HR Wallingford

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Review of Low Velocity Measurement Techniques

HR Wallingford

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SUMMARY

This report describes the review of low velocity measurement techniques carried out by HR Wallingford under NRA Research and Development Project B01.2.90.

Information was obtained from all ten NRA Regions on the extent of gauging problems associated with low velocities of flow, and visits were made to all the Regional Offices. Contacts were also made with equipment manufacturers and other external organisations and information was obtained on low velocity measurement techniques.

All available methods of flow gauging have been considered with respect to low velocity measurement. Methods which may be suitable have been identified, and information on the use of these methods in NRA Regions has been obtained.

Methods of measuring low velocities of flow are recommended, as follows:

Continuous measurement:	Ultrasonic gauge Electromagnetic gauge
Non-continuous measurement:	Electromagnetic current meter

Further work is recommended to verify the accuracy of these methods for measuring low velocity flows. Recommendations are also given for further work in connection with other methods which may prove to be suitable for low velocity measurement.

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1 INTRODUCTION

1.1 Background

There are many locations on rivers in England and Wales where the velocity of flow is sometimes too low to be measured using rotating element current meters and there is insufficient head available to permit the use of flow measurement structures. An alternative method of gauging is required at these locations, and in December 1990 the National Rivers Authority (NRA) commissioned HR Wallingford (HR) to undertake a review of low velocity measurement techniques. The objectives of the review include identification of the extent of the low velocity problem within NRA regions, and the provision of recommendations for the most likely best option for measuring low velocities of flow in rivers.

1.2 Terms of Reference

The Terms of Reference are contained in Schedule 2 of the Memorandum of Agreement between the NRA and HR, and a copy is contained in Appendix 1. The specific objectives of the study may be summarised as follows:

1. To identify the extent of the low velocity problem
2. To give guidance on the most likely best option for measuring low velocity flows
3. To describe flow measurement techniques used in current practice
4. To determine the limitations of each technique for the measurement of low velocities of flow
5. To assess capital and maintenance costs.

The scope of work incudes the following items.

a) Request data from NRA Regional Offices and subsequently visit each Region
b) Establish contacts with appropriate external organisations
c) Review flow measurement techniques and identify those which may be suitable for measuring low velocities
d) Make provisional recommendations for the most likely best option
e) Prepare Project Report.

1.3 Methodology

The general methodology used for the study was as follows:

1. Obtain data from NRA Regional Offices
2. Visit NRA Regional Offices
3. Obtain information from equipment manufacturers and visit some of the manufacturers
4. Contact other external organisations and visit if necessary
5. Carry out an independent review of flow measurement techniques
6. Prepare an Interim Report, containing provisional recommendations as to the most likely "best option"for low velocity flow measurement
7. Prepare a Project Report.

In order to obtain information from NRA Regional Offices, a questionnaire was prepared and agreed with the Project Leader and sent to NRA Regional Offices in January 1991. A copy of the questionnaire is contained in Appendix 2. Replies to the questionnaire were requested by 15th March, and all NRA Regional Offices were visited during April and May 1991. A schedule of visits is given in Appendix 3, including a list of the NRA staff members met by the Consultants. During the visits additional items of information were requested. A summary of information obtained from the NRA Regions is contained in Appendix 4. The NRA Regions have shown considerable interest in the project and their assistance and co-operation is gratefully acknowledged.

A number of site visits have also been made to gauging sites including the following:

Date	River	Site	NRA Region	Remarks
18 April	Mersy	Westy	North West	Ultrasonic gauge
23 April	Parrett	Westover Bridge	Wessex	Former ultrasonic gauge
29 April	King's Dike	Stanground	Anglian	Low velocity site Ultrasonic gauge planned
16 May	Pang	Pangbourne	Thames	Crump Weir Possible experimental site
11 July	Itchen	Riverside Park	Southern	Ultrasonic gauge (reflector)

Information on equipment for low velocity measurement has been collected from the NRA Regions and independently by the Consultant.

Information on flow measurement equipment has been requested from several manufacturers as listed in Appendix 5, which also contains a copy of the letter sent to the manufacturers. Visits have been made to

Sarasota Automation, manufacturers of ultrasonic and electromagnetic gauging equipment, and Aqua data systems, manufacturers of electromagnetic current meters. A summary of information obtained from equipment manufacturers is contained in Appendix 6. Contacts have been made with a number of external organisations as listed in Appendix 5 and a visit has been made to the Institute of Hydrology which is responsible for the UK Surface Water Archive. Considerable interest has also been shown in the project by the British Waterways Board.

Whilst the collection of information was in progress a review of flow measurement techniques was carried out. The purpose of the review was to identify the full range of flow measurement techniques and consider their applicability to low velocity flow measurement. The review is contained in Appendix 7.

The Interim Report for the study was submitted at the end of May 1991 (HR, 1991). The framework and draft contents of the Project Report were agreed with the Project Leader in July 1991.

1.4 Framework of the report

The low velocity problem is described in Section 2, including the distinction between sites where continuous measurement is required and sites where non-continuous measurement is required. Section 2 also contains details of the extent of the low velocity problem, based on information provided by the NRA.

Flow measurement techniques are summarised in Section 3, with reference to the detailed review of flow measurement techniques given in Appendix 7. Flow measurement techniques which may be considered for low velocity measurement are discussed in further detail including current use within the NRA.

Recommendations for the most likely best options are given in Section 4 together with budget costs.

Section 5 contains proposals for a pilot scheme to test methods of low velocity measurement together with recommendations for further research and an overall strategy for the improvement of low velocity flow measurement.

2 THE LOW VELOCITY PROBLEM

2.1 Description

Low velocities of flow in rivers occur in England and Wales in a variety of situations. These include rivers affected by the tide, lowland rivers with shallow gradients, rivers subject to backwater from structures or tributaries, lowland drainage systems and abstractions from or discharges into main rivers. Low velocities also occur in upland rivers particularly at low flows subject to natural or artificial controls or weed growth affecting the lower parts of stage-discharge curves.

Flows where low velocities occur can be measured by flow measurement structures if sufficient head is available, and low velocities are not a problem at such sites. Therefore, whilst low velocities of flow occur at many locations throughout England and Wales, it is only a problem for flow measurement where insufficient head is available for the use of a flow measurement structure.

Rotating element current meters (propeller or cap types) have a minimum speed of response of about 0.03 metres per second. At this speed the accuracy of the meters is poor and not acceptable for flow gauging. Below this speed meters generally do not operate and, in addition, rating tanks where current meters are calibrated, do not normally operate accurately at speeds as low as 0.03 m/s. However, velocities of this order and below are quite common throughout the country under the conditions outlined above.

The low velocity problem therefore occurs where the velocity of flow is less than about 0.03 m/s, and there is insufficient head available for gauging structures. The problem is not new and it was mainly because of the difficulties of gauging low velocities that the ultrasonic and electro-magnetic methods were developed in the nineteen seventies.

In addition to the need for continuous flow gauging at network stations, there is also a need for current meter gauging of low velocities in connection with calibration of gauging sites, routine current metering, abstractions, discharges and other flow or water resources purposes.

2.2 Extent

In the national survey carried out, the extent of the low velocity problem at sites where continuous flow measurement is required can be expressed in terms of the number of existing gauging stations which are affected, and the number of other sites where gauging is required for water resources purposes but not carried out at present. The number of such sites is summarised in Table 1.

It will be noted from the table that there are a total of 28 gauging stations where it is believed that low velocities are a problem and a further 44 low velocity sites where continuous flow measurement is required but not carried out at present. It is clear from Table 1 that the most critical Region is Anglia where 26 sites suffer from low velocities. Although these figures are small compared to the total hydrometric network in England and Wales of about 1200 stations, the low velocity sites are often at important locations on major lowland rivers where flows for water resources purposes may be critical. Of the 28 gauging stations referred to above, 22 are either ultrasonic or electromagnetic gauges. The NRA generally consider that the measurement of low velocities at these sites is satisfactory, and therefore there are only 6 gauging stations where low velocities are a problem Thus the total number of sites where flows are not gauged or unsatisfactorily gauged because of the low velocity problem is 50.

The locations of the low velocity sites are shown on maps of NRA Regions in Figures 1 to 10. NRA Northumbrian Region is included for completeness, although no problems have been reported in this area. Approximate boundaries of catchment areas affected by the low velocity problem are also indicated where information is available.

The information on the extent of the low velocity problem is subjective. Low velocities occur at many other gauging stations but are not considered to be a problem by the relevant NRA Regions. There are also sites where low velocities occur and gauging is desirable, but there are other reasons why gauging is not carried out.

The need for non-continuous gaugings of low velocities was identified by all NRA Regions for a variety of reasons including the following:

1 Calibration gauging of structures under low flow conditions.
2 Routine gauging at river sites where low velocities occur.
3 Gauging flows in low level drainage systems. Current meter gaugings are preferred to continuous measurement in these areas where a large number of small channels exist.

During the national survey a number of gauging stations were identified where the rating at low flows in uncertain and cannot be checked using rotating element current meters. These include velocity-area sites, non-standard structures, and standard structures where conditions are not ideal for flow measurement.

All the NRA Regions carry out routine flow gauging using current meters for a number of reasons including the provision of supplementary flow data for water resources purposes, and work in connection with particular projects. Almost all the Regions reported that low velocities are a problem at some of these sites.

Large areas of lowland drainage systems exist, particularly in the Anglian, Southern, Yorkshire and Wessex regions of the NRA where low velocities are predominant and create difficulties in the assessment of flow.

There is also a need in at least six of the NRA Regions where low velocities create difficulties in connection with licence regulation and consents for water abstractions from, and discharges to, rivers. These include fish farms, sewage outfalls and gravity water supply abstractions where there is no head available for measurement structures. A relatively economic and reliable method of continuous flow measurement is required in these cases.

Two problems in measurement have therefore been identified as follows:

1 Continuous measurement of flow under low velocity conditions, the main problems being in the Anglian Region of the NRA.

2 Current meter measurements of low velocities either for establishing the low flow segments

of gauging station rating curves or for spot measurements of various kinds.

3 FLOW MEASUREMENT TECHNIQUES

3.1 General

A review of flow measurement methods is presented in Appendix 7 which summarises existing methods in use in the UK river gauging network. For each method comment is offered with regard to its suitability or otherwise, for use in low velocity regimes. The results are summarised in Table 2. From the review it can be concluded that the most suitable methods for continuous measurement of low velocity flows where little or no head loss is available are:

a) the ultrasonic gauge
b) the electromagnetic total flow gauge.

This conclusion was confirmed by the six Regions of the NRA which use one or both gauges. The number of ultrasonic and electromagnetic gauges in the NRA Regions is given in Table 3. Some further work is required to determine the accuracy of both methods in the measurement of low velocities of flow, and this is discussed further in Section 5.

The most suitable method for non-continuous measurement of low velocities is the electromagnetic current meter, although checks on the accuracy of this method for low velocity measurement are required. Nine of the ten NRA Regions have purchased electromagnetic current meters (see Table 3).

Other methods which have been investigated for measuring low velocities include the doppler velocity sensor, dilution gauging and the Rising Air Float Technique (RAFT), although it is thought unlikely that these methods will be successful.

3.2 Ultrasonic and electromagnetic gauges

Ultrasonic and electromagnetic gauges were developed with the problems of low velocity measurement in mind. Several ultrasonic gauges were installed in the mid 1970s but were not successful. One such location is the low velocity site on the River Parrett at Westover (Plate 1), where the original ultrasonic gauge has been abandoned and the need for flow gauging still exists. The methods are, however, sound and with improvements in technology it has been possible to successfully operate both ultrasonic and electromagnetic gauges at low velocity sites. Some examples include the ultrasonic gauge on the Mersey at Westy (1985, Plate 2), the ultrasonic gauge at Pilling's Lock on the Soar (1984, Plates 3 and 4) and the electromagnetic gauge at Syston on the Wreake (1982, Plate 5). Another early electromagnetic gauge is at Conagar Bridge on the Little Test (1980, Plate 6) although this is not specifically a low velocity site. A reflector system has been developed for ultrasonic gauges to eliminate the need for cables across the river. An example of an ultrasonic reflector gauge is the low velocity site at Riverside Park on the Itchen (1981, Plate 7).

The principle of each gauge is given in the review but basically both gauges were introduced for situations where a stable stage-discharge relation was not possible because of conditions of low velocities or variable backwater and a measuring structure was unsuitable or not feasible. The ultrasonic gauge is

Plate 1 The River Parrett at Westover. This low velocity site is the location of one of the early Harwell ultrasonic gauges.

Plate 2 The ultrasonic gauge on the River Mersey at Westy showing the four transducing mounting points.

Plate 3 The ultrasonic gauge at Pilling's Lock on the River Soar.

Plate 4 Transducers at Pilling's Lock ultrasonic gauge

Plate 5 The electromagnetic gauge at Syston on the River Wreake

PHOTOGRAPH TO FOLLOW

Plate 6 The electromagnetic gauge at Conagar Bridge on the Little Test.

Plate 7 The ultrasonic reflector gauge at Riverside Park on the River Itchen

based on the principle of timing ultrasonic pulses traversing the river at an angle to the flow, the time varying according to the flow velocity which is computed from the velocity components. The electromagnetic gauge is based on electromagnetic induction where electrodes set in the river banks sense the voltage generated by the water flowing through a vertical magnetic field set up by an electromagnetic coil.

Both gauges therefore measure velocity and with the addition of a water level gauge enable a continuous determination of discharge to be made by the velocity area principle. The electromagnetic technique is such that the average velocity in the flow cross-section is determined by a method of automatic integration. The ultrasonic gauge determines a line, or path average velocity, and the average velocity in the flow cross-section is determined from the number of paths in the system. The computation is analogous to flow computation by current meter using the summation of panels, or segments, of flow by the mid-section or mean-section methods. Panel dimensions can be derived from the fixed geometry of the system. The flight paths themselves define the 'horizontals' (analogous to the 'verticals' of conventional gauging) and panel widths are defined by the differences in elevations of the ultrasonic flight paths.

The choice of gauge will usually be decided on a cost basis but these are certain specific conditions relevant to each gauge. Generally, the electromagnetic gauge is employed in rivers less than 20-30 metres wide, because of coil costs, and the ultrasonic gauge is more suitable for wider rivers up to 300 metres or more.

Both gauges can measure velocities as low as 0.002 m/s and flow reversal. They are therefore both suitable for use in situations where the flow rate is subject to abrupt changes caused by the operation of control structures and tidal effects.

Limitations

There are a number of important limitations with the ultrasonic gauge. As with any velocity-area method a stable bed profile is important. Changes in cross-sectional area caused by bed movement will clearly affect the calculation of discharge, and regular surveys should be carried out where the section is not stable. In addition, the lower flight paths will be blocked by the accretion of silt.

A flat bed is desirable at an ultrasonic site to allow the lowest flight path to be parallel to the bed. There is at least one site in the UK where a navigation channel occupies part of the section, and the bed level is lower than the remainder of the section. It is not possible to measure flow velocities in the deepened part of the section using the ultrasonic method. It is not necessary for the bed to be horizontal as it is possible to direct flight paths at an angle to the horizontal. A sloping bed is therefore acceptable providing it is reasonably flat.

Ultrasonic flow measurement is affected by anything that blocks the flight paths and therefore blocks or attentuates the signal. Obstructions include suspended sediment, weeds, air bubbles and boats. It is therefore, necessary to keep ultrasonic gauging sites clear of weeds for effective operation. Gas bubbles associated with weeds are more troublesome that the weeds themselves, causing blockage and refraction of the signal.

Variations in water density cause the ultrasonic signal to be refracted and miss the target transducer. Such variations can be caused by temperature gradients, salinity and influents which are not fully mixed. Refraction of signals is known to occur at Blackwall Bridge on the River Rother where the section is deep and very slow moving, and some temperature stratification data for this site is understood to be available. Temperature stratification is also believed to have caused the failure of the early ultrasonic gauging station on the River Nere at Orton. Guidelines on acceptable density gradients for ultrasonic gauges are currently not available as little information exists, but this could prove to be a serious problem on some of the large, deep East Anglian rivers where gauging is required.

