>
<td>2</td>
<td></td>
<td>Barrick <em>et al.</em>, 2003. Gauging.</td>
</tr>
<tr>
<td><strong>PIV</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface flow</td>
<td>-</td>
<td>4.0</td>
<td>-</td>
<td>10</td>
<td></td>
<td>Cruetin <em>et al.</em>, 2003</td>
</tr>
<tr>
<td>Surface flow</td>
<td>-</td>
<td>6.4</td>
<td>-</td>
<td>1</td>
<td></td>
<td>Bradley <em>et al.</em>, 1999</td>
</tr>
</tbody>
</table>
Table 11.2: Suitability of methods under differing site and flow conditions

<table>
<thead>
<tr>
<th>Site or flow condition</th>
<th>Acoustic transit time Single path</th>
<th>Acoustic transit time Multipath</th>
<th>Acoustic Doppler Uplooking</th>
<th>Acoustic Doppler Sidelooking</th>
<th>Electromagnetic Buried coil</th>
<th>Electromagnetic Slab</th>
<th>Doppler Radar</th>
<th>Natural light PIV</th>
<th>Seismic induction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low velocity (&lt; 20mm/s)*</td>
<td>✓</td>
<td>✓</td>
<td>X</td>
<td>X</td>
<td>✓</td>
<td>✓</td>
<td>Repeatable at 10-20mm/s</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>High velocity (&gt; 1000mm/s)*</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Shallow water (&lt; 100mm)*</td>
<td>X</td>
<td>X</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>X</td>
</tr>
<tr>
<td>Deep water (&gt; 2m)*</td>
<td>✓ (2)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Wide channel (~ 50-100m)*</td>
<td>✓</td>
<td>✓</td>
<td>X</td>
<td>✓</td>
<td>X</td>
<td>X</td>
<td>✓</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>Wide stage range</td>
<td>X</td>
<td>✓</td>
<td>◯</td>
<td>X</td>
<td>◯</td>
<td>◯</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Clear water (&lt; 3mg/l suspended solids)*</td>
<td>◯</td>
<td>✓</td>
<td>◯</td>
<td>✓</td>
<td>◯</td>
<td>◯</td>
<td>✓</td>
<td>(3)</td>
<td>✓</td>
</tr>
<tr>
<td>High aeration</td>
<td>X</td>
<td>X</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>High sediment load (1-10 x10^3mg/l)*</td>
<td>X</td>
<td>X</td>
<td>✓</td>
<td>✓</td>
<td>◯</td>
<td>◯</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Very high sediment (&gt;10 x10^3mg/l)*</td>
<td>X</td>
<td>X</td>
<td>✓</td>
<td>✓</td>
<td>◯</td>
<td>◯</td>
<td>✓</td>
<td>(5)</td>
<td>✓</td>
</tr>
<tr>
<td>Variable backwater</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>N/A</td>
</tr>
<tr>
<td>Reverse flow</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>N/A</td>
</tr>
<tr>
<td>Stratified flow (salinity/ thermal)</td>
<td>X</td>
<td>X</td>
<td>✓</td>
<td>✓</td>
<td>◯</td>
<td>◯</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Densely vegetated channel or banks</td>
<td>X</td>
<td>X</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>X</td>
<td>✓</td>
<td>X</td>
</tr>
<tr>
<td>Compound channel/ floodplain flows</td>
<td>Depends on configuration</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Skewed or irregular approach channel</td>
<td>◯ (8)</td>
<td>◯ (8)</td>
<td>◯ (7)</td>
<td>◯ (7)</td>
<td>◯</td>
<td>◯</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Bed irregularities</td>
<td>◯ (2)</td>
<td>Calibration for lowest panel</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes:
* Indicative figures
1 Continuous wave ~100-200 mm, pulsed ~500 mm.
2 Provided suitable index velocity or other calibration exists
3 System requires artificial seeding or bubbler
4 Potential for range bias error
5 For surface seeding only
6 Increased potential for sediment blockage
7 Secondary circulation can reduce accuracy - requires calibration.
8 Preferably cross path configuration
9 Sediment accretion breaks contact between electrodes and water
10 Range-gated device best suited
11 Accuracy reported to decrease
12 May be possible using an array of transducers
Interpretation of data on accuracy
Some degree of caution is needed in interpreting Table 11.1. The figures are taken from a variety of tests (almost all field evaluations), and are considered to be as reliable as can reasonably be achieved. However, the following points should be noted:

- The evaluations have not been carried out using a standardised experimental design. The quoted figures are therefore suitable only for broad comparisons.

- Table 11.1 should not be interpreted as providing definitive statements about the performance of any gauging method (if indeed such statements can ever be made), but rather as a basic summary of results that have been reported.

- Conditions vary greatly between the installations listed. Some of the data in Table 11.1 therefore corresponds to conditions that were chosen as suitable for a given method. In other cases, the results illustrate the drop in accuracy associated with ‘difficult’ site conditions.

- The standard error of deviations is a function both of the variance of the deviations and the number of gaugings considered. It may be inflated for a smaller sample, although this effect becomes small as sample size increases beyond around 30 observations.

In general, the accuracy of a given measurement method is related to the technology employed and the velocity averaging or discharge calculation technique, but also to the suitability of the site for a particular technique, the quality of the cross-sectional area data, and the care taken to develop and improve calibrations. The choice of method to achieve greatest accuracy will be most constrained by site characteristics.

Transit time ultrasonics
There is significantly more operational experience of transit time ultrasonics than of the other non-invasive methods listed in Table 11.1, both in Britain and elsewhere. The survey of transit time applications by Melching and Meno (1998) received input on 241 gauges worldwide. At that time the United Kingdom reported 56 gauges, whereas there are now more than 150; the United States reported 102 gauges and many more have since been commissioned. The knowledge of the strengths and limitations of transit time ultrasonics has thus been developed on the basis of thousands of operational years with these devices.

Acoustic Doppler velocity meters
For acoustic Doppler velocity meters (ADVMs), the performance over a wide range of conditions is still not fully understood. Although there are at least 350 in situ devices in the United States (Oberg, 2003), there remains further scope to be done to evaluate the usefulness and accuracy of these instruments. Many applications have been continuous wave side-lookers, whereas most new installations would probably use newer pulsed, range gated or profiling instruments. There is inevitably less experience with these devices. The available data do, however, indicate the potential of Doppler acoustics and further illustrate that non-invasive flow measurement methods, if employed properly, can provide flow measurements of a similar accuracy to weirs and other hydrometric structures.
Radar and PIV
At first glance, the results might appear to suggest that Radar and PIV methods provide more accurate discharge measurements than ultrasonic transit time and electromagnetic methods. This is probably related to the fact that the data experiments quoted were carried out as test projects, rather than under operational conditions. However, the results do seem to demonstrate future potential.

11.4 Suitability of Site and Expected Flow Conditions
One particular issue is the robustness of methods to conditions that are not ideal. Studies that report the accuracy of flow measurement technologies tend to have operated the test systems under at least reasonably suitable conditions. The optimum accuracy so obtained tends to be within about ±5% to ±10% of gauged flows for most techniques. What is not often reported is the quantitative deterioration in accuracy when operating conditions become less than ideal. In this respect, the data reported by King et al. (2002) for Doppler acoustics are illuminating, highlighting the significant deviations that can occur.

Assessing measurement accuracy under poor operating conditions may sometimes be difficult because the techniques used to determine the reference discharge could also become difficult to apply. This will be the case particularly for flood flows, where gauging can be hazardous, and for low flows in situations where there is no low flow control structure for comparison. Comparisons at high flows may be improved in future by the use of ADCPs for gauging.

It is therefore concluded that quantitative indications of accuracy should be combined with statements of suitability. Table 11.2 summarises the main conditions for suitability of the non-invasive methods, and highlights the most critical causes of inaccuracy related to gauging conditions. This table is intended to provide a generic overview of suitability issues, not a detailed guide. One reason for this is that instrument specifications change all the time; for example the minimum and maximum penetration depths for Doppler acoustics have improved over the last few years. For the more experimental methods, the parameters for acceptable conditions are not known in detail. Every gauging station site has to be considered on its own merits. It is stressed that the figures suggested in Table 11.2 for parameters such as velocity, depth and sediment load are indicative only, although they have been drawn from published reports or manufacturers’ specifications.

11.5 Costs

The total cost of commissioning and operating a gauging station varies according to the site, the requirements for accuracy and range, the technologies chosen and, to some extent, market conditions. Attempts to generalise costs therefore run the risk of being misleading. In an attempt to provide a realistic basis for comparison, we have sought to establish costs actually incurred by the Environment Agency for recent gauging station installations. Figures were supplied by the Environment Agency for stations selected by the project board, and this range of reported values is shown in Table 11.3.

This scope of this review did not include a market analysis of individual manufacturers’ instruments. However, Table 11.3 outlines typical costs for instrumentation. Costs for electromagnetic devices are based on actual gauging stations, although it is understood
that the UK supplier for this technology has ceased to offer it commercially. The costs in Table 11.3 generally reflect channels of substantial size. For small channels, costs for feasibility, design and installation may be lower. King et al. (2002) have suggested indicative costs for a two metre wide channel of approximately £8000 for a low cost weir, £5500 for a single up-looking Doppler and £8000 for a side-looking Doppler (these costs would correspond to ‘Total capital’ in Table 11.3). For a four metre wide channel, the corresponding estimates were of the order of £41,000 for a weir, £9,000 for two up-looking Doppler instruments and £14,000 for a side-looking Doppler installation.