The electromagnetic gauge is more suitable where weeds are a problem and is used extensively to measure flows in important fishing rivers in the Hampshire district of the Southern Region of the NRA, where considerable weed growth occurs and weed cutting is not permitted. The electromagnetic method is also less susceptible to cross-sectional area changes than the ultrasonic method and is preferred where the section is subject to siltation or accretion.

The other constraints described above do not preclude the use of the ultrasonic method, but the key factor will be the periodic nature of the problems and the time needed to stabilise the situation or to revert to normal conditions.

The use of the ultrasonic gauge should be avoided in wide shallow rivers because the ultrasonic signals will, in all probability, be reflected from the surface or bed and therefore, interfere with direct transmission. This will cause large errors in measurements of time, and timing differences are critical in the system design. A minimum requirement for depth of flow, 'd', may be determined for preliminary survey purposes using the following simplified equation:

$$d > 0.03 \sqrt{L} \text{ metres}$$

(for an operating frequency of 500 kHz)

where L is the path length between transducers.

The ultrasonic gauge is also subject to errors if the direction of flow is not parallel to the river banks. For the most recent installations multi-crossed paths are normally included in the design to correct for any conditions of oblique (skew) flow in the measurement section (the area of flow contained by the transducers). These paths are generally installed at the same level.

One of the main constraints with the electromagnetic gauge is external influences on the magnetic field, including power sources and conductors. These can cause large errors in the measurement of velocity and should be avoided. The electromagnetic gauge also has a higher power requirement than the ultrasonic gauge and, as mentioned earlier, is only used in rivers of up to 20-30 metres in width from cost considerations.

The limitations of the ultrasonic and electromagnetic techniques are summarised in Table 4. Both methods rely on electric equipment and are therefore, liable to failures. However, the standards of reliability of such equipment appears to be steadily improving and breakdowns are rare. Different problems have been experienced with these relatively new technologies in different Regions of the NRA, with the result that some Regions have a distinct preference for one method over the other. However, with the present quality of available equipment both methods are viable low velocity measurement techniques and selection should be based on site considerations.

The number of ultrasonic and electromagnetic gauges in NRA Regions are given in Table 3, which is based on the more detailed information contained in Appendix 4.

Costs

A summary of costs of recent gauging sites is given in Table 5, based on the more detailed data given in Table A 4.4 of Appendix 4. The costs of ultrasonic gauges do not vary appreciably with river width and the majority of installations cost between £75,000 and £150,000 for a range of widths between 8 m and 60 m. There was insufficient information to demonstrate the increase in electromagnetic gauge costs with width, and the majority of installations cost between £100,000 and £300,000 for a range of widths between 10 and 20 metres. The costs of gauging structures on rivers less than about 10 m in width is generally in the £30,000 to £100,000 range which compares favourably with the electronic methods. At larger widths, the cost of gauging structures increases. Very few large gauging structures have been built in recent years and costs were only obtained for one structure exceeding 20 m in width constructed since 1985. It is however, apparent that electronic methods of flow measurement are similar in terms of cost to conventional gauging stations for medium sized rivers and ultrasonic gauges are cheaper for larger rivers.

Site works almost always cost several times more than the gauges themselves, the estimated cost of the most expensive proposed ultrasonic station being £750,000 due to high site costs.

Two of the most expensive installation costs in ultrasonic stations are the cable installation, which can cost as much as £20,000 and steel sheet piling which costs about £1,000 per metre run. In order to cut out cable costs a reflector system is available although not all such systems have been successful, particularly in silty rivers where the reflector is affected by silt. There are also difficulties with lining up beams in a reflector system.

An interesting development in ultrasonic gauges has been the production of "portable" gauges. These consist of two or four transducers which may be mounted on piles or poles driven into the bed, together with cables and instrumentation. They provide a single path or cross path and may be used for small channels such as fish farms, or for project investigations of limited duration. The packages of equipment offered by manufacturers for portable ultrasonic gauges cost about £7-8,000.

Operation and maintenance costs have been estimated for ultrasonic and electromagnetic gauging stations as follows:

1	Estimated cost of annual operation and maintenance of the hydrometric network in England and Wales, based on data provided by the NRA Regions and assuming a 150% overhead allowance Costs include data collection and processing	£5,500,000

2	Number of gauging stations (approximately)	1,220
3	Annual cost per station	£4,600
4	Annual cost of maintenance agreement with equipment manufacturer for ultrasonic and electromagnetic gauges (per station)	£1,500
5	Estimated annual cost of operation and maintenance of ultrasonic and electromagnetic gauging stations based on 3 above, plus a marginal allowance for higher maintenance costs	£5,000

The figures in 1 above, agree closely with figures produced in 1991 for the calculation of the benefit-cost ratio oxhydrometric data (DOE/CNS, 1991).

Accuracy

The accuracy of ultrasonic and electromagnetic gauges in the determination of low velocities is unknown because there are no suitable means available to check the results. In most of the Regions where these gauges have been installed the NRA have carried out check gaugings at higher velocities using rotating element current meters and the results have generally been impressive. Data for 136 check gaugings obtained from one Region showed that 80% were within ±10% and 60% within ±5%. 4% were grossly in error caused by faults on one gauge. Considering the systematic errors involved in current meter gauging these results suggest that electronic methods of flow gauging can be very accurate. It was noticeable that the errors increased at low velocities, but this probably reflects the reduced accuracy of rotating element current meters under these conditions. Accuracies of the order of 2% have been estimated for electronic methods under normal flow velocities.

Under low velocity, and therefore possibly low depth, conditions both methods are subject to the accuracy of water level measurement. The effects of changes in bed profile will affect the accuracy of ultrasonic flow calculations. At low velocities the measurement of velocity using the ultrasonic method depends on the measurement of smaller and smaller time differences and the uncertainty in measurement accuracy will increase. The measurement of velocity is also affected by skew flow, which is more likely to occur at low velocities.

For low velocities an accuracy of $\pm 5\%$ is suggested for ultrasonic gauges down to a certain discharge, with the uncertainty becoming a fixed amount below this figure.

i.e For flows greater than a certain discharge, Q_L

uncertainty = $\pm 5\%$

For flows less than Q_L

uncertainty = 0.05 Q_L m/s

At low velocities the signal measured by the electromagnetic gauge gets smaller and smaller and the measurement of small signals in "noise" becomes a limitation. Low frequency background "noise" is a particular problem under these conditions.

Water level and depth measurement

In both gauges, depth of flow requires to be measured, recorded and keyed into the systems. In the case of low velocity flows the accurate measurement of depth is particularly important where shallow depths occur.

In the ultrasonic method, the depth of flow is determined by a single transducer mounted under the water with its beam pointing vertically up towards the surface. The ultrasonic pulse transit time to the surface and its reflection to the same transducer gives a measure of depth. The depth determined is the average depth across the measuring section. Normally in the case of the electromagnetic gauge the depth of flow is determined by measuring stage and using a relation of stage versus depth. Stage may be measured conventionally or by an ultrasonic 'look-down' gauge.

Standards

In addition to the listed bibliography in Appendix 7, two new detailed ISO standards are at the final stage of approval. They are ISO 6416(R) for the ultrasonic gauge and ISO 9213 for the electromagnetic gauge, both having been prepared by the UK British Standards Committee on flow measurement.

3.3 Electromagnetic current meters

The electromagnetic current meter is considered to be the best available method of calibration and spot gauging of low velocity flows. The technology is relatively new but the calibration results given on page 11 of Appendix 7 are encouraging.

The meter works on the same principle as the electromagnetic gauge, with the coil and the electrodes being mounted in the probe head. The meter can theoretically measure down to 0.002 m/s although it has not been possible to check this. The meter requires zero setting and it has been found that even placing the meter in a bucket of water is unsatisfactory for such sensitive instruments. It is claimed that the meters are unaffected by the presence of electrical noise but this requires confirmation.

All the NRA Regions except Northumbrian have purchased electromagnetic current meters since 1986. Northumbrian Region have the least requirement for low velocity flow measurement of all the ten NRA Regions, but have arranged a demonstration of an electromagnetic current meter. The Regions have had mixed success with the electromagnetic current meter and clearly the technology is still to be fully proved. There have been problems with faulty meters, incorrect calibrations, and also failure by some users to operate and maintain the meters correctly. It appears however that these problems are being overcome.

One category of river where flow gauging by electromagnetic or ultrasonic gauges is not practicable is a large river severely affected by weed growth or salinity. One such river is the Dee in North Wales, where a suspended electromagnetic current meter is being used for flow measurement.

The cost of electromagnetic current meters is of the order of £2.250 upwards including the control box. Accessories including wading rods, suspension cables, fins and weights are available. An interesting development currently under consideration is the use of several electromagnetic current meters in conjunction with floats and rods to form a "net" across a river which would provide a continuous gauging facility. There are clearly some reservations about such a method, including navigation and vulnerability to interference and damage by trash. However, if these problems could be overcome it could provide a possible method for continuous flow measurement for such sites as the Dee mentioned above.

The accuracy of flow gauging using electromagnetic current meters at low velocities is unknown. The instrument itself is believed to be very accurate, although this requires confirmation. However, other uncertainties become important including accurate depth measurement, accurate bed survey information and the effect of skew flow and secondary currents. For higher flows the accuracy associated with normal velocity-area flow measurement would be appropriate. (i.e $\pm$5%).

3.4 Other methods

Several other methods for low velocity measurement have been tried by the NRA and other possibilities exist as a result of new technological developments. The methods are described in Appendix 7 and summarised in Table 3.

Doppler velocity sensor

The doppler velocity sensor utilises a beam of acoustic energy which is projected into the flow and scattered by the suspended particles. The reflected signal has a shift in frequency which is proportional to the flow velocity. The principle of the method is similar to the laser doppler anemometer (LDA), which is the modern technology for accurate measurement of flow velocities in the laboratory. The LDA focuses twin laser beams on a particular point in the flow, and provides an accurate measurement of the velocity at that point. It does however, require calibration to match the frequency shift to the velocity. The doppler velocity sensor does not focus on a particular point in the flow and it is not clear exactly which velocity is being measured. It is claimed that the velocity measured is the average velocity in the section but this seems unlikely.

Before this method can be considered further it is essential that extensive and exhaustive proving tests are carried out to establish what velocity is actually being measured, and the effect of changes in concentration of suspended particles on the velocity measurement.

It is of concern that the doppler velocity sensor is being used to measure flow velocities in UK sewers. In view of the apparent shortcomings of the method it is important that it is proved without delay.

Dilution gauging

Dilution gauging is described in Section 2.5 of Appendix 7. It has been used to gauge flows successfully in upland rivers in North Wales. NRA staff in the area have reported that the method is very reliable for certain types of rivers under certain conditions, for example riffle streams at low flows, but it is not suitable for more general application. The method is very time consuming and staff availability is therefore a constraint. The method is not suitable for lowland rivers because of tracer mixing difficulties, and is not recommended. Trials on the Little Stour in Kent failed for this reason.

Rising Air Float Technique (RAFT)

RAFT is briefly described in Section 2.9 of Appendix 7. Trials of the method have been carried out in Scotland (Caledonian Canal and the River Devon at

Glenochil) and in the Yorkshire and Anglian Regions of the NRA. The particular problems under investigation included low velocities and flow gauging at sites with excessive weed growth.

None of the trials carried out have been successful. A disturbing feature of the results was the lack of repeatability between successive gaugings on the same day. Check current meter gaugings also identified considerable inaccuracies in the method. Problems with the method are numerous, and include the following:

1. There is uncertainty in the rate of bubble rise, which is based on laboratory calibration.
2. The flow gauging appears to be affected by the air supply pressure and the size of bubbles.
3. Observation of the bubble pattern is difficult under certain conditions of light and shade, not to mention at night! Observation was also affected by wind, rain, turbulence and weed.
4. Recording the bubble pattern and abstracting discharge measurements is fraught with difficulties, clumsy and expensive.

There is clearly scope for research to overcome the problems described above and the method may provide a viable alternative to other techniques at difficult sites. However, further work on RAFT is not recommended for low velocity measurement as other methods are more likely to succeed.

Miscellaneous

A number of other options for low velocity flow measurement were considered but no other methods have been identified which offer a realistic alternative to the methods described earlier. The use of vertical rod floats will provide a first estimate of velocity but the method is not particularly accurate and difficult to log. There are a number of possibilities for flow measurement on small channels and abstractions and discharges using water wheels and electronic gauges attached to pipe culverts. These all have limitations in terms of head loss, and a water wheel will only operate under a limited range of upstream water levels which are related to the wheel diameter.

4 BEST OPTIONS FOR LOW VELOCITY MEASUREMENT

4.1 Method

Recommendations for the most likely best option for low velocity flow measurement are given below:

Continuous flow measurement

The recommendation for the most likely best option for flow measurement at locations where flow measurement structures are not suitable is the ultrasonic gauge. The electromagnetic gauge is a possible alternative at sites on smaller rivers where conditions are not suitable for ultrasonic gauges. Further work to confirm the suitability of these methods is recommended in Section 5.2.

Non-continuous flow measurement

The recommendation for the most likely best option for non-continuous measurement of low velocity flows is the electromagnetic current meter. Further work to confirm the accuracy and reliability of electromagnetic current meters is recommended in Section 5.2

4.2 Costs

Budget costs for the above techniques are given below.

Technique	River Width (m)	Costs (£k) Capital	Operation and maintenance (per annum)
Ultrasonic	Up to 60	75-150	5
Electromagnetic	Up to 20	100-300	5

Electromagnetic current meters cost from £2,250 upwards, not including wading rods or suspension equipment. The total cost including suspension equipment is of the order of £3,000. The above costs are estimates for guidance purposes. Whilst instrumentation costs do not vary much, the cost of civil works can vary enormously. Recently constructed or planned ultrasonic stations vary in price from £24,000 in a small river where no civil works were required to £750,000 for a major river where extensive earthworks and bank protection were required. Operation and maintenance costs are based on the discussion given in Section 3.2

5 FURTHER WORK

5.1 General

There are a number of uncertainties in connection with low velocity flow measurement which require further investigation. These include the following:

1 Accuracy of the ultrasonic gauge at low velocities.

2 Accuracy of the electromagnetic gauge at low velocities.

3 Accuracy of the electromagnetic current meter at low velocities.

In addition, the following items of research work are desirable to improve low velocity flow measurement.

4 Investigation into the effects of temperature and salinity stratification on ultrasonic flow measurement, including collection of data from the few sites where these problems are known to exist.

5 An independent check on the total flow calculation used at ultrasonic sites, particularly in the case where some of the flight paths are not working.

6 Research into the improvement of the ultrasonic reflector system, as this method avoids the often high cost of cabling across rivers.

7 Research into the use of radio communication for large ultrasonic sites.

8 Research into the improvement of power supplies for electronic gauges, including low power systems, improved batteries or solar power.

9 Investigation of the accuracy of velocity measurement using the doppler velocity sensor.

Another area of interest in connection with the electromagnetic gauge is the possibility of eliminating the need for bed insulation, as this would considerably reduce construction costs. Discussions with manufacturers indicate, however, that this may not be practicable.

5.2 Strategy

The following strategy is proposed for further work.

1. Select a pilot station near a gauging structure which has a reliable rating at low flows, and where low velocities regularly occur in the river.
2. Examine the accuracy of the electromagnetic current meter at low velocities. Current meter rating tanks do not generally cover the velocity range required, and it may be necessary to construct a purpose built laboratory rig. The current meter would also be used at the pilot station referred to in 1, above, to gauge low velocity flows and compare the results to flows obtained from the gauging structure. An alternative method would be to check the gauging volumetrically, but this presents practical problems. All available makes of current meter should be tested.
3. Having established the accuracy of the electromagnetic current meter, it would then be used to check flow gaugings at ultrasonic and electromagnetic sites where low velocities occur. This would provide a first guide to the accuracy of ultrasonic and electromagnetic gauges at low velocities of flow.
4. The pilot station referred to in 1, above, would be used to test methods of low velocity flow measurement. The programme would be varied according to perceived needs and available budget. This is discussed further in Section 5.3 below.

5.3 Proposed pilot scheme

Site Selection

The site for the pilot station would be where a British Standard weir is available to provide an accurate measurement of flow. The actual experimental site would be selected either upstream of downstream of the weir at a location where low velocities occur and good access exists. The site should also satisfy the requirements of the gauges and other equipment which are to be tested. For ultrasonic and electromagnetic gauges these include a straight stable reach of river, and acceptably low levels of electrical noise.

It is suggested that a shortlist of possible sites is prepared. For each site an average velocity-duration curve should be prepared based on historic records, in order to establish the proportion of time when low velocities occur. Whilst this may be initially time consuming, the effort will be well worthwhile as the amount of time per year when useful experimental work can be carried out will depend entirely on the length of time when low velocities occur.

Techniques to be tested

It is recommended that the following items are investigated at the pilot station:

1 Electromagnetic current meter, as discussed in Section 5.2 above.

2 Ultrasonic flow gauge. This would require the installation of an ultrasonic gauge. It would only be necessary for the gauge to cover the range of flows where low velocities occur, and

therefore only two or three cross paths would be required.

3 Electromagnetic flow gauge. This would require a major investment, the justification of which is discussed below.

4 Testing the total flow calculation of the ultrasonic method, particularly when some of the paths are not functioning.

5 The doppler velocity sensor. Other possible methods of low velocity measurement would also be tested including, for example, RAFT.

It may appear hard to justify the construction of ultrasonic and electromagnetic gauges at the pilot station in terms of cost. However, this may be the only practical way of establishing the accuracy of these gauges at low velocities of flow. The ultrasonic equipment is relatively portable and it may be possible to re-use it elsewhere on completion of the trials. One possible way to offset the cost of the electromagnetic gauge would be to select a structure which has a reliable rating at low flows but is drowned at high flows. The electromagnetic gauge could then provide a full range flow gauging station.

Once the initial programme of experiments at the pilot station is complete, it would then form a test bed for new developments and further research including, for example, improvements in the ultrasonic reflector technique and improved power supplies for ultrasonic and electromagnetic gauges.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Low velocities of flow occur in many rivers in England and Wales. Such flows may be gauged using flow measurement structures, but difficulties are encountered measuring low velocities where insufficient head is available for structures.

6.2 There are about 50 sites in the NRA Regions which are currently ungauged or unsatisfactorily gauged because of the constraint of low velocity of flow. Low velocity flows are gauged at a further 22 sites using either ultrasonic or electromagnetic techniques.

6.3 It is recommended that the following methods are used to measure low velocities of flow.

Continuous measurement - Ultrasonic gauge
- Electromagnetic gauge

Non-continuous measurement
- Electromagnetic current meter

6.4 There are a total of 34 ultrasonic gauges and 26 electromagnetic gauges currently in use in the NRA Regions. Most of these are understood to perform well, although it has not been possible to check their accuracy at low velocities of flow.

6.5 A total of 14 electromagnetic current meters have been purchased by the NRA Regions. The technology is new and problems have been encountered, but the method is now considered to be reliable.

6.6 A number of constraints have been identified with both ultrasonic and electromagnetic gauges, and these must be taken into account when deciding which method to use for new gauging stations.

6.7 Further work is recommended to check the accuracy of the recommended methods at low velocities, and to investigate the improvement of some aspects of the methods.

6.8 Other potential methods of low velocity measurement including the doppler velocity sensor, dilution gauging and the rising our float technique are not recommended for use at present.

6.9 It is recommended that a pilot station is established which will be used as a test site for low velocity measurement methods.

7 ACKNOWLEDGEMENTS

The helpful co-operation of all ten NRA Regions is gratefully acknowledged. The considerable effort and time spent by NRA staff has made and will continue to make a major contribution to the project. In addition to the NRA personnel listed in Appendix 3, information was provided by David Anderson, Vaughan Hughes and Ray Renshaw of NRA Welsh Region. Information was also providing by the Institute of Hydrology and equipment manufacturers.

The study was carried out by Reg Herschy as independent consultant, and Rodney White and David Ramsbottom of HR Wallingford.

8 REFERENCES

HR, 1991. 'Review of Low Velocity Measurement Techniques, Interim Report', Report EX 2359, HR Wallingford, May 1991.

DOE/CNS, 1991. The Benefit - Cost of Hydrometric Data-River Flow Gauging', CNS Scientific and Engineering Services, FR/D 0004, March 1991, prepared for the Department of the Environment.

TABLES.

TABLE 1

Number of low velocity sites where continuous flow gauging is required

NRA Region	Number of low velocity sites Existing gauging stations Ultrasonic(2)	Electro magnetic(3)	Other(1)	Flows not gauged at present(1)	Total
South West	-	-	-	3	3
Wessex	1	-	1	4	6
Southern	3	-	-	10	13
Thames	4	1	-	-	5
Anglian	-	-	1	25(4)	26
Severn Trent	3	1	-	-	4
Welsh	-	-	-	2(5)	2
North West	2	-	-	-	2
Yorkshire	2	5	4	-	11
Northumbria	-	-	-	-	-
TOTALS	15	7	6	44	72

Notes

1) Based on Appendix 4, Table A 4.1.

2) Based on Appendix 4, Table A 4.2.

3) Based on Appendix 4, Table A 4.3. The "other" existing gauging stations are sites where low velocity flows are unsatisfactorily gauged at present.

4) Excludes an undefined number of rivers near the Suffolk Coast and in the Norfolk Broads area (Anglian Region).

5) Excludes two sites on canals.

6) There are a large number of sites where non-continuous low velocity flow gauging is required including:

calibration gauging at structures
watercourses in low lying coastal areas in NRA Southern Region.

TABLE 2

Suitability of flow measurement techniques to low velocity measurement

	Method	Suitability	Remarks
1	Velocity area		Suitable for continuous gauging where a unique stage discharge relationship exists. Otherwise only suitable for calibration and spot gaugings
	- rotating element current meter	No	
	- electromagnetic (EM) current meter	Yes	Meter requires proving at low velocities
	- doppler velocity sensor	Unlikely	Method requires proving
2	Weirs and flumes	Yes	Operating head required
3	Ultrasonic	Yes	Requires proving at low velocities. Some limitations
4	Electromagnetic	Yes	Requires proving at low velocities. Some limitations
5	Dilution	No	Some success in upland rivers in North Wales where sufficient turbulence occurred to allow mixing. Unsuccessful on a lowland river in Kent
6	Slope-area	No	Inaccurate at low velocities
7	Stage-fall-discharge	No	Inaccurate at low velocities
8	Moving boat method with EM current meter	No	Generally suitable for large rivers where velocities exceed 0.15 m/s
9	Floats	No	Inaccurate
10	Rising Air Float Technique (RAFT)	Unlikely	Requires further investigation. Trials in Scotland and in the Anglian and Yorkshire Regions of the NRA were unsuccessful
11	Water wheel type meters	Yes	Operating head required. Other limitations

TABLE 3

Ultrasonic and electromagnetic flow measurement in the NRA

NRA Region	Number of gauging stations Ultrasonic (1)	Electromagnetic(2)	Number of Electromagnetic current meters
South West	-	-	2
Wessex	2	-	1
Southern	3	6	2
Thames	13	5	1
Anglian	-	-	1
Severn Trent	12	10	2
Welsh	-	-	3
North West	2	-	1
Yorkshire	3	5	1
Northumbria	-	-	-
TOTALS	35	26	14

Notes

1) Based on Appendix 4, Table A 4.2

2) Based on Appendix 4, Table A 4.3

3) Small "portable" ultrasonic gauges have been installed in UK fish farms and two have been purchased by NRA Yorkshire Region

TABLE 4

Constraints for ultrasonic and electromagnetic flow gauges

Constraint	Ultrasonic Gauge	Electromagnetic Gauge
River width	No limit for UK rivers. Widths up to 300 metres have been gauged.	20-30 metres maximum
River geometry	Straight reach required. Symmetrical cross section preferred. Flat bed desirable. Not suitable for wide shallow rivers.	Straight reach required Symmetrical cross section desirable
Bed movement	Directly affects flow measurement. Stable bed desirable	
Weeds, air bubbles or suspended sediment	Blocks or attentuates signal. Can cause failure or errors in velocity measurement	No effect
Variation in water density caused by temperature gradients, salinity or impurities	Refracts signal. Can cause failure or errors in velocity measurement	The magnetic field is affected by salinity gradients, causing errors in velocity measurement
Skew and curved flow	Directly affected. Cross paths provide an approximate correction	No effect
Electrical noise	No effect	Directly affected
Electrical conductors (eg. steel piles)	No effect	Can distort magnetic field
Construction	Relatively straightforward. Little interference with the river	Bed lining and coil required. The coil must either be above the channel or below the bed. Major river works including possible channel diversion required.
Calibration	Not required	Normally required

TABLE 5
Typical Gauging Station Costs
(adjusted to 1991 prices)

Type	River width (m)	Cost (£)		
		Civil Works	Equipment	Total
Ultrasonic	8-60	40-110	27-42	75-150
Electromagnetic	8-20	55-220	20-40	100-300
Conventional (weirs)	5-20	30-130	5-10	35-140
Large Crump weir	40	800	5	805

Notes

1) Based on Appendix 4, Table A 4.4. Data is based on costs of NRA gauging stations constructed since 1985.

2) Costs vary considerably depending on conditions at individual sites. The cost of ultrasonic gauges range from £24,000, where the installation was within small existing concrete channels, to £750,000 for a major river where extensive earthworks and bark protection are required.

FIGURES.

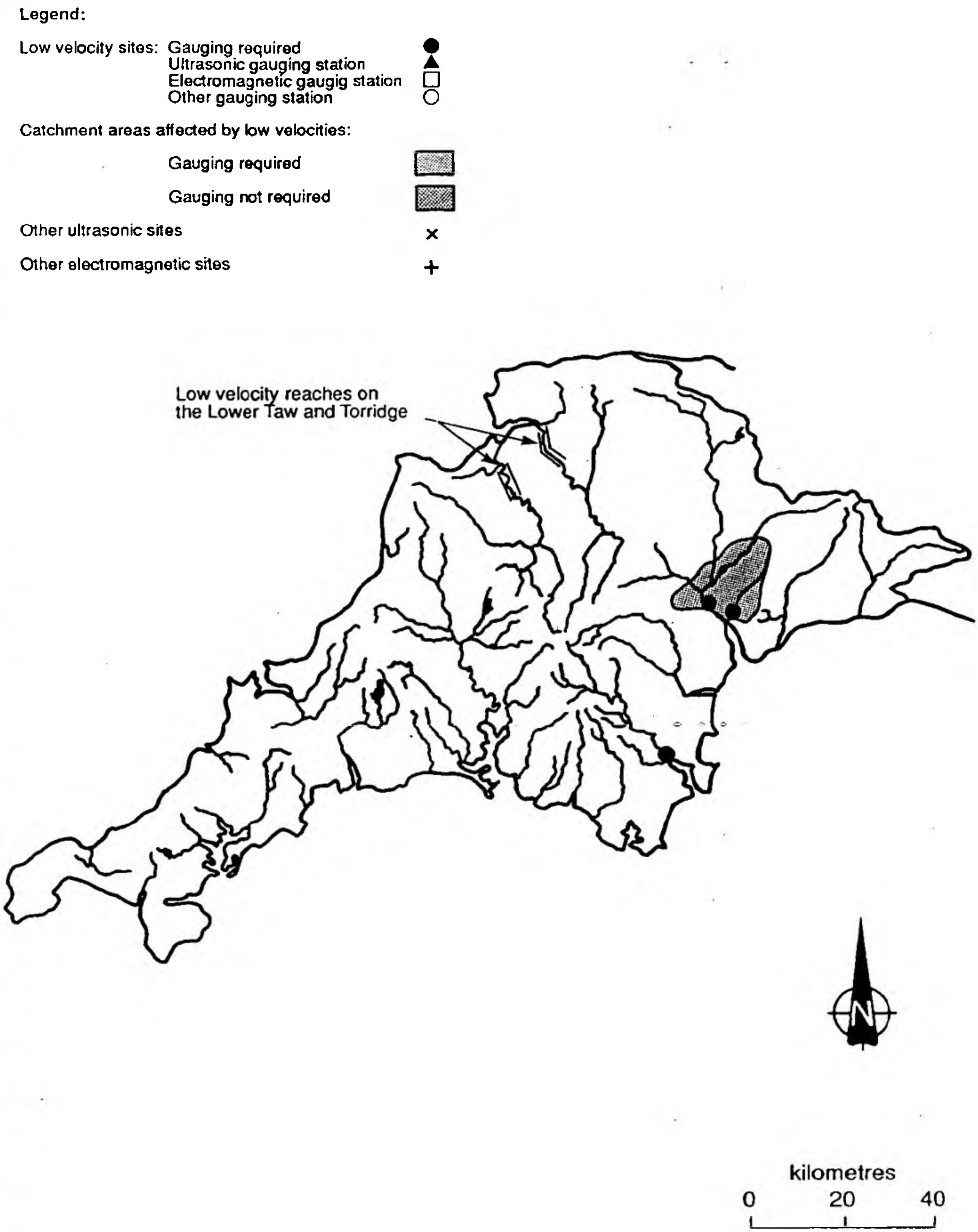

Fig 1 NRA South West Region

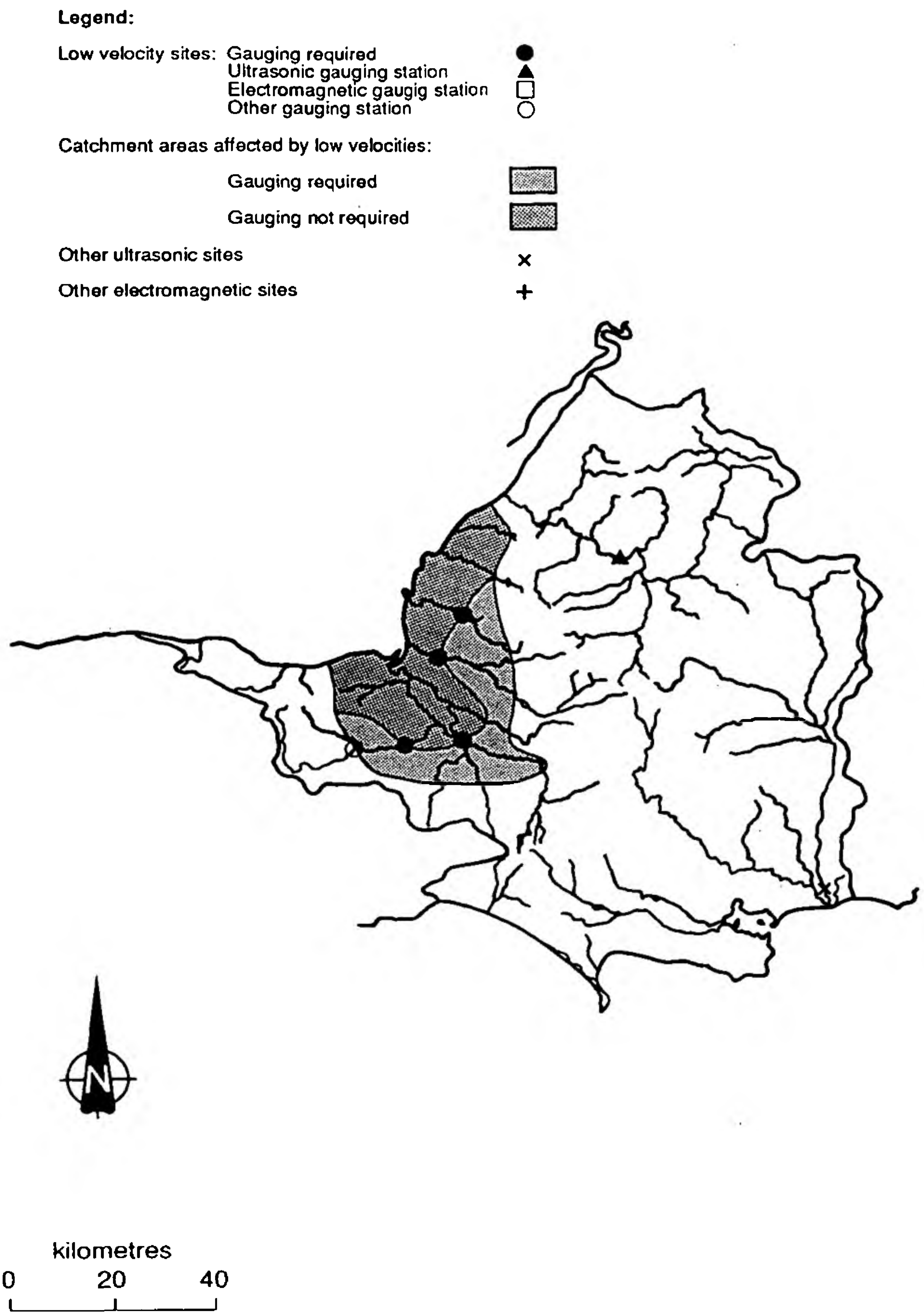

Fig 2 NRA Wessex Region

Legend:

Low velocity sites: Gauging required ●
Ultrasonic gauging station ▲
Electromagnetic gaugig station □
Other gauging station ○

Catchment areas affected by low velocities:

Gauging required

Gauging not required

Other ultrasonic sites ×

Other electromagnetic sites +

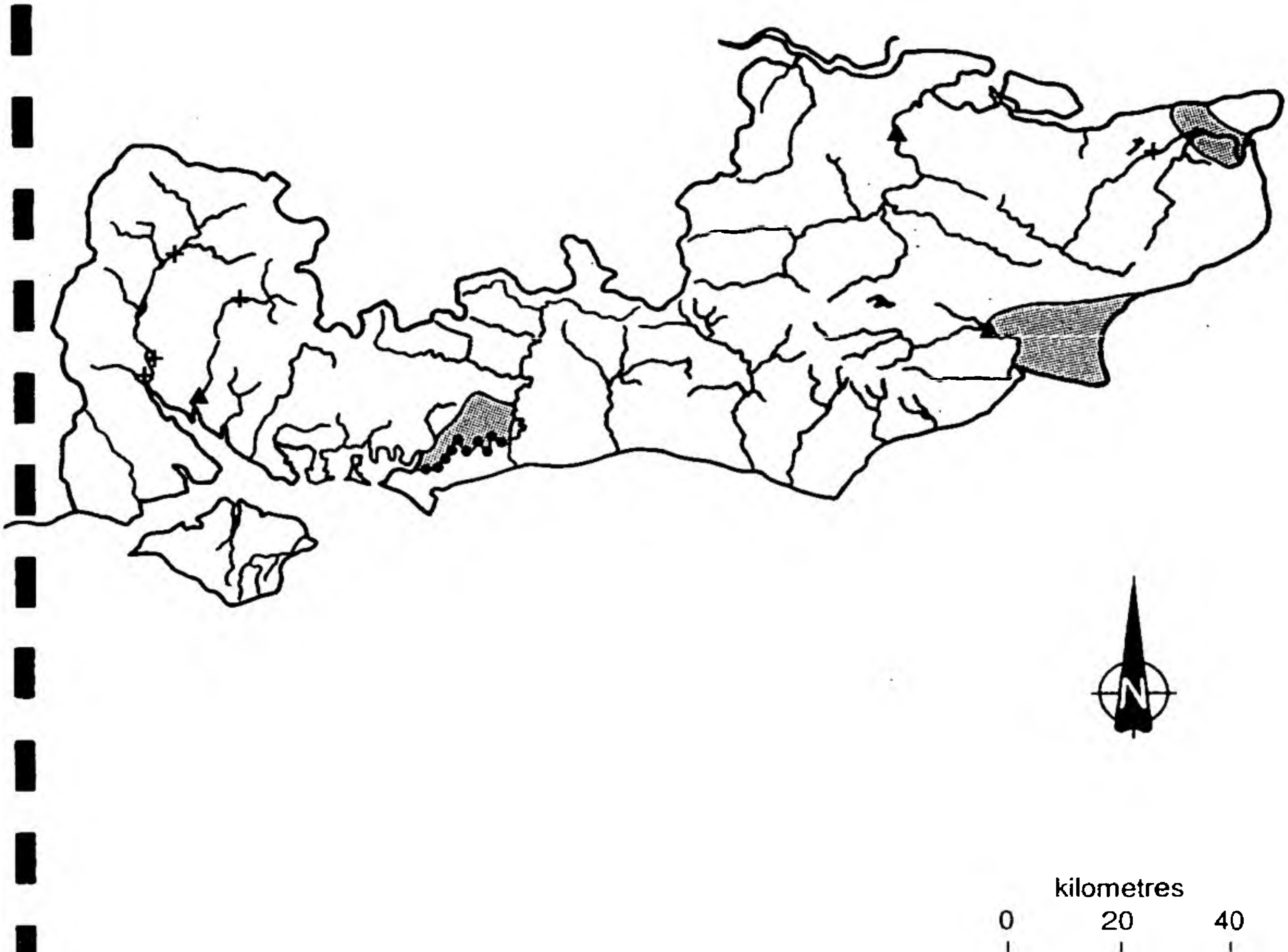

Fig 3 NRA Southern Region

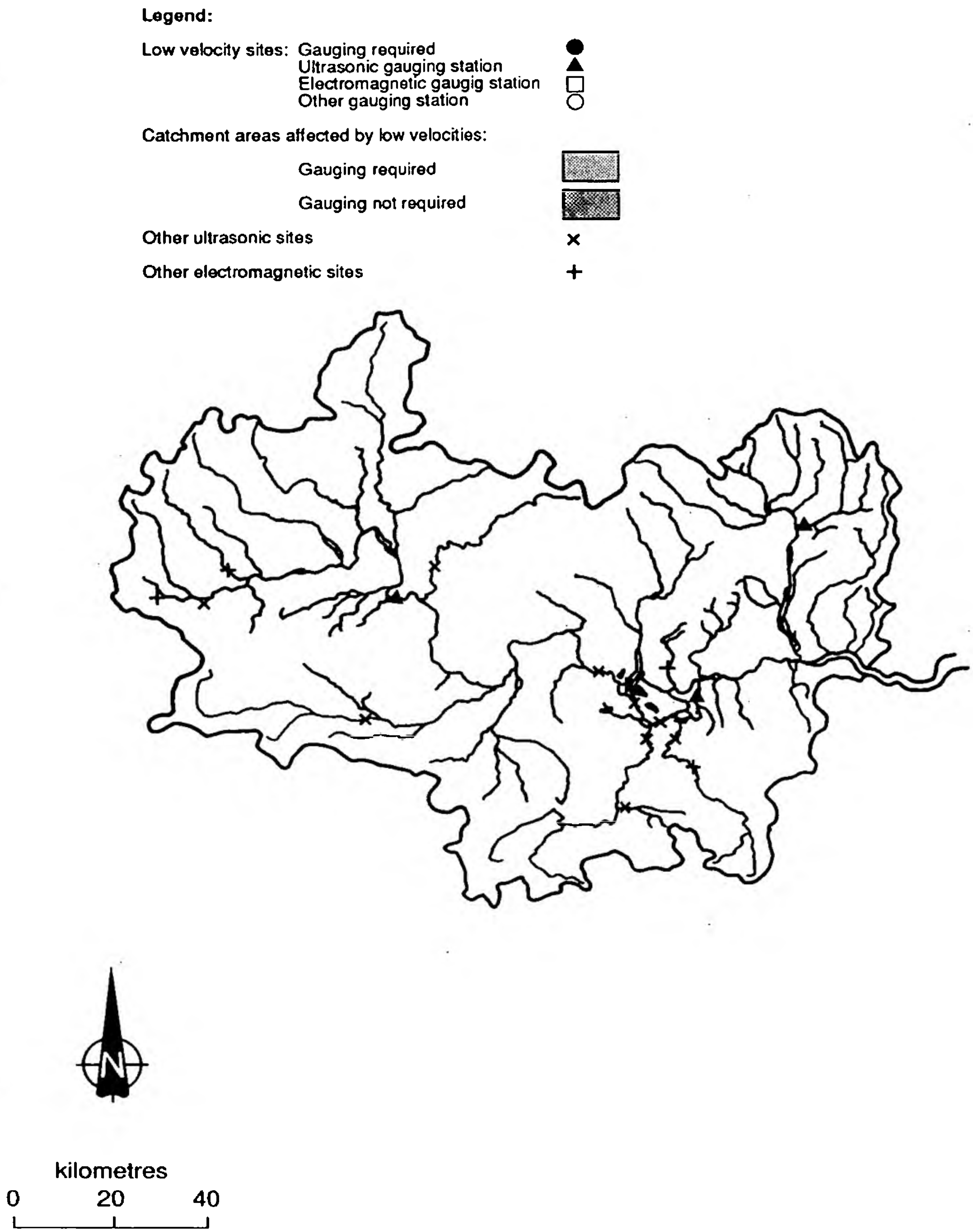

Fig 4 NRA Thames Region

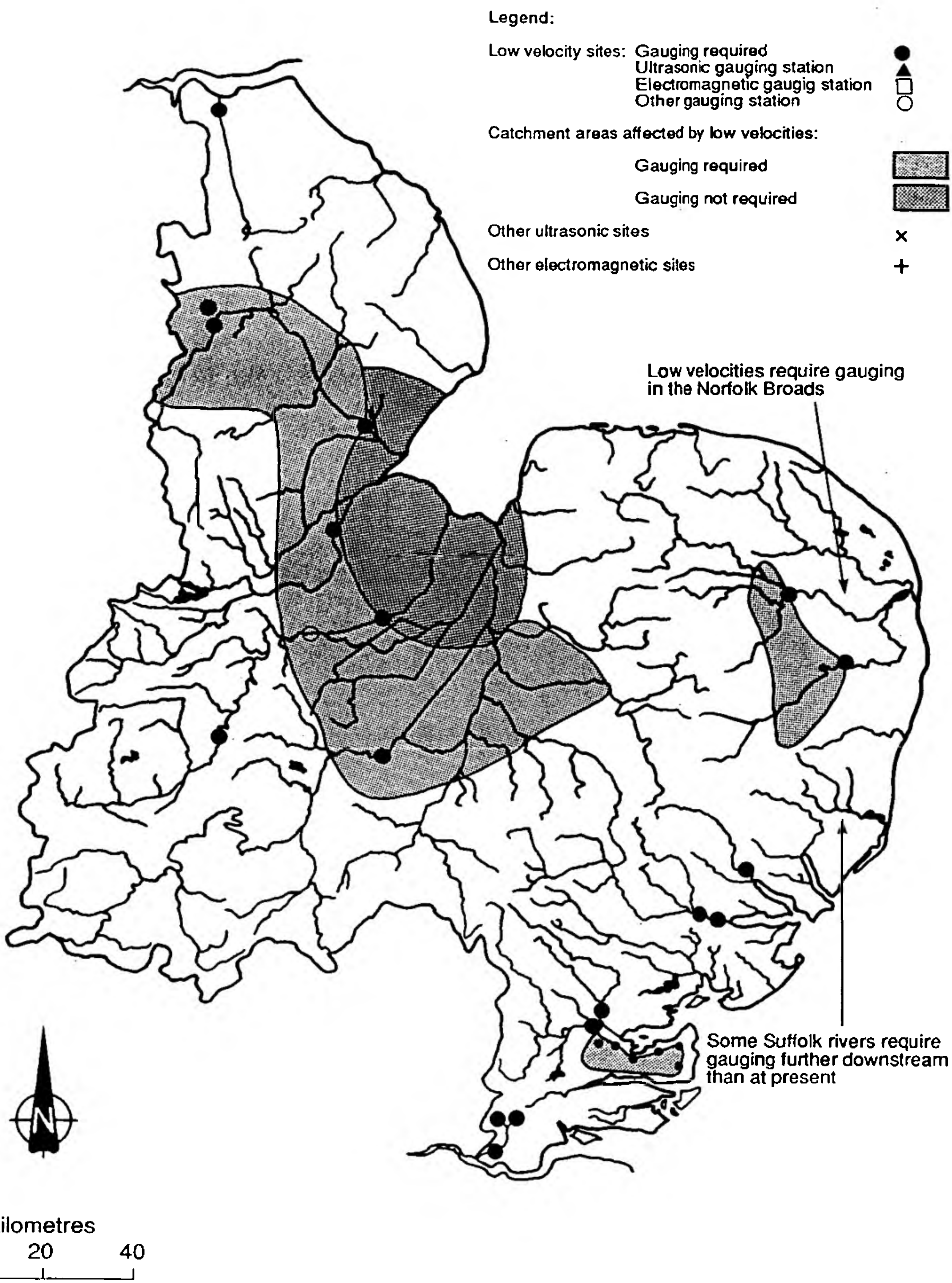

Fig.5 - NRA Anglian Region

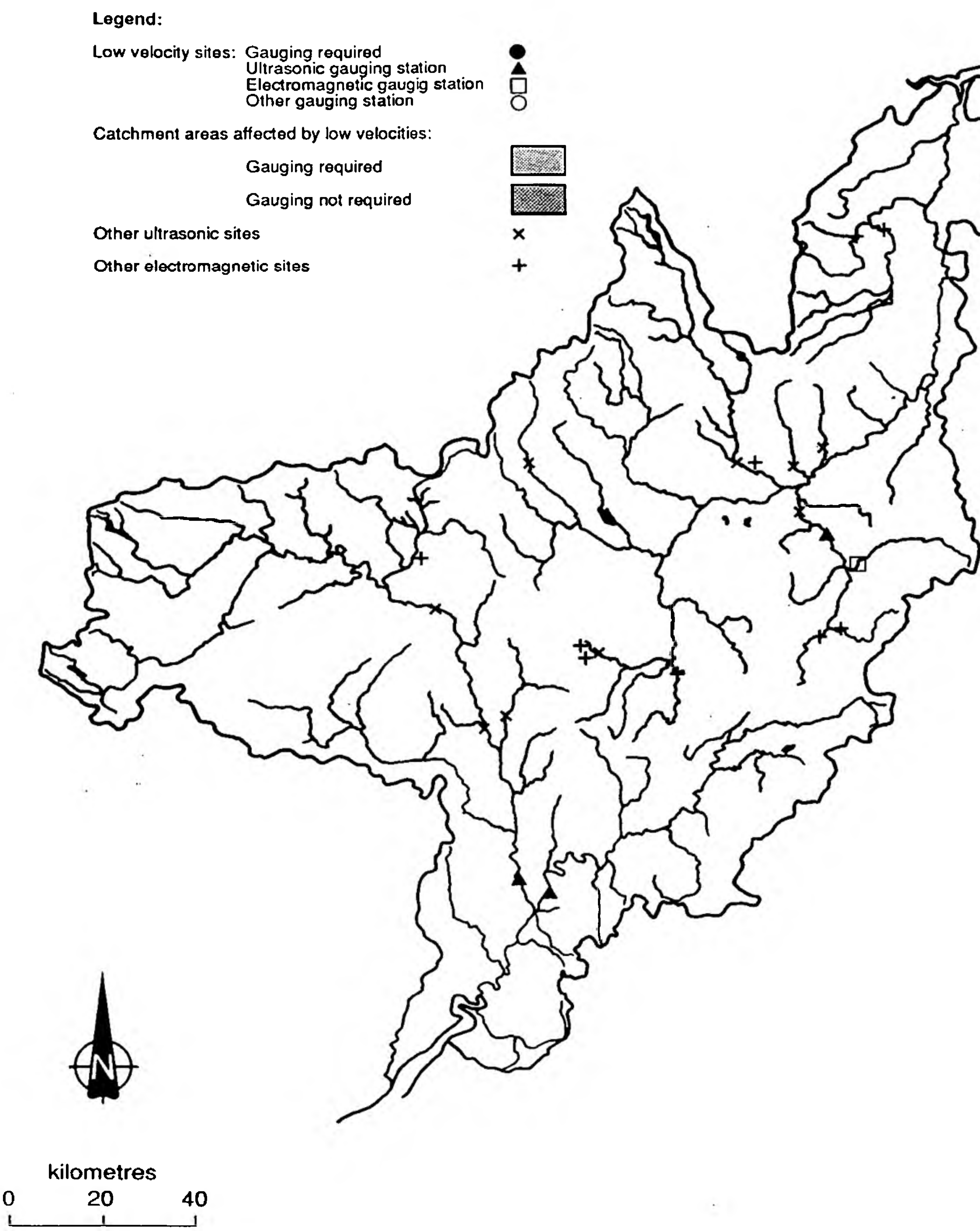

Fig 6 NRA Severn Trent Region

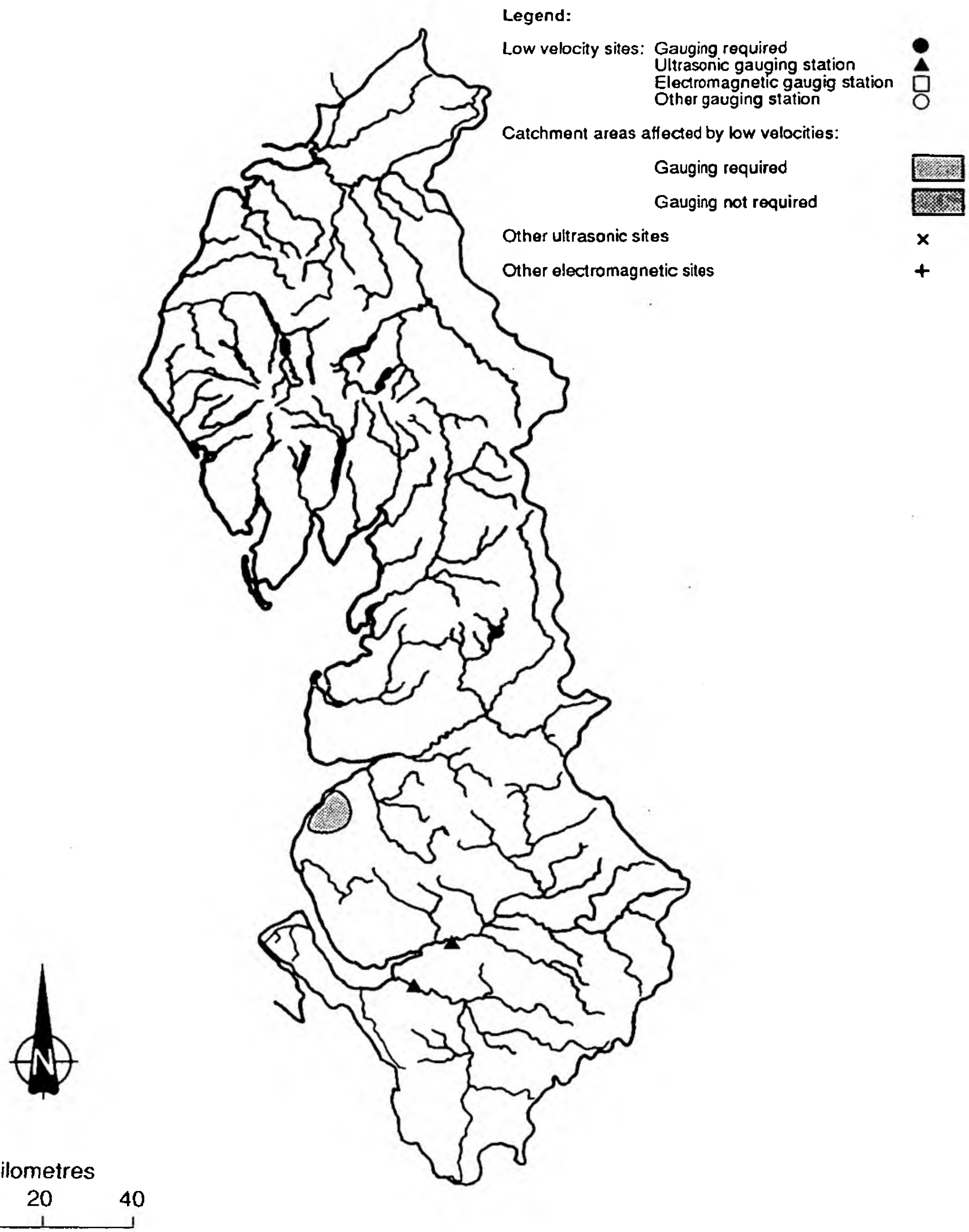

Fig 7 NRA North West Region.

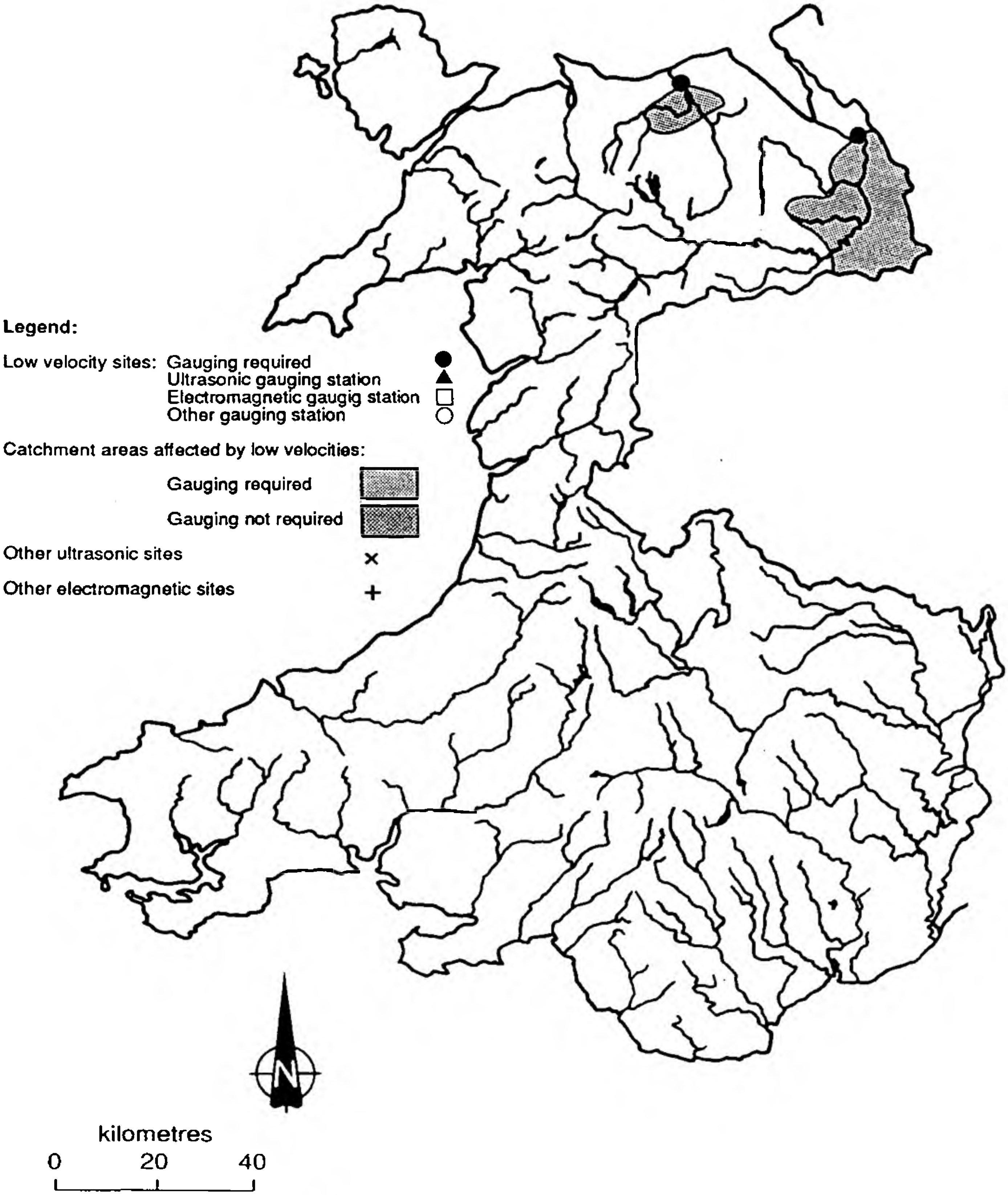

Fig 8 NRA Welsh Region

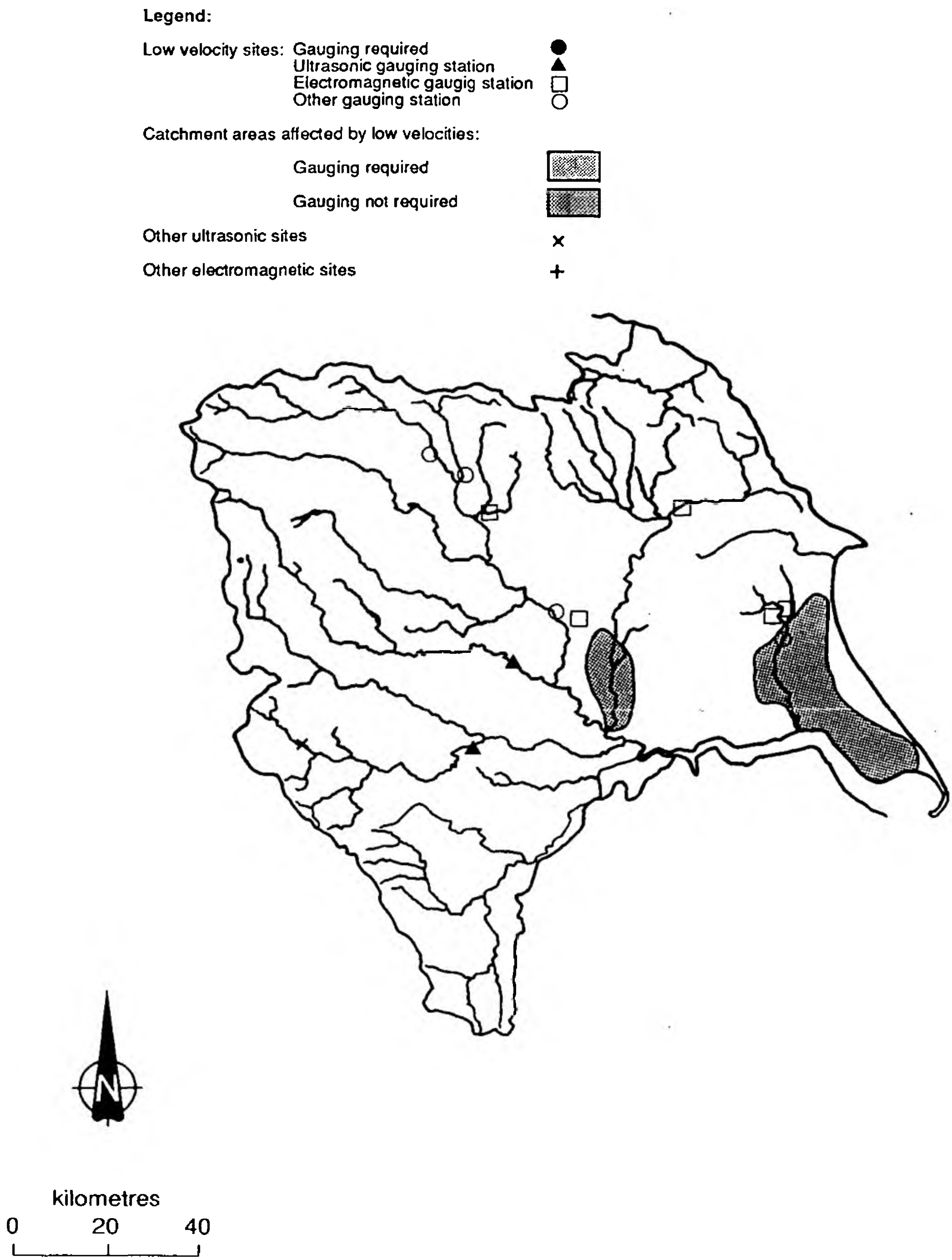

Fig 9 NRA Yorkshire Region

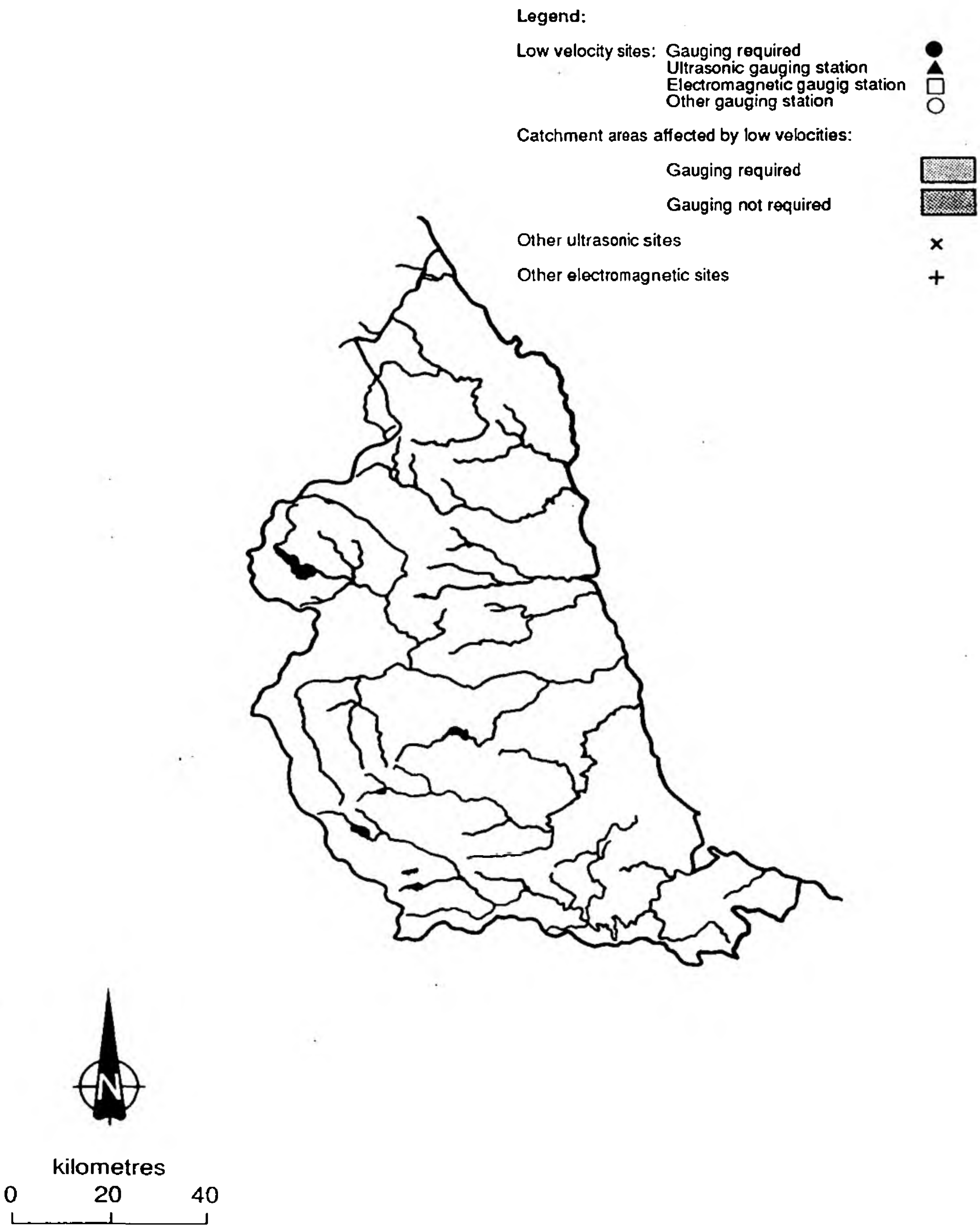

Fig10 NRA Northumbrian Region

APPENDICES.

APPENDIX 1

Terms of Reference

R&D PROJECT INVESTMENT APPRAISAL

R&D COMMISSION: B WATER RESOURCES

TOPIC: B01 HYDROMETRIC DATA

TITLE: REVIEW OF LOW VELOCITY MEASUREMENT TECHNIQUES