### Table 11.3: Indicative costs of gauging technologies (£k)

<table>
<thead>
<tr>
<th>Instrument Description</th>
<th>Feasibility &amp; design</th>
<th>Instrumentation</th>
<th>Installation</th>
<th>Total capital</th>
<th>Operation &amp; maintenance (p.a.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single path transit time ultrasound</td>
<td>12 to 40</td>
<td>10 to 30</td>
<td>15</td>
<td>37 to 85</td>
<td>1 to 5 (Note 2)</td>
</tr>
<tr>
<td>Multi-path transit time ultrasound</td>
<td>12 to 60</td>
<td>20 to 100</td>
<td>180 to 245</td>
<td>212 to 405</td>
<td>1.5</td>
</tr>
<tr>
<td>Up-looking Doppler ultrasonic</td>
<td>20</td>
<td>2 to 10 (Note 1)</td>
<td>5 to 50</td>
<td>27 to 80</td>
<td>1 to 5 (Note 2)</td>
</tr>
<tr>
<td>Side-looking Doppler ultrasonic</td>
<td>10</td>
<td>2 to 10 (Note 1)</td>
<td>5 to 15</td>
<td>17 to 45</td>
<td>1 to 5 (Note 2)</td>
</tr>
<tr>
<td>Buried coil electromagnetic</td>
<td>30 to 70</td>
<td>30+</td>
<td>310</td>
<td>350 to 500</td>
<td>1.5</td>
</tr>
<tr>
<td>Slab electromagnetic</td>
<td>5 to 10</td>
<td>5 to 40</td>
<td>30 to 200</td>
<td>40 to 250</td>
<td>1.5</td>
</tr>
<tr>
<td>Doppler Radar</td>
<td>5 to 10</td>
<td>5 (Note 4)</td>
<td>10 to 20</td>
<td>20 to 35</td>
<td>1 to 5 (Note 2)</td>
</tr>
<tr>
<td>Natural PIV</td>
<td>unknown</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seismic induction</td>
<td>5</td>
<td>1</td>
<td>5</td>
<td>11</td>
<td>5 to 10 (Note 3)</td>
</tr>
<tr>
<td>Weir</td>
<td>50 to 60</td>
<td>-</td>
<td>100 to 350</td>
<td>150 to 410</td>
<td>0.5 to 1</td>
</tr>
</tbody>
</table>

Notes:
1 Per transducer. (Continuous wave device ~ £2k, profiling or broadband device ~ £5-10k.)
2 Reflects requirement for a larger number of check gaugings for index velocity calibration
3 As for note 2, but reflecting likely inaccessibility and difficulty of gauging at sites
4 Per transducer

Data source: figures in normal type are ranges of actual costs reported by Environment Agency, NW and Midlands regions or instrument manufacturers/agents. Figures in italics (for methods not in operational use by the Environment Agency) are speculative, or based on typical costs for similar installations.

It is notable that instrumentation is generally a relatively small proportion of overall cost, especially for those methods that require extensive civil engineering, particularly channel diversion and work across the river bed. This has been one of the main attractions of side-looking Doppler technology, which does not require laying cables or other work on the channel bed. It is also expected that newer methods will incur hidden costs when first applied as hydrometric personnel become familiar with the technology and set up new data processing and management procedures.

### 11.6 References


12 CONCLUSIONS AND RECOMMENDATIONS

12.1 Introduction

This report has identified non-invasive flow measurement methods under research or in operational use in the UK and elsewhere, and discussed the opportunities to deploy them as permanent alternatives to hydrometric structures on watercourses in England and Wales. It has also reviewed the pressures against hydrometric structures in rivers. The main conclusions and recommendations are given below.

12.2 Main Conclusions of the Review

Pressures against structures

Pressures against the use of flow measurement structures may be quite local, depending on flow regime, aquatic ecology, sediment fluxes, visual intrusion and health and safety. The broader policy and management frameworks that currently limit (or are anticipated to limit) the deployment of flow measurement devices are:

- The Water Framework Directive (WFD)

  The WFD, which came into force in 2000, aims to achieve and maintain prescribed standards of ‘ecological status’ for surface and groundwater bodies. In many cases this will weigh heavily against installation of new structures. The significance of existing gauging structures will be assessed as part of a larger catchment picture (along with other anthropogenic modifications of the water body).

- The Habitats Directive and Birds Directive

  Where river reaches fall within Special Areas of Conservation (SACs) or Special Protection Areas (SPAs) as defined by the Habitats and Birds directives they are likely to receive designation as Protected Areas under the WFD. This can result in severe restrictions being placed on the sites, and control structures are unlikely to be allowed.

- The Salmon and Freshwater Fisheries Act (1975)

  Restriction on movement of game and coarse fish is currently one of the main problems with in-stream structures. The Act provided legislative powers requiring facilities for fish passage.

Where non-invasive methods can provide measurement of acceptable accuracy at no greater cost than building or modifying a structure, the non-invasive solution is therefore likely to be favoured (although any saving in capital cost must be balanced against recurring costs associated with maintenance and calibration requirements of non-invasive techniques).

What is not yet clear is the position of existing structures. Some of the new legislative developments are likely to make existing weirs subject to modification or removal if they are causing a significant obstruction to the free movement of fish (especially coarse
fish) or other species. It will probably require greater impact on ecological status to remove or modify an existing structure than to prevent the installation of a new one.

Physically removing structures could be costly, and may sometimes have undesirable environmental impacts. Modifications can be made to improve fish passage, and Environment Agency research continues to address the issues of cost and measurement accuracy for modified weirs. If new designs for flow measurement weirs allow slower swimming coarse fish to pass, without reducing the accuracy of low flow measurement, weirs could continue to be maintained from the fisheries point of view.

**Use of non-invasive methods**
The most widely used methods for continuous flow measurement remain open channel rated sections and, particularly in the UK, structures. Non-invasive methods are still not as widely used, but there are now many transit time ultrasonic gauging stations (at least 150 in the UK) and this can be considered a mature technology for continuous flow measurement. Full channel buried-coil electromagnetic stations are also well established in the UK, but there are fewer than 40 stations.

There do not appear to be any major types of non-invasive technology for continuous flow measurement in natural rivers that are unknown in Britain but well developed or widely used elsewhere. There is, however, a growing operational experience with Doppler acoustics in the United States, where some 350 fixed devices are now in use.