PROPOSAL NO.: B01.02.90 **PROJECT NO.:** 0280

CLASSIFICATION OF R&D: SPECIFIC

PROJECT LEADER: MR P. GRANGE

POST TITLE: DEMANDS ENGINEER

REGION: ANGLIAN

ADDRESS: KINGFISHER HOUSE
ORTON GOLDHAY
PETERBOROUGH

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TELEPHONE: 0733 371811

FAX: 0733 231840

CONTRACTOR: HYDRAULICS RESEARCH LTD

ADDRESS: WALLINGFORD
OXFORDSHIRE

POSTCODE: OX10 8BA

TELEPHONE: 0491 35381

FAX: 0491 32233

CONTRACT SIGNATORY: DR. W.R. WHITE

PROJECT MANAGER: MR D. RAMSBOTTOM

CONTRACT DETAILS

START DATE: 01/91 **REFERENCE:** INITIAL CONTRACT

END DATE: 10/91 **REFERENCE:** INITIAL CONTRACT

CONTRACT TYPE: COMPETITIVE TENDER

OBJECTIVES:

OVERALL PROJECT OBJECTIVE

To carry out a detailed appraisal on the techniques available for the continual and accurate measurement and auto-recording of low velocity river flows which will determine the most appropriate and reliable technique for permanent site installations within NRA Regions.

SPECIFIC OBJECTIVES

1. To identify the total river catchment area in each Region of the NRA which is currently ungauged or unsatisfactorily gauged owing to the constraint of low velocity of flow.

2. To give some early guidance as to the likely best option in order that a prototype experimental/pilot station can be set up and maintained during/immediately following the Project period.

3. To describe the techniques used in current practice, the extent of current use and identify their operational performance in field conditions, and where possible, identify their shortcomings in situations where flow rate is subject to abrupt changes due to operation of river control structures and/or tidal effects.

4. To determine limitations of each technique in terms of site environment, river channel dimensions and conditions, reliability and accuracy of instrumentation in the expected normal channel flow situation.

5. To assess capital and maintenance costs for purchase and installation of the equipment in each case including building/civil engineering accomodation works.

BACKGROUND:

River flow gauging is a prerequesite function of the NRA with regard to efficient and effective management of the water environment generally.

A significant percentage of river catchment areas are ungauged owing to conventional gauging techniques being inappropriate or impractical in many loactions. These locations largely feature low velocities of flow in wide lowland sections of rivers with low channel gradients. Esturial tidal influences and/or the operation of river control structures, including navigation locks, may also be an additional problem in this respect.

It is important for the NRA to identify the existence of an acceptable solution from modern technology which will enable lowland river reaches and upland canalised rivers to be reliably gauged. Appropriate technology does exist in principle and to some extent has been put into practice, though its performance and reliability are not widely appreciated.

CONTEXT

This is essentially a "stand-alone" project within the Topic programme. Associated project B01.1 proposes to review current hydrometric field techniques in general. The latter project will widely acknowledge the current limited and perhaps experimental appreciation of the latest developments in open channel flow measurement.

STRATEGY:

METHOD

A "state-of-the-art" survey by the external contractor is to be undertaken, supervised by the Project Leader, with support from NRA Regions in the provision of available information and data.

The following information outlines the work programme, with the full details shown in the Plan of Approach, Schedule 5 of the Research Contract.

1. Agree visits to and data information requirements of the NRA Regional Offices, with the Project Leader.

2. Visit each NRA Region in respect of item "1".

3. Establish contacts with appropriate external organisations.

4. Undertake preliminary review of flow measurement techniques

5. Make PROVISIONAL recommendations as to the likely "best-option" in the event that a pilot station is developed for monitoring during/immediately following the project contract period by NRA staff.

6. Produce framework for Project Report and draft contents.

7. Complete draft Report.

8. Complete Project Report following review by NRA, and other NRA publications as detailed in Schedule 1 of the Research Contract.

TARGETS & TIMESCALES:

WORK ITEM	COMPLETION DATE	PROJECT DURATION (months)
Prepare, agree and send request for information	31.1.91	1
Agree schedule of visits to NRA Regional Offices	15.2.91	1.5
Preliminary review of flow measurement techniques	15.3.91	2.5
Visit NRA Regional Offices	17.5.91	4.5
Final review of flow measurement techniques	24.5.91	4.75
Interim report, including recommendations as to most likely "best-option"	31.5.91	5
Framework and draft contents of Project Report	30.6.91	6

Complete Draft Report	31.7.91	8
Review by NRA	30.9.91	9
Complete Final Project Report and other NRA Reporting Document (NRA Report)	31.10.91	10

OUTPUTS:

ITEM	DUE DATE	COPIES
Interim report	31.5.91	15
Draft Project Report	31.7.91	15
Final Project Report	31.10.91	15
NRA Report - Series Document	31.10.91	50

Reports should be produced in accordance with the Reporting Guidelines Paper R&D(90)20 (enclosed).

BUDGET £'000:

YEAR	EXTERNAL	INTERNAL	OTHER	TOTAL
PRE 1987	0.0	0.0	0.0	0
1987/88	0.0	0.0	0.0	0
1988/89	0.0	0.0	0.0	0
1989/90	0.0	0.0	0.0	0
1990/91	10.0	0.0	0.0	10
1991/92	16.5	0.0	0.0	16.50
1992/93	0.0	0.0	0.0	0
1993/94	0.0	0.0	0.0	0
1994/95	0.0	0.0	0.0	0
TOTAL	26.50	0	0	26.50

COSTS £'000

ITEM	FINANCIAL YEAR 1990/91	FINANCIAL YEAR 1991/92	TOTAL
Staff	9.0	13.6	22.6
Travel and subsistence	1.0	0.9	1.9
Capital	0.0	0.0	0.0
Reports	0.0	2.0	2.0
TOTAL	10.0	16.5	26.5

BENEFITS:

The NRA has clearly defined responsibilities under the 1963 Water Resources Act and the Water Act 1989, to assess the resources of water available to meet competing demands and to allocate, distribute, augment and to promote the proper use of these resources. Flow gauging of river flows is a primary hydrometric function pre-requesite to meeting these obligations. Without a comprehensive flow monitoring system, much of the environmental management functions of the NRA becomes impossible.

This Project seeks to extend the coverage of the hydrometric network where the density of flow measurement is either inadequate or non-existent due to the nature of the flow regime, namely "low velocity of flow". The project is to serve as a guide to the selection of a reliable technique (assuming such an option exists) for the future prototype development of river gauging sites at locations where low velocity flow is currently a prohibiting factor.

The benefit to the NRA from this Project overall is considerable, as flow measurement is a critical factor to all water environmental management functions: water resources; pollution control; water quality management; flood alleviation and control and conservation management. It is an essential facet of the NRA function and one which must be fully addressed.

The proposed Report is seen to be a precursor to a phased expansion of the NRA's national gauging network and it is only upon its completion stage that meaningful assessment of benefit can be made taking local circumstances into account.

It is envisaged that immediately following the completion of this Report, a pilot station will be developed in line with the Report's recommendations at a suitable site in order to monitor performance prior to committment of the identified solution. Thus, this study will ensure the most appropriate option is identified and ensure that the investment in such a station(s) is justified.

ASSUMPTIONS/RISKS:

Two major uncertainties in these proposals or their associated costs are evident. Maximum benefit arising from this investigation is dependent upon the depth of experience and knowledge of the Research Contractor. Secondly, a good response is required in respect of current practices and experience to date of any gauging techniques under review by the Contractor.

Associated development proposals for a pilot station following a technique recommended in the Report wll be sited at a location where such a station would have an identifiable long-term benefit to NRA resource management. The siting will have to be determined later into the Project.

There is a risk, however, that a Project will identify no reliable technique currently existing to provide a continuum flow gauging and recording in lowland river conditions such as those identified earlier in "Objectives". On that basis, the Project will likely identify the need for development Research. Such a project out-turn would be regarded as progressive.

OVERALL APPRAISAL:

The Research Project intends to resolve a major shortfall in the ability of the NRA to provide satisfactorily fully comprehensive Regional flow gauging networks. The main area of concern is a less than desirable network to regulate and monitor lowland river sections in respect of residual flows in lower reaches and estuaries. Control of abstractions, water quality regulation and ecological considerations generally are all compromised by the lack of flow gauging provisions in these areas.

It is very difficult indeed to provide a financial appraisal for much far reaching benefits as explained in the DoE National Study on Flow Gauging. This is due to the fact that the true benefits are difficult to identify in financial terms and often difficult to identify in factual terms in the longer term. However, gauging network developments in a National basis are assessed to give cost-benefit ratios greater than 1.2 according to the latter study.

A success-based outcome of this Project will provide a major step forward in the hydrometric function of the NRA, provided that Regional staff provide a good response and co-operate fully with the research contractor.

APPENDIX 2

Questionnaire

NRA RESEARCH AND DEVELOPMENT PROJECT B01.2.90
REVIEW OF LOW VELOCITY MEASUREMENT TECHNIQUES

Data requirements from NRA Regional Offices

1. Details of the existing hydrometric network including :

   (a) Layout map of the current network
   (b) List of gauging stations including details for each station of the method of flow gauging, the range of flows and annual run-off statistics

2. Layout maps of the Region showing areas where the low velocity problem exists. These areas should be sub-divided as follows :

   (a) Areas which are not gauged because of the low velocity problem
   (b) Areas which are unsatisfactorily gauged because of the low velocity problem
   (c) Areas where gauging is not required
   (d) Specific sites in need of monitoring should be shown

3. General comments on the need for a new technique of flow gauging at locations where the low velocity problem exists including, for example, the number of locations in the Region where the planned new technique would be applied if suitable.

4. Details of existing gauging sites where the low velocity problem occurs including, for each site :

   (a) Date of installation/commissioning
   (b) Flow measurement technique
   (c) Range of flows measured
   (d) Instrumentation for measurement, collection and processing
   (e) Approximate channel dimensions and details of any nearby structures which may affect flow gauging
   (f) Comments on the performance and shortcomings of the flow measurement technique
   (g) Is the flow rate subject to changes due to the operation of river control structures and/or tidal effects? If so, what effect does this have on flow measurement
   (h) Comment on the accuracy of flow gauging. What accuracy is acceptable?

5. Details of past and/or ongoing NRA research efforts to solve flow measurement problems in low velocity situations. You may wish to consult your NRA Regional R & D Coordinator.

6. Costs of gauging station installations constructed in the last five years, particularly those where low velocities exist. Details to include :

   (a) Capital costs - civil engineering and buildings
       - equipment
   (b) Approximate dimensions of installation and range of flow monitored
   (c) Annual staff costs or man months per year for operation and maintenance of the streamflow network
   (d) Other operation and maintenance costs

APPENDIX 3

Schedule of visits to NRA Regional Offices

APPENDIX 3

Schedule of visits to NRA Regional Offices

Region	Date (1991)	Venue	Those present	HR
Welsh	16 April	Cardiff	Terry Spierling John Arrowsmith David Thomas	Reg Herschy David Ramsbottom
North West	18 April	Warrington	Ron Shaw Ray Rushton	Reg Herschy David Ramsbottom
Northumbria	19 April	Newcastle-on-Tyne	David Archer David Stewart	Reg Herschy David Ramsbottom
South West	22 April	Exeter	Sheila Turner Ann Dixon	Rodney White David Ramsbottom
Wessex	23 April	Bridgwater	Andy Gardiner Bill Hampton	Rodney White David Ramsbottom
Anglian	29 April	Peterborough	Peter Grange John East Geoff Brighty Neil Osborne	Rodney White David Ramsbottom
Yorkshire	30 April	Leeds	Peter Towlson David Shields	Rodney White David Ramsbottom
Southern	1 May	Winchester Worthing Pevensey	Peter Midgley Simon Taylor Richard Wilton John Headey	Reg Herschy David Ramsbottom
Severn Trent	3 May	Solihull	Jim Waters Richard Iredale	Reg Herschy David Ramsbottom
Thames	16 May	Reading	Tim Webb	Reg Herschy David Ramsbottom

APPENDIX 4

Summary of information provided by the NRA Regions

APPENDIX 4

Summary of information provided by the NRA Regions

Table A 4.1	Sites where low velocity flow gauging is required
Table A 4.2	Ultrasonic gauging sites in the NRA Regions
Table A 4.3	Electromagnetic gauging sites in the NRA Regions
Table A 4.4	Costs of ultrasonic and electromagnetic gauging sites in the NRA Regions

Other data obtained included

Details of experience using ultrasonic gauges, electromagnetic gauges and electromagnetic current meters

Details of experience of using RAFT, and dilution gauging

Information on costs and staff numbers involved in operating and maintaining the hydrometric network

Lists of gauging stations in all NRA Regions

In some cases maps were provided indicating the extent of the low velocity problem, and the catchment areas affected.

Table A 4.1 Sites where low velocity flow gauging is required

NRA Region	River	Site	Channel width (m)	Channel depth (m)	Flow range (m^{3}s)	Remarks
South West	Exe	Trews Weir	40	5	1-700	Former Harwell ultrasonic site
	Dart	Totnes Weir	25		0.3-600	
	Clyst	-	15		0-100	Exact location not fixed
Wessex	Parrett	Westover	32	2-4	0-150	Former Harwell ultrasonic site
	Brue	Bason Bridge	15	3	0.3-50	Former electromagnetic site at Westhay
	Tone	Bishops Hull	20		0.3-120	
	Tone	Knapp Bridge	20	2	0-120	
	Axe	Lower Weare	5		0-10	
	Frome	Leonards Mill	20			Cableway Calibration gauging required
Southern	Bremere Rife	Hunston				Ten sites
	Pagham Rife	Runcton Merston Merston Oving				Typical width 2-3m Typical depth
	Aldingbourne Rife	Aldingbourne Westergate				1m

Table A 4.1 (Cont) Sites where low velocity flow gauging is required

NRA Region	River	Site	Channel width (m)	Channel depth (m)	Flow range (m³s)	Remarks
		Barnham Binsted Meadow Lodge				
	Various	Stour marshes	up to 3m	<1m		Licence regulation Flow measurement difficult due to low velocities and weed
	Various	Pevensey, Romsey and Walland Marshes. Shirley Moor	up to 3m	<1m		As above
Anglian	Gripping	Ipswich	45(bed)		0.05-50	
	Waveney	Ellingham Mill	15(bed)		0.4->100	
	Yare	Norwich-Whitlingham	20-30(bed)		1->100	
	Various	Suffolk Coastal Rivers	5-10(bed)			Requirement for low flow measurement (0-3m³/s)
	Various	Broads rivers eg Thurne	15(bed)			As above (0-2m³/s)
	Ely Ouse	Denver	40		0-200	
	Ely Ouse	Brownshill Staunch	35		0-300	
	Lower Witham	u/s Grand Sluice	20(bed)	5	0-150	
	Lower Welland	Spalding	20(bed)	6	0-150	

Table A 4.1 (Cont) Sites where low velocity flow gauging is required

NRA Region	River	Site	Channel width (m)	Channel depth (m)	Flow range (m^3s)	Remarks
	Ancholme	u/s S Ferriby Sluice	10 (bed)	5	0-100	
	Fosdyke Canal	Lincoln	15 (bed)	3	0-25	
	Upper Witham	Lincoln	15 (bed)	3	0.5-55	
	Lower Nene	u/s Dog-in-a-Doublet	30 (bed)	5	0-250	
	Middle Nene	Lower Ringstead Lock	10 (bed)	4	1-150	
	Nene	Orton	30		0-300	Existing gauging site
	Chelmer	Between Hoe Mill and water supply intake	15 (bed)		0-75	
	Blackwater	Between Wickham Bishops and water supply intake	15 (bed)		0-50	
	Stour	Flatford area	15-20(bed)		0-c100	
	Stour	Stratford St. Mary	15-20(bed)		0-c100	
	Lime Brook Mundon Wash Latchingdon Brook Mayland Brook Asheldam Brook Bradwell Brook		1-2 (typical)		0-10 (typical)	Small watercourses which require gauging as near to the tidal limit as possible

Table A 4.1 (Cont) Sites where low velocity flow gauging is required

NRA Region	River	Site	Channel width (m)	Channel depth (m)	Flow range (m^3s)	Remarks
	Mardyke	Stifford Bridge	10(bed)		0-40	
	Mardyke East arm	Bulphan	2 (bed)		0-15	
	Mardyke West arm	Blankets	2 (bed)		0-15	
Welsh	Dee	Chester	50			There is a former on ultrasonic site on the Lower Dee
	Clwyd	Rhuddlan	30		0.5-150	
	Several Canals		3-6			
Yorkshire	Hull	Hempholme	20		0.2-30	Former Harwell ultrasonic site. Severe weed problem
	Ouse	Skelton	40-50	5.5-10	4-600	Ultrasonic gauge planned
	Bedale Beck	Leeming	8		0.3-120	
	Wiske	Kirby Wiske	5		0.1-100	

Notes

1 The above information is based on data provided by the NRA Regions.
2 Channel dimensions are approximate to give an indication of channel size.
3 The flow ranges to be measured are approximate. the upper end of the range includes flood flows, and in many cases flood pain flow would occur possibly bypassing the gauging station. Measurement of flood flows does not form part of this project.