Other methods, such as Doppler Radar, Particle Imaging Velocimetry (PIV), and seismic induction are at a research level, at least for application to natural open channel sites.

**Performance of non-invasive technologies**
Under suitable conditions, and with appropriate calibration, non-invasive methods have been reported to provide accurate measurement of discharge, comparable in some cases to the accuracy of stage-discharge ratings or measurement structures. This statement applies to systems that are in operational use, namely transit time or Doppler ultrasonics and buried coil electromagnetic gauges.

There are limited data available for research-level methods. Published sources suggest that Doppler Radar and PIV systems (including the Rising Air Float Technique, RAFT) could potentially achieve similar accuracy under the right conditions, although it remains to be seen whether accuracy achieved under test conditions could be maintained reliably in operational use. Doppler Radar and surface PIV measure surface velocity only, and accuracy for discharge measurement would be subject to the ability to establish a suitable index velocity calibration or velocity profile, and to account for the effects of wind shear. RAFT has the advantage that it integrates both over depth and width (under the assumption that the floats or bubbles have a constant vertical rise velocity). The seismic induction approach is not yet sufficiently tested to report on its accuracy.

Non-invasive methods do not control the flow of water and are inherently dependent on operating conditions. The accuracy achieved by non-invasive gauging stations therefore depends on careful matching of methods and site or flow conditions.
Whatever method is used, there is still a requirement for continuous and careful review and checking of data. There is no such thing as a ‘fit-and-forget’ gauging method. No method completely eliminates the need for, or value of, check gaugings. When considering non-invasive methods, the possible ‘hidden’ costs of monitoring performance, updating calibrations and diagnosing errors should not be overlooked.

**Choice of transit time and Doppler ultrasonics**

There should not be an automatic assumption that transit time ultrasonics should be replaced by side-looking acoustic Doppler devices. A transit time ultrasonic that uses many paths may provide better measurements of vertically-averaged velocity over a wide stage range compared with a single side-looking Doppler, even if this has an index velocity calibration.

Side looking Doppler systems have some significant advantages, particularly the ability to cope with high sediment loads (\(\sim 10^3\) mg/l), which may be especially useful for measuring flood flows, and the fact that they do not need cross-channel cables. There may be greater justification to consider side-looking Doppler devices at sites where the alternative under consideration is a single path transit time ultrasonic. In this situation, the issues of depth variation in velocity are common to both approaches. A profiling or range-gated Doppler may have an advantage in that its power, frequency and range can be tuned for the site to attempt to find an optimum measurement volume or a suitable set of measurement cells. A Doppler system may represent better value for money.

For measurement of clear water, particularly at low velocities, a transit time system would be preferred over a Doppler system, in part because the transit time method does not depend on the presence of scatterers. There is also an advantage in determining small velocities by measurement of time of travel along the whole length of the ultrasonic beam, which will be greater than the channel width and which provides a horizontally integrating measurement.

**Electromagnetic stations**

Although there is sometimes distrust expressed of buried coil electromagnetic stations, the technology should not be written off at existing sites as it appears capable of providing acceptable measurement under conditions where other methods are difficult or impossible to apply. This conclusion is reached from aggregated comparison of deviations between EM station flows and check gaugings, although difficulties have been reported at some sites.

At the time of writing, there is no longer a supplier offering buried coil EM gauging station technology commercially, and there is no indication of future commercial development.

**Deployment opportunities**

Newer technologies promise greater flexibility in deployment (mainly because of the reduced or minimal need for civil engineering works in the channel). This is one of the particular attractions of side-looking Doppler acoustics, which would not ordinarily require cables to be routed across the channel.

Hybrid solutions should be actively considered in view of the flexibility of deployment of some non-invasive methods. Particular examples may be gauging sites that:
• operate as a transit time ultrasonic but switch to side-looking ADVMs if sediment loads exceed a certain threshold (there is at least one such system in commercial production already),

• make use of Doppler radar to capture surface velocities at high flows that would otherwise bypass the gauge (mounted, for example, under bridge arches over a floodplain),

• make use of data from temporary or discontinuous ultrasonics to derive improved stage-discharge ratings, as discussed in Environment Agency Science Report W189.

A broad conclusion emerging from this review is that non-invasive technologies may encourage the use of hybrid approaches at gauging stations. Two examples have already been given. Further opportunities may exist to combine small structures for accurate measurement at low flows with transit time or Doppler ultrasonics for higher flows (although structures can create flow conditions such as shear and secondary circulation that affect the performance of non-invasive sensors). Also, at sites where existing weirs have to be modified, non-invasive methods could be used to measure the flow through bypass channels or fish passes, allowing accuracy to be maintained.

12.3 Targeted Research Recommendations

Drawing on the review, the following points are suggested as relatively short-term, targeted research projects. Table 12.1 summarises issues to be addressed and proposed approaches. In addition, evaluation of fixed acoustic Dopplers should be continued.