Table A 4.2 Ultrasonic gauging sites in the NRA Regions

NRA Region	River	Site	Channel width (m)	Channel depth (m)	Flow range (m^3s)	Remarks LV indicates low velocity site
Wessex	Avon (Bristol)	Bathford	29	4	0.5-300	LV
	Avon	Knapp Mill	25		2-100	Former ultrasonic sites at Westover (Parrett), Taunton (Tone) and Westhay (Brue)
Southern	Itchen	Riverside Park	15		0-25	LV Reflector
	Rother	Blackwall Bridge	35	2.5	0.3-	LV Former Harwell ultrasonic site
	Medway	Allington	35	2.5	1-250	LV Reflector
Thames	Thames	Kingston	70		0-500	LV
	Thames	Walton	58			
	Thames	Staines	58			
	Thames	Royal Windsor Park	50		10-400	
	Thames	Sutton Courtenay	35		1-350	LV
	Mole	Esher	20		0.75-45	
	Wey	Weybridge	15		1-75	
	Kennett	Newbury	8			

Table A 4.2 (cont) Ultrasonic gauging sites in the NRA Regions

NRA Region	River	Site	Channel width (m)	Channel depth (m)	Flow range (m^3s)	Remarks LV indicates low velocity site
	Thame	Wheatley	19		1-50	
	Ray	Water Eaton	5		0.25-25	Gauge in wingwalls of weir
	Cranleigh Waters	Cranleigh Waters	10		0.01-25	LV
	Stort	Glen Faba	c5			LV
	New River		c5			
Severn-Trent	Severn	Saxon's Lake	50	2	0-500	LV
	Severn	Bewdley	40		6-600	
	Severn	Buildwas	40	6		
	Avon	Bredon	15	1.5	1-150	LV
	Trent	Darlaston	10		1-140	
	Derwent	Derby	20		2-300	
	Erewash	Sandiacre			0-20	
	Leen	Triumph Road				
	Soar	Kegworth	25			
	Soar	Pilling's Lock	15	1.5	0.3-120	LV

Table A 4.2 (cont) Ultrasonic gauging sites in the NRA Regions

NRA Region	River	Site	Channel width (m)	Channel depth (m)	Flow range (m^3s)	Remarks LV indicates low velocity site
	Tame	Bescot	c5			Formerly an electromagnetic station
	Stour	Kidderminster	15		0.5-80	
North West	Mersey	Westy	28	2-3	0-80	LV
	Weaver	Pickerings Cut	30	6	0-150	LV
Yorkshire	Wharfe	Tadcaster	35	3-6	0.6-450	LV
	Calder	Caldene Bridge	10-20	0.5-4.5	0.3-130	
	Calder	Methley	50	3-5.6	2.7-380	LV

Notes

1 The above information is based on data provided by the NRA Regions

2 Channel dimensions and flow ranges are approximate, and are intended to give an indication of Channel size and flow range

Table A 4.3 Electromagnetic gauging sites in the NRA Regions

NRA Region	River	Site	Channel width (m)	Channel depth (m)	Flow range (m^3s)	Remarks LV indicates low velocity site
Southern	Test	Broadlands/ Longbridge	20		2-40	Unlined bed
	Test	Testwood	12	2	2-40	
	Little Test	Conagar Bridge	6	1.25	2-10	Overhead coil
	Test	Chilbolton	10	1.5		
	Itchen	Easton	8	1		
	Stour	Vauxhall Bridge	20		0.5-50	Further stations planned in Hampshire District
Thames	Coln	Fairford	15			
	Colne Brook	Hythe End	15			
	Mole	Leatherhead	18		0.5-30	
	Swill Brook	Oaksey	c4		0-5	
	Pinn	Uxbridge	c5		0-15	LV
Severn Trent	Wreake	Syston	12	2	0.1-100	LV
	Soar	Littlethorpe	6		0.1-20	
	Sence	South Wigston	10		0.1-25	

Table A 4.3 (Cont) Electromagnetic gauging sites in the NRA Regions

NRA Region	River	Site	Channel width (m)	Channel depth (m)	Flow range (m^3s)	Remarks LV indicates low velocity site
	Tame	Park Hill				
	Tame	James Bridge	5-10			
	Strine	Crudgington	c5			
	Ryton	Blyth	10		0.1-30	
	Idle	Mattersey	16-18			
	Blythe	Whita cre	12			PLC gauge
	Outfall	Spondon			1-1.5	Overhead coil. Outfall to sewage works
Yorkshire	Cod Beck	Dalton	15	0.1-4.1	0.1-48	LV
	Derwent	Low Marishes	10		-	LV
	Foss	Huntington	10	0.6-2.8	0.04-30	LV
	West Beck	Snakeholm Lock	8		0.2-20	LV
	Driffield Canal	Snakeholm Lock	15		-	LV

Notes

1 The above information is based on data provided by the NRA Regions.

2 Channel dimensions and flow ranges are approximate, and are intended to give an indication of channel size and flow range.

Table A 4.4 Costs of Ultrasonic and Electromagnetic gauging stations in NRA Regions

Year (approx)	Channel width (m)	Channel depth (m)	Capital Costs (£1000's) Civils	Equipment	Total	Remarks
Ultrasonic gauges						
1984	40	6			110	
1985	28	3		42		
1986	50	3-5.6	230	65	295	
1988	29	4		42	48	Replacement of Harwell installation
1988	8		40	29	69	
1988	15	1.5		39		
1989	19		86	36	122	
1989	10-20	0.5-4.5	100	80	180	
1990	58		93	27	120	
1990	30	6	96	26	122	
1990	35	3-6	490	55	545	
1991	58		108	27	135	
1991	c10			22	24	Existing concrete rectangular channel
1991	c10			22	24	
Under construction	30	2-6	50	30	80	
Planned	20	2	c50	36	c86	
Planned	40-50	5.5-10	700	50	750	
Electromagnetic gauges						
1982	20				65	
1987	10	0.6-2.8	151	38	189	10m square coil
Not known	15	0.1-4.1	140	39	179	15m square coil
1988	10	1.5			250	
1990	15		59	36	95	
1990	15		64	36	100	
1991	12	2	204	c30	234	Reconstruction of existing station. Civil costs do not include diversion channel
Planned	6-8	0.3-1.25			c250	
Comparative costs of other gauges						
1985	c40		595	3	598	Crump weir 35m crest width
1987	16		49	10	59	Velocity area site with flat-V weir

1987	c5		24	2	26	Flat-V weir. Crest width 3.5m
	7.8		50	5	55	Crump weir
1989	11		21	10	31	Velocity area site with flat-V weir
1990	c15		124	6	130	Flat-V weir 10m crest width. 2.25m height

Notes

1 The above costs are based on information provided by the NRA Regions.
2 The costs are provided for guidance but are not directly comparable. They vary according to site conditions, scope of civil works and miscellaneous items including land purchase and provision of power supplies.

APPENDIX 5

Equipment manufacturers and external organisations contacted

APPENDIX 5

1. Equipment manufacturers contacted

Aqua Data Systems
Burmarc Ltd (Agent for Marsh-McBirney Inc)
Detechtronic Ltd
Ferranti International
Leica UK Ltd (Agents for Ott Instrumentation)
Martek Ltd (Agent for Stedtnitz Maritime Technology Ltd)
Sarasota Automation
Scan Group
SEBA Hydrometric GmbH
Valeport Marine Scientific Ltd
Warren Jones

A copy of the letter sent to the above manufacturers is enclosed.

Dear Sir

NRA RESEARCH AND DEVELOPMENT PROJECT B01.2.90
REVIEW OF LOW VELOCITY MEASUREMENT TECHNIQUES

We are currently undertaking a review of low velocity measurement techniques in order to provide recommendations to the NRA for the most appropriate methods. We are concerned with velocities which are too low to measure accurately with a propeller-type current meter in rivers and other open channels where insufficient head is available for the use of flow measurement structures.

We are currently considering a number of different methods including ultrasonic gauges, electromagnetic gauges, ultrasonic current meters, electromagnetic current meters, doppler flow meters and mechanical devices. In order to ensure that our information is up-to-date, we would be grateful if you would send us your latest literature on methods of measuring flows where low velocities exist together with costs, and details of any planned developments which may be relevant.

If you have any queries please do not hesitate to contact me and I look forward to hearing from you shortly.

Yours faithfully

D M RAMSBOTTOM
River Engineering Department

2. External organisations contacted

Association of Consulting Engineers
British Waterways Board
The Department of the Environment
The Institute of Hydrology - Surface Water Archive
- Catchment Section
The Ministry of Agriculture Fisheries and Food

A copy of the letter sent to the above organisations is enclosed.

Dear

NRA RESEARCH AND DEVELOPMENT PROJECT B01.2.90
REVIEW OF LOW VELOCITY MEASUREMENT TECHNIQUES

We are undertaking a review of low velocity measurement techniques on behalf of the National Rivers Authority (NRA) in order to provide recommendations for the most appropriate methods. A brief background to the project is enclosed.

We are concerned with velocities which are too low to be measured by current meter in rivers and other open channels, at locations where insufficient head is available for the use of flow measurement structures.

The purpose of this letter is to inform you that the project is being carried out, and to ask if you have any experience of the measurement of low velocities of flow in open channels. The methods we are currently considering include electromagnetic gauges and current meters, ultrasonic gauges and current meters, doppler flow meters, and mechanical devices.

If you require further information or have any queries please do not hesitate to contact me.

Yours

D M RAMSBOTTOM
River Engineering Department

APPENDIX 6

Data obtained from equipment manufacturers

APPENDIX 6

Data obtained from equipment manufacturers.

Nine of the eleven equipment manufacturers contacted replied to the request for information given in Appendix 5, and the present position regarding manufacture of low velocity flow measurement equipment is understood to be as follows.

1 Ultrasonic gauge

At least three manufacturers are known to manufacture an ultrasonic gauge which includes velocity and depth measurement. The method was established in the 1970s and it is understood that installations exist in at least nine continental European countries, Canada, the United States and elsewhere.

2 Portable Ultrasonic gauge

Two manufacturers are known to produce portable ultrasonic gauges providing single or cross path velocity measurement at one depth. This is a relatively recent development and installations have been installed in the UK, notably at fish farms.

3 Electromagnetic gauge

Electromagnetic gauges have been installed since the late 1970s, but only one manufacturer is known to the consultant who produces this equipment.

4 Electromagnetic current meter

Electromagnetic current meters have been in production since the mid 1980s and they are produced by at least three manufacturers. They may be used with either wading rods or suspension cables, although not all the manufacturers provide both options. The "net" concept is being developed by one manufacturer, in which several electromagnetic current meters are supported by rods and floats across a section to provide a continuous gauging installation.

5 Slope-area method

The slope-area method has been disregarded for low velocity measurement in this review because of the inaccuracies associated with measuring small differences in water levels. At least one manufacturer is developing much more accurate methods of measuring water levels and water level differences, which may make the slope area method a practical possibility.

APPENDIX 7

Summary of existing methods of river gauging

CONTENTS

NATIONAL RIVERS AUTHORITY
REVIEW OF LOW VELOCITY MEASUREMENT TECHNIQUES

SUMMARY OF EXISTING METHODS OF RIVER GAUGING

1. BACKGROUND

1.1 Introduction

Streamflow is the combined result of all the climatological and geographical factors that operate in a drainage basin. It is the only phase of the hydrological cycle in which the water is confined in well-defined channels which permit accurate measurements of the quantities involved on a continuous basis.

1.2 Objectives of a streamflow programme

There are many different uses of streamflow data within the broad context of water management, such as water supply, pollution control, irrigation, flood control, energy generation and industrial water use. The importance placed on any one of these purposes may vary and the emphasis for any one need may also change over short or longer periods of time. What appears to be axiomatic, however, is that none of these needs can be met without reliable streamflow data being available at the right time, the right place and of the right quality.

1.3 Categories of streamflow data

The type of streamflow information required may be classified into two categories. The first is that required for planning and design while the second is that required for current use - that is, operational management.

Data for planning and design may not necessarily have an immediate use but are valuable in the long term for civil engineering works such as river crossings of various types and for flood forecasting and control. Planning and design data are also used to examine long-term trends, as are data on the stream environment.

Current use data have an immediate high return value since the data are invariably required initially for operation and control. Current use streamflow stations are operated for as long as the need remains.

Designers of water control and water-related facilities increasingly use the statistical characteristics of streamflow rather than flow over specific historic periods. The probability that the historical sequence of flow history at a given site will occur again is remote. Indeed, when a hydrologist makes just one measurement of discharge it is probable that the exact conditions under which the discharge occurred may rarely happen again.

It is often desirable to consider the future, not in terms of specific events but in terms of probability of occurrence over a span of years. For example, many highway bridges are designed on the basis of the flood that will be exceeded on the average only once in 50 years. Storage reservoirs are designed on the basis of the probability of failure of a particular capacity to sustain a given draft rate. The water available for irrigation, dilution of waste or other purposes may be stated in terms of the mean flow, or probability of flow magnitudes, for periods of a year, season, month, week or day. In addition there is a trend towards flow simulation based on statistical characteristics such as the mean, standard deviation and skew. To define statistical characteristics adequately, a record of at least 30 years is desirable for reliable results.

1.4 Cost effectiveness

The cost effectiveness of river gauging is an important management consideration but the wide variety of uses of streamflow data makes the quantifying of natural benefits difficult. However, in a study carried out for the Department of the Environment in 1989 (See Bibliography), the annual benefits were found to be in the range of £11 million to £60 million, the best estimate being £21 million and the annual cost of operating the streamflow network was £9 million. The benefit-cost ratio was therefore in the range 1:2 to 7 with a best estimate of 2.3. It was concluded, therefore that even at the lowest level of benefit-cost ratio the UK river gauging network represents a good investment.

1.5 Summary of methods

The methods of measurement of discharge in open channels may be summarised as follows.

<u>Velocity-Area Method (see Fig A7.1)</u>

The discharge is derived from the sum of the products of stream velocity, depth and distance between observation points; the stream velocity being normally obtained by a current meter. For a continuous record of discharge in a stable prismatic open channel with no variable backwater effects, a unique relationship is established between water level (stage) and discharge. Once established this stage-discharge relation is used to derive discharge values from recordings of stages. Because rotating element current meters are non-operational below a minimum speed of response (usually 0.03m/s), the velocity-area method is unsuitable for rivers having low velocities for a large proportion of the time. In rivers having acceptable measurable velocities (of the order of 0.15m/s) for a large proportion of the time, and where a stage-discharge relation is effective, that portion of the relation for low velocities can normally only be estimated with a large uncertainty.

Weirs and Flumes (see Figs A7.2 & A7.3)

The relation between stage (or head) and discharge over a weir or through a flume is established from laboratory or field calibration. The discharge is subsequently derived from this rating equation. Weirs and flumes operate particularly effectively under low velocity conditions.

Ultrasonic Method (see Fig A7.4)

The velocity of flow is measured by transmitting an ultrasonic pulse diagonally across the channel in both directions simultaneously. The difference in time transits is a measure of the velocity; this has to be multiplied by the area of flow to derive discharge.

The ultrasonic method was developed particularly for low velocity conditions and has proved effective for all velocity conditions including negative flow.

Electromagnetic Method (see Fig A7.5)

The discharge is found by measuring the electromotive force (emf) produced by a moving conductor (the flowing water) through a magnetic field produced by a coil placed either below or above the open channel. The emf is proportional to the average velocity; the stage measurement and length of conductor are related to area of flow.

The electromagnetic method is particularly effective under low velocity conditions in rivers containing weeds or silty beds as well as rivers under backwater conditions.

Dilution Method (see Fig A7.6)

A tracer liquid is injected into the channel and the water is sampled at a point further downstream where turbulence has mixed the tracer uniformly throughout the cross-section. The change in concentration between the solution injected and the water at the sampling station is a measure of the discharge. Dilution methods are normally unsuitable under low velocity conditions because of tracer mixing difficulties.