<table>
<thead>
<tr>
<th>Table 12.1: Targeted programme of research and development</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Issues</strong></td>
</tr>
<tr>
<td>The Rising Air Float Technique (RAFT) has been tested but seen little development, despite being in theory a method that integrates over depth and across the channel.</td>
</tr>
<tr>
<td>One of the factors that has prevented development for continuous flow measurement has been the difficulty of measuring the area bounded by a bubble envelope. It seems likely that image processing techniques developed for Particle Imaging Velocimetry could be adapted to unlock the potential of RAFT.</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>
Table 12.1: Targeted programme of research and development

<table>
<thead>
<tr>
<th>Targeted Programme</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>T2a</td>
<td>To review the available data on EM performance, including careful analysis of gauging history and collating the local reviews that exist for some stations.</td>
</tr>
<tr>
<td>EM stations in the UK are becoming more difficult to support and maintain as the component technology ages.</td>
<td>T2b</td>
</tr>
<tr>
<td>The potential for adaptation of slab-type EM gauges for natural rivers has not been tested.</td>
<td>T3a</td>
</tr>
<tr>
<td></td>
<td>T3b</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 12.1: Targeted programme of research and development

<table>
<thead>
<tr>
<th></th>
<th>T4a</th>
<th>T4b</th>
<th>T4c</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>To carry out a small 4-6 month pre-feasibility study for siting of Doppler radar installations.</td>
<td>If successful, commission at least one test site for trials. This could build on existing trials at Triumph Road in Nottingham, but should also include a more natural site.</td>
<td>To explore the potential for a non-contact surface velocity measurement using Doppler radar to help gather data under flood conditions. (Although this may best be viewed as ‘semi-continuous’ flow measurement, it could be the subject of a separate science project; possible links with the Flood Management Science Programme could be explored.)</td>
</tr>
</tbody>
</table>

12.4 Strategic Research Recommendations

The study brief requires recommendations to be made for further research. In addition to the specific, targeted projects suggested above, Table 12.2 sets out a number of more strategic research recommendations, generally concerned with more speculative development of non-invasive technology, or ways in which non-invasive measurement could be used.
Table 12.2: Strategic research recommendations

S1 Improving flood flow measurements

The broader strategic issue behind this recommendation is to explore, through research, the potential benefits of capturing relatively short continuous (i.e. 15 minute or better) records during flood events.

Non-invasive methods offer the potential to provide accurate measurements of flow on a continuous basis, but also to offer some (albeit potentially less accurate) measurement on a semi-continuous basis in situations where conventional hydrometric methods are difficult to apply.

A prime example may be measurement of flood flows, including bypassing. Here the traditional approaches are spot gauging, which is hazardous, or reconstruction using an ‘engineering method’ such as the slope-area approach. Whilst ADCP technology promises to enhance the capability for spot gauging, there may be potential to exploit Doppler radar to make surface velocity measurements during flood events, either fixed sensors or a mobile system. This could make it possible to quantify flow pathways that may otherwise not be measured. Two research topics that would help to evaluate whether this approach would be worthwhile are:

- Hydraulic analysis of channel and floodplain conveyance at selected sites to determine the benefits in characterizing surface velocity over a greater range of flow depths and extents,
- Experimental trials of fixed or mobile Doppler radar for flows typical of flood events (e.g. turbid water, high velocities), ideally during real flood conditions.

Work on these topics could be suitable to attract some funding from the research councils, perhaps for PhD studentships or full-time researchers. The Environment Agency could consider part sponsorship, to ensure the research fed into hydrometry, or at least maintain a close involvement by allowing researchers access to Environment Agency gauging sites. The research should address the practical issues of maintaining the effectiveness of instrumentation that is not in use most of the time (this has been a difficulty in attempts to use transit time ultrasonics to measure occasional flows on a flood plain).

S2 Development of research-level technologies

There are two techniques reviewed here that warrant further research, but have not yet been shown to be suitable for operational use in hydrometry. These are Particle Imaging Velocimetry (‘natural PIV’ in this review) and seismic induction.

Natural PIV

Natural PIV has the potential to deliver highly accurate measurements of surface velocity vectors, especially at low velocity, and is a non-contact technique. However, it does require a tracer for ‘seeding’ – air bubbles and soluble corn starch have been used elsewhere for this purpose. It is not yet known whether natural PIV could be developed for any operational use, where mean velocity is the
Table 12.2: Strategic research recommendations

main concern, and the ability to resolve the 2D velocity vector field is unlikely to be of as much interest as for researchers.

However, it is suggested that attempts to develop natural PIV remain sufficiently novel to be of interest to the academic community and it is in the Environment Agency’s interests at least to support this type of work in principle (e.g. by allowing access to sites etc.), if not financially.

Seismic induction

Similar comments apply to the seismic induction method. This has to date been supported by private resources and limited University support. The methods shows some potential, and work to date has begun to develop an understanding of technical issues such as the optimum ‘tuning’ of the method within the frequency spectrum, but it is at a point where a more secure programme of research would help to improve the understanding of the processes that lead to the measurement variable, and refine and assess robustness of the relationship links to flow.

Perhaps most crucially, there needs to be research to explore the potential to apply the method with minimal or no calibration. If a full range of gaugings is needed to calibrate the signal response to stream flow, developers would have to show the advantages for hydrometry over use of a rated section.

S3 National comparative assessment of data quality

A recent Science project (W6-058) for the Environment Agency has led to development of a methodology and software tool for the assessment of gauging station data quality. This system is planned for use across the Environment Agency hydrometry teams, and will generate a large and valuable data resource on gauging station performance. It includes transit time ultrasonics and buried coil EM stations, and calculates uncertainties according to principles set out in the relevant ISO/BSI standards.

It is proposed that data on uncertainty and check gauging deviations, produced during evaluation of the data quality classification, should be collated at a national level. It would then be possible to compare the performance of the established non-invasive methods with structures and rated sections on a network-wide basis.
APPENDIX 1 – consultation on use of non-invasive methods

A1.1 Overview

A consultation with users of non-invasive methods was included in the project brief. The aim of this consultation exercise was to determine which techniques are currently being used for flow gauging, how are these being used and why. In particular it was hoped that the consultation process would identify any new techniques or new applications of existing techniques of which the Environment Agency was not already aware. An additional aim was to canvas your experiences with such techniques, particularly in respect to typical operating accuracies and method selection. Therefore a number of key overseas hydrometric agencies were contacted, in addition to those operating in Great Britain.

Questionnaire survey

At the outset it was decided that use of a questionnaire would be an efficient method of consulting with busy hydrometrists in a large number of countries. Questionnaires were sent by either post or email to 37 key hydrometric staff in over 20 countries. A number of individuals were also contacted directly, either by telephone or in person. In total 15 responses were received.

There was a good response to the consultation process by hydrometrists working in the United States. A number of responses were received from the US Geological Survey and US Bureau of Reclamation. This reflects the level of expertise and resourcing for non-invasive flow measurement technologies in the US.

However, in general there was a poor response to the questionnaire from the Environment Agency’s European counterparts. One reason for this is that most European countries rely on stage-discharge calibrations for flow gauging and, whilst they might use non-invasive technologies (such as ADCP for example) for spot gauging, non-invasive methods are not widely used on a continuous basis.

Literature Review

Where questionnaire responses were not received from particular countries, efforts were made to determine, by other means, the types of gauging methods used. For example some European agencies allow access to river flow databases or provide information on the Internet regarding gauging station distribution and types of gauging station.

Many non-invasive methods are being used on an experimental basis and have yet to be applied on an operational basis. Therefore an additional literature review was undertaken in order to identify any additional techniques and determine research groups active in this field. This included contacting a number of suppliers and manufacturers of hydrometric instruments. Relevant literature is described in the main Science report.

A1.2 Respondents

Table A1 lists respondents to the questionnaire. Respondents are listed by organisation. In some cases there was more than one respondent per organisation. For reasons of data protection contact details for respondents are not listed.
Table A1.1 List of questionnaire respondents

<table>
<thead>
<tr>
<th>Country</th>
<th>Organisation</th>
<th>Contact(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Denmark</td>
<td>Environment and Energy</td>
<td>Dr Ole Smith</td>
</tr>
<tr>
<td>Finland</td>
<td>Finnish Environment Agency</td>
<td>Dr Markky Puupponen</td>
</tr>
<tr>
<td>New Zealand</td>
<td>National Institute of Water and Atmospheric Research Ltd (NIWA)</td>
<td>Dr Alistair McKerchar</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mr John Fenwick</td>
</tr>
<tr>
<td>UK</td>
<td>Scottish Environment Protection Agency (SEPA)</td>
<td>Mr Steve Anderton</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dr John Burns</td>
</tr>
<tr>
<td></td>
<td>Rivers Agency, Northern Ireland</td>
<td>Mr Derrick Pinkerton</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dr Noel Higginson</td>
</tr>
<tr>
<td></td>
<td>Environment Agency of England and Wales</td>
<td>Mr Clive Hallam (Midlands)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mr David Stewart (NHPT)</td>
</tr>
<tr>
<td>USA</td>
<td>United States Geological Survey</td>
<td>Mr Kevin Oberg</td>
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<tr>
<td></td>
<td></td>
<td>Mr William Coon</td>
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<tr>
<td></td>
<td></td>
<td>Dr Scott Gain</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mr Scott Morlock</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mr Philip Turnipseed</td>
</tr>
<tr>
<td></td>
<td>US Bureau of Reclamation</td>
<td>Mr Tracey Vermeyen</td>
</tr>
</tbody>
</table>

A1.3 Questionnaire

The questionnaire was based on a number of themes:

A. Types of non-invasive flow measurement techniques used.

B. Reasons for selecting non-invasive methods.

C. Performance of non-invasive methods.

D. Use of ultrasonic velocity meters (UVMs), also known as ‘Transit-time ultrasonics’.

E. Use of acoustic Doppler velocity meters (ADVMs).

F. Use of electromagnetic meters (fixed coils & slabs).
G. Use of emerging technologies.

The questionnaire was formatted so that respondents were required to either tick boxes or write short (one line comments).

A1.4 Responses

The following is a summary of the findings of the consultation process. It should be noted that not all respondents were able to answer all questionnaires.

Section A. Types of methods used

Responses to section A indicated that:

- Acoustic methods are the most commonly used non-invasive flow gauging technique.
- Transit time ultrasonics are widely used in the UK, USA and Europe, and there is a strong experience base in use of transit time methods.
- Side-looking Doppler methods are widely used in USA, but have not yet been widely implemented on an operational basis.
- Up-looking Dopplers are less widely used for gauging in natural rivers.
- Electromagnetic methods were generally used in England and Wales only, although one or two examples in the USA were given.
- Emerging technologies, including Radar Doppler, PIV, laser Doppler are not being used by any of the consultees on an operational basis. Few respondents were aware of emerging technologies.
- In most cases non-invasive methods are used at less than 25% of gauging stations. Some countries did not use any non-invasive techniques for continuous flow gauging (e.g. Finland), instead relying on open channel-stage discharge measurements.

Section B. Reasons for selecting non-invasive methods

Reasons cited for choosing non-invasive measurement techniques generally fell into two categories, that they were the most appropriate method given the hydraulic conditions at the site or that the method offered a number of advantages over other suitable gauging techniques. These reasons are listed below.

Reasons why non-invasives are most appropriate method of measurement

- to enable measurement of flows during variable backwater conditions,
- to enable measurement of flows where water-surface slope is shallow,
- to enable measurement of reverse flows (e.g. tidal streams and estuaries).
Reasons why non-invasives are most advantageous method of measurement.

- capital costs,
- maintenance costs,
- accuracy and reliability of measurement,
- they better enable measurement of high flows,
- ease of use and installation.

With the exception of respondents within the Environment Agency and SEPA, environmental concerns including visual intrusion, impediment to fish passage, changes to the natural flow regime and disruption of habitat were not cited as reasons for selecting non-invasive techniques.

Familiarity of the technique and reliability of method were also cited as often being considerations for the use of the non-invasive methods. From responses to later questions it appears that hydrologists tend to place greatest trust in those methods which are most familiar. Techniques that were not familiar to users were perceived to be of poorer accuracy and reliability.

Other reasons that had been considered occasionally included “safety”, “to enable measurements under ice cover conditions”, “ease of maintenance”, because “the width of river was too great for structures” and “navigation requirements”.

Consultees were asked to rank (in descending order of importance) the four most important considerations. A variety of responses were given. By way of example, rankings given by three respondents from different organisations (all non EA) are given below:

<table>
<thead>
<tr>
<th>Consultee 1</th>
<th>Consultee 2</th>
<th>Consultee 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy of measurement slopes</td>
<td>Variable backwater</td>
<td>Shallow</td>
</tr>
<tr>
<td>Capital cost</td>
<td>Accuracy of measurement</td>
<td>Capitol costs</td>
</tr>
<tr>
<td>High flows measurement</td>
<td>Ease of use/installation</td>
<td>Safety</td>
</tr>
<tr>
<td>Maintenance costs costs</td>
<td>Reverse flows</td>
<td>Maintenance</td>
</tr>
</tbody>
</table>

Consultees were also asked to comment on whether they would consider installing weirs or flumes for flow measurement. Again respondents had a range of opinions regarding use of weirs and flumes - some would be happy to consider weirs, whilst others would not. The following comments were received:
• “Weirs and flumes, whilst initially expensive, require very little maintenance and instrumentation costs can be very low to medium, depending on the method of level measurement. Likewise, these structures are proven, well understood and accepted.”

• “Weirs are used to save on calibration costs (of open channel ratings).”

• “Weirs may be useful where there is poor bed control for an rating – weirs offer stable stage/discharge relationship particularly at low flows, which simplifies maintenance of the relationship and reduces need to shift low-flow control of rating.”

• “Would not consider using a weir, as this is an obstruction to fish passage.”

Section C. Performance of non-invasive structures

Consultees were asked to rank the methods in order of their perception of their performance. The results were broadly as follows (although clearly performance will be related to site situation and measurement objectives on a case-by-case basis):

1. Side-looking Dopplers
2. Transit Time Ultrasonics
3. Up-looking Dopplers
4. EM meters
5. Doppler radar
6. PIV

Of particular interest is that respondents from the USA thought that side-looking Dopplers performed better than transit time devices. It should be noted, however, that single-path rather than multi-path UVM arrays are generally used in the USA.

Consultees usually considered methods to perform well due either to their own experiences with the method or because the method was well-established and widely used. Where users did not have experience of methods, they usually assumed that these would perform poorly. Most users indicated that they had most practical experience with acoustic measurement methods.

Section D. Ultrasonic velocity meters (UVM) ‘transit-time ultrasonics’

Use of transit time methods

The questionnaire survey indicated that transit time ultrasonics or UVMs are widely used in the USA and in Europe.
In general most users were satisfied with the performance. However one respondent indicated that he was not happy to continue using transit time arrays as “they are too difficult to install and data processing is time consuming”.

Reasons for use of transit time methods

The main reasons quoted for use of transit time methods were:

- To enable measurement of flows during variable backwater conditions.
- To enable measurement of reverse flows (e.g. tidal streams & estuaries).
- To better enable measurement during high flows.
- Provision of accurate measurements.
- Good reliability.
- Low maintenance costs.

Installation details

Most respondents indicated that their installations used either a single path or two paths in the vertical. Fewer multi-path devices were used. Reasons for using multi-path devices included:

- Primary flow direction changes with stage.
- Large stage variation
- Cross-section is highly irregular.
- Irregular velocity distribution within vertical section.

Factors typically influencing the operational reliability of UVMs included:

- Damage or malfunction of transducers.
- Difficulties in stage measurement (e.g. stage below minimum threshold).
- Damage or malfunction of transmitter / receiver.
- Damage to cables.
- UVM software / programming of software.
- Power surges or failures.

The following models were reported to have been in or be in use:
• OTT - Sonic Flow.
• Peek / Thermo - 1408, Mulipath.
• Accusonic - 1200, 7300.
• AFFRA – Deltaflex.

Pros and cons of transit time methods

Comments regarding the limitations of transit time methods included:

• “Inaccuracy at low flows due to small scale bed features, where water is shallow relative to scale of bed features. Requirement for cabling to run across river bed, and to maintain transducers at far bank.”

• “A major limitation for some sites is operation in high flows with high suspended solids.”

• “The main limitation is installation is more complex because of cross-channel cables and the need for at least one pair of transducers.”

• “Path length, Thermal gradients in the vertical, Algal fouling, Alignment, Mean velocity calibration requires traditional measurement and rating.”

• “Difficult to calculate average channel velocity with changing stage. Calculations are laborious.”

Comments regarding the advantages of the transit time approach included:

• “Ability to measure velocity throughout flow range (esp. high flows).”

• “Excellent accuracy, particularly in low-velocity environments.”

• “More cost effective than current meter gauging.”

• “There are less calibration requirements.”

• “Ability to cope with backwater effects and so on.”

• “Low level of visual / habitat intrusion”

• “Relatively easy to install and only minor maintenance required.”

• “As the UVM processor – the expensive part of the system -- is located on land damage to transducers not as expensive as loosing a whole ADVM unit, for example.”

There was a trend in the USA for replacing transit time devices with side-looking ultrasonics.
Section E. Use of acoustic Doppler velocity meters (ADVMs)

Use of acoustic Doppler methods (ADVMs)

The questionnaire responses indicated that acoustic Doppler methods are widely used both in the USA. In general most users were satisfied with the performance of acoustic Doppler instruments.

Note: some of the respondent included the use of ADCPs in the discussion on acoustic Doppler methods.

Reasons for use of acoustic Doppler methods

The main reasons quoted for use were:

- To enable measurement of flows during variable backwater conditions.
- To enable measurement of flows where water-surface slope is shallow.
- To enable measurement of reverse flows (e.g. tidal streams & estuaries).
- To better enable measurement during high flows.

Cost did not seem to be an important factor

Installation details

Most respondents indicated that both up-looking and side-looking devices were use.

- Side-looking devices were favoured over up-looking devices.
- Pulsed Doppler methods were favoured over continuous beam devices.
- Both concave and convex transducer heads were reported to be used.

Factors that were typically found to be influencing the operational reliability of ADVMs included

- Damage or malfunction of transducers
- Software
- Damage to cables
- Power surges or failures

The following models were reported to have been in or be in use:

- Sontek – Argonaut SL, Argonaut XS
- Nortek – Easy Q
• RDI - Rio Grande
• MGD Technologies – ADFM

Pros and cons of acoustic Doppler methods

Comments regarding the limitations of acoustic Doppler methods included:

• “ADPs cannot measure velocity across the whole section. There is still a requirement to carry out some form of flow gauging to calibrate sampled flow velocity to mean section velocity.”
• “Sideways looking instruments are not suited to shallow channels, because of reflections from bed and water surface.”
• “Expensive if the unit is damaged extensively or lost.”
• “Accuracy not as good as UVMs in extremely low velocity regimes.”
• “Cost, complexity and maintenance.”

Comments regarding the advantages of acoustic Doppler methods included:

• “No cables in channel, Fewer components to fail, Fewer alignment problems.”
• “Easy to install & remove making this equipment very suitable for temporary installations.”
• “No need to install equipment at the far bank.”
• “Cheap, relative to costs of all other flow measurement systems (time of flight ultrasonics, E-M, cableways, structures).”
• “Ease of programming.”
• “Good for low head loss conditions”.

Section F. Use of electromagnetic meters (fixed coils & slabs)

Use of full channel width EM meters

EM meters are only widely used in England and Wales. They are used for confined channels in the USA.

No respondents reported the use of slab type EM meters.

Reasons for use of EM meters

The main reasons quoted for use of EM meters were:
• To enable measurement of flows during variable backwater conditions, especially when caused by weed growth.

• Familiarity with technique.

Installation details

Buried and bridged coils were used in the UK.

Factors typically influencing the operational reliability of EM gauges included:

• Suspected damage to membrane (often not visible).

• Obsolescence of component electronics.

‘Pros and cons’ of Electromagnetic meters

Comments regarding the limitation of full channel width EMs included:

• “High capital cost.”

• “Due to use in very weedy rivers, the difficulty in checking performance, although this is not a limitation in the kit, more a limitation in checking options.”

Comments regarding the advantages of use of full channel width EMs included:

• “The only technique available to measure weedy rivers.”

Section G. Use of emerging technologies

The questionnaire responses indicated that emerging technologies are not being used on an operational basis.

Some consultees would be prepared to install new technologies before they had been widely tested. The USGS are particularly interested in applying, on an experimental basis, any new technologies, especially if these are able to overcome some of the representation problems associated with ultrasonics. One respondent made the following comment:

“The more confined (or shorter) the beam the more reliable the instrument. Long path UVM’s fail more often (signal attenuation and alignment problems) than short path configurations. Side-lookers can be even more reliable, but that reliability comes at the cost of beam length and horizontal definition. Both UVMs and ADVMs can be very accurate for what they measure, but what they measure is not always a very good indication of flow.”

There was also interest in non-contact methods such as Doppler radar. It was though that avoiding the need to immerse instruments in the water, would eventually lead to better reliability over time, and give rise to safer working practices.