Slope-Area Method

The discharge is derived from measurements of the slope of the water surface and the area of flow over a fairly straight reach, assuming a roughness coefficient for the channel boundaries. The slope-area method is normally used to measure floods or high discharges and only used under backwater conditions, when the velocities are low, when other methods are unavailable.

Stage-Fall-Discharge Method

In a stable open channel affected by backwater, a relation is established between stage, fall (slope) and discharge, the latter being determined by current meter. Because the stage-fall-discharge method requires a measurement of velocity by current meter, the same restrictions apply for low velocity measurement as in the velocity-area method.

Moving Boat Method (see Fig A7.7)

A current meter is suspended from a boat which traverses the channel normal to the streamflow. The component of the velocity in the direction of the stream is computed from the resultant velocity and the angle of this resultant. The discharge is the sum of the products of the stream velocity, depth and distance between observation points. The moving boat method is, therefore, in effect, a velocity-area method.

The moving boat method is unsuitable for low velocity measurements since a rotating element current meter is employed to measure the stream velocity component. In addition since the speed of the boat is related to the current velocity, the duration of measurement would normally be unacceptably long in large rivers.

Float Gauging

The water velocity is measured by recording the time taken for a float to travel a known distance along the channel. Observations are made using floats at different positions across the channel and discharge is derived from the sum of the products of velocity and area of flow. Generally, this method is used only when the velocity is either too fast or too slow to use a current meter. Because of their inherent inaccuracy, floats are only used in the UK (if at all) to measure velocity during a preliminary investigation or as a spot measurement.

The above methods are described in some detail by Ackers, White, Perkins & Harrion (1978) and by Herschy (1985) and design recommendations given in a number of British Standards (see Bibliography) and only a brief introduction will be given here.

1.6 The present UK network

The table below provides breakdown of the approximate number of each type of gauging station in England and Wales. Because of the somewhat irregular hydrometric conditions experienced in the UK the network consists of about half velocity-area stations and half measuring structures. The table does not include stage-only stations and many minor stations for specific purposes.

Types of gauging stations in England and Wales

Station Type	Number
Velocity-area (calibrated sectn.)	293
Flume	91
Flume/Crump weir	2
Flume/Velocity-area	4
Broad-crested weir	27
Compound Broad-crested weir	33
Compound Broad-crested weir/Velocity-area	6
Broad-crested weir/Velocity-area	9
Broad-crested weir/Crump weir	1
Crump weir	174
Crump weir/Velocity area	19
Compound Crump weir	100
Compound Crump weir/Velocity-area	1
Flat V weir	124
Flat V weir/Velocity-area	44
Essex weir	23
Thin-plate weir	68
Thin-plate weir/velocity-area	3
V-notch	15
Ultrasonic	35
Electromagnetic	26
Unclassified	125
TOTAL	1223

It is difficult to state with any precision the costs of the different gauging methods because they vary with inter alia the width of river, site conditions etc. Typical present-day costs for gauging stations are shown.

Typical present-day costs of gauging stations

Velocity area	£25 000	-	100 000
Crump or Flat V weirs	£50 000	-	500 000
Ultrasonic gauges	£50 000	-	750 000
Electromagnetic gauges	£50 000	-	350 000

1.7 Measurement of water level (stage)

All the methods used to measure discharge in open channels depend to a greater or lesser extent on the measurement of stage. In fact, it could be argued that stage is the most important single measurement in hydrometry. Certainly this is the case in measurements where a small relative uncertainty in stage may produce a significant relative uncertainty in discharge.

In the UK hydrometric network the objective is to measure stage to ±3mm and in most cases this can generally be achieved by the use of stilling wells and float operated solid state recorders with optical shaft encoders. The use of vertical or inclined staff gauges, reading to ±10mm, to check such instruments is normally unsatisfactory and although staff gauges are always installed at stations it is now normal practice to use some more accurate means to read outside river levels. This may be performed using some additional device such as a portable vernier on the staff gauge or some quite separate device such as a datum plate and point or tape gauge. In weirs and flumes it is now customary to install a datum plate on the abutment wall and take the measurement to water surface level by means of a portable tape gauge reading to millimetres or better. Checking the stage measurement within the stilling well creates no problem and can be performed from datum plates on the bench. Generally, where the bank is sloping, inclined gauges are to be preferred to vertical staff gauges where they are best installed in such a manner as to closely follow the contour of the river bank. The profile of the bank may be such that a gauge of a single slope may be used, but usually it is necessary to construct the gauge in several sections, each with a different slope. The uncertainty in the stage-discharge relation depends largely on the uncertainty with which stage can be measured. In measuring structures the uncertainty in the measurement of head can have significant effect on the discharge. It can also be stated that in methods of streamflow measurement where a correlation is established between stage, fall or slope and discharge, the uncertainty in the determination of stage has a significant effect on the overall uncertainty in discharge.

2. EXISTING METHODS OF RIVER GAUGING

2.1 The velocity-area technique

The velocity-area method of measurement, as the term suggests, consists of the determination of stream velocity and area of flow, the discharge being derived from the product of these measurements, so that (see Fig A7.8):

$$Q = VA \ m^3/s$$

This general equation applies to all variations of the velocity-area technique although the actual methods of obtaining the velocity and area may differ.

These measurements may be carried out by wading (when the depth and velocity permit); by cableway (when the span permits and the river is too deep to wade); by boat (if the river is too wide for a cableway installation); by moving-boat method (if the river is of sufficient width and depth); by floats (if these satisfy the necessary requirements) by ultrasonic or electromagnetic gauges (if these satisfy the necessary requirements); ultrasonic or electromagnetic gauges (if the limiting conditions of width and depth are observed); or by slope-area or stage-fall discharge (if these are the only methods available for measuring floods or flow under backwater conditions). The discharge so obtained is normally used to establish a relation between stage and discharge. Once derived this stage-discharge relation is employed to determine discharge values from continuous records of stage.

Not all current meter measurements, however, are made to establish a stage-discharge relation and for many purposes individual determinations or 'spot measurements' are very often required for management functions. Such measurements may not require the measurement of stage but otherwise the method of measurement is the same. At some stations, however, a record of stage only may be required for purposes such as flood warning. At most network gauging stations, however, both stage and discharge are measured to establish a relation between these two variables.

Measurement of velocity

The mean velocity at each point in each vertical is determined by current meter. Conventional propeller and cup-type current meters provide acceptable accuracy at velocities of 0.15 m/s and above but at low velocities, say 0.10 m/s and below, the uncertainty increases, on average to about 20 percent at 0.03 m/s (see table). Below 0.03 m/s the propeller and cup-type meters are generally unreliable. However, limited experience with the new electromagnetic solid state current meter with a direct read-out and with a range of velocities from zero to 4 m/s shows encouraging results (see Fig A7.9). The meter has been tested and calibrated by both HR Wallingford and the United States Geological Survey and at a velocity of 0.03 m/s the uncertainty was found to be less than one percent. The absolute mean error in the USGS calibration was found to be 0.76 percent with a maximum error of 1.8 percent and a minimum error of 0.13 percent.

Current Meter rating $(X'_c)^a$
(Propeller and cup-type)

Velocity (m/s)	Uncertainties (%)	
	Individual rating	Group or standard rating
0.03	20	20
0.10	5	10
0.15	2.5	5
0.25	2	4
0.50	1	3
Over 0.05	1	2

The above values are given as a guide and are based on experiments performed in several rating tanks.

2.2 Weirs and flumes

The principle of the method of measurement is to establish a relationship between head and discharge, usually in the laboratory, and apply this relation to the field installation. A measurement of head is therefore required at the gauging station and this value inserted in the appropriate equation to obtain a corresponding value of discharge. A selection of weirs have been check calibrated in the field and weirs whose calibrations have been developed in the laboratory have shown no significant departure from their original calibration. By far the most serious uncertainty in this form of gauging is the inaccuracy in the measurement of head, especially at low flows where, by comparison, any small uncertainty in the coefficient becomes insignificant. The particular equations and design criteria for weirs and flumes are given in the relevant BSI standards (see Bibliography) but a summary of the measuring structures, and their equations of discharge, most commonly employed in the UK follows:

<u>Full width rectangular thin plate weirs (see Fig A7.10)</u>

The Hydraulics Research equation is:

$$Q = 0.564\left(1+\frac{0.15h}{P_1}\right)b\sqrt{g}\,(h+0.001)^{3/2}$$

where Q is the discharge in m^3/s, h is the head in metres, b is the length of crest in metres, P_1 is the height of the crest in metres and g is in m/s^2 and equal to 9.81.

The limitations for the use of this equation are:

$h > 0.02m$

$P_1 \geq 0.15m$

$\frac{h}{P_1} \leq 2.2$

$\frac{L}{P_1} = 2.5 \text{ to } 3$

where L is the distance from the weir to the upstream head measurement position (m).

<u>Rectangular thin plate weirs with end contractions (see Fig. A7.11)</u>

The Kindsvater and Carter equation is

$$Q = 0.554\ (1-0.0035\ \frac{h_1}{P_1})(b+0.0025)\sqrt{g}\ (h_1 + 0.001)^{3/2}$$

with the limitations

(a) $b/B \geq 0.2$

(b) $h_1/P_1 < 2$

(c) $b > 0.15$ m

(d) $h_1 > 0.03$ m

(e) $P_1 > 0.10$m

Triangular (V Notch) Thin Plate Weir (see Fig A7. 12)

The recommended equation is (Kindsvater and Carter equation).

$$Q = \frac{8}{15} \sqrt{(2g)}\ C_d \tan \frac{\theta}{2}\ h_e^{5/2}$$

where θ is the angle included between the sides of the notch and C_d is the coefficient of discharge

$$h_e = h + k_h$$

The three sizes of V notches commonly used are:

(a) A 90° notch in which the dimension across the top is twice the vertical depth (tan θ/2=1).

(b) A half 90° notch (θ = 53°8') in which the dimension across the top is equal to the vertical depth (tan θ/2 = 0.5)

(c) A quarter 90° notch (θ=28°4') in which the dimension across the top is half the vertical depth (tan θ/2 = 0.25).

For fully contracted notches C_d and k_h vary with the notch angle, θ, as shown below.

Relationship between C_d, k_h and θ

θ (degrees)	40	60	80	90
C_d	0.592	0.576	0.576	0.578
k_h (m)	0.0028	0.0011	0.0010	0.0010

The limitations are (see Fig 12)

$h > 0.05m$

$P > 0.45m$

$\frac{h}{P} \leq 0.4$

$B > 0.9m$

<u>Triangular Profile (Crump) Weirs (see Fig A7. 13)</u>

The Crump profile has a 1:2 upstream slope and a 1:5 downstream slope. The recommended equation is:

$$Q = 0.633 \sqrt{(g)}\ bH^{3/2}$$

where H is the total upstream head. The limitations for the use of this equation are as follows.

H/P should not be greater than 3.0

b/H should not be less than 2.0

Fr, the Froude Number, should not be greater than 0.5

$$\text{where } Fr = \frac{\bar{v}}{\sqrt{gd}}$$

the head measuring section should be located at a distance of twice the maximum head ($2H_{max}$) from the crest-line of the weir

H_2/H should not be greater than 0.75, where H_2 is the downstream gauged head (modular, or free flow, limit)

For non-modular flow, when the downstream head H_2 exceeds 0.75H, discharge is reduced by a factor f where

$$f = Q/Q_{mod}$$

and the discharge equation becomes

$$Q = 0.633 \sqrt{(g)}\ b\ f\ H^{3/2}$$

For the solution of this equation see BS3680 Part 4B

<u>The flat V weir (see Fig A7. 14)</u>

The flat V weir has the same section as the triangular profile weir, 1:2 upstream slope and 1:5 downstream slope, but in elevation has a crest slope, n, of 1:10, 1:20 or 1:40 so that it takes the form of a shallow V when viewed in the direction of flow. With this geometry, it is therefore less sensitive to low flows but at the same time has a wide flow range.

The discharge over a flat V weir may be within the V, above the V and within vertical side walls, or above the V and within trapezoidal side walls. To allow for these conditions, a shape factor, Z, is included in the discharge equation.

The equation of discharge is

$$Q = \frac{4}{5} C_d \sqrt{g}\ n\ H^{5/2} \qquad \text{when } H \le P_v$$

where P_v is the difference between the highest and lowest crest levels

and

$$Q = \frac{4}{5} C_d\ f_v \sqrt{g}\ n\ H^{5/2} \left[1 - \left(1 - \frac{P_v}{H}\right)^{5/2}\right] \text{ when } H > P_v$$

In the drowned flow range a reduction factor, $f_v = Q/Q_{mod}$, is included and the revised equations are

$$Q = \frac{4}{5} C_d f_v \sqrt{g} n H^{5/2} \qquad \text{when } H \le P_v$$

and

$$Q = \frac{4}{5} C_d f_v \sqrt{g} n H^{5/2} \left[1 - \left(1 - \frac{P_v}{H}\right)^{5/2}\right] \text{ when } H > P_v$$

It is often convenient to replace $[1-(1 - P_v/H)^{5/2}]$ by a factor Z, equal to unity when flow is within the V $(\frac{P_v}{H} = 1)$ and a function of P_v/H when the V-full discharge is exceeded.

For a solution of these equations see BS3680 Part 4G.

<u>Rectangular Standing Wave (Critical Depth) Flume (see Fig A7. 15)</u>

The rectangular throated flume consists of a constriction of rectangular cross-section symmetrically disposed with respect to the approach channel. There are three types of rectangular flume:

i) with side contractions only,
ii) with bottom contraction or hump only,
iii) with both side and bottom contractions.

The discharge equation is:

$$Q = 0.544 C_v C_d b \sqrt{(g)} h^{3/2}$$

where

$$C_d = \left(1 - \frac{0.006L}{b}\right)\left(1 - \frac{0.003L}{h}\right)^{3/2}$$

where l is the length of throat and b is the width of throat. C_v, the coefficient of velocity, is evaluated from the following equations (for side contractions only), or from tables in BS3680 Part 4C:

$$\frac{2b}{3\sqrt{3B}} C_v^2 - C_v^{3/2} + 1 = 0$$

where B is the width of the approach channel

The units of application of the equations are (see Fig A7. 15):

$$b > 0.1m$$

$$\frac{b}{B}\left(\frac{h}{h+P}\right) < 0.7$$

$$\frac{h}{b} < 3$$

$$h > 0.05\ (m) \text{ or } < 2m$$

$$p < 0.90\ (m) \text{ when } \frac{h}{P} < 0.3$$

where P is the height of the hump. If no hump P = 0

The head measuring section is at 3 to $4h_{max}$ upstream of the leading edge of the entrance transition.

Trapezoidal Throated Flume (see Fig A7. 16)

This flume is suitable for larger installations and at sites where there is a large range of flows and where it is important to measure low flows accurately.
The discharge equation is:

$$Q = \left(\frac{2}{3}\right)^{3/2} C_v C_d C_s \, b\sqrt{(g)}\, h^{3/2}$$

where $C_d = (1-0.006\,\frac{L}{b})(1-\frac{0.003L}{h})^{3/2}$

C_s is a shape coefficient which takes into account the non-rectangular section and m is the slope of the flume sides (m horizontal: 1 vertical). Before C_v can be calculated, C_s requires to be found. C_s is a function of mH/b, where H is the total head allowing for velocity of approach. This leads to a slightly more complicated calculation since only gauged head is known and whilst gauged head is satisfactory for design purposes, in order to evaluate discharge successive approximations are required to deduce C_s.

As a first approximation it may be assumed that

$$\frac{mH}{b} = \frac{mh}{b}$$

and C_s may be obtained from the table below.

Approximation of the shape coefficient C_s

mh/b	0.02	0.05	0.10	0.20	0.30	0.40	0.50	1.0	1.5	2.0	3.0	4.0	5.0
C_s	1.02	1.04	1.07	1.14	1.20	1.30	1.35	1.70	2.0	2.4	3.2	3.8	4.6

BS3680 Part 4c (see Bibliography) provides examples of both this procedure and a graphical procedure for calibrating a trapezoidal flume.

The limits of application for the equation of discharge are:

$h > 0.05m$ or $0.05L$, whichever is the greater

$\frac{h}{L} < 0.5$ (but may rise to 0.67 with an additional uncertainty in C_d of 2 percent)

Fr < 0.5 where $Fr = \frac{\bar{v}}{\sqrt{gd}}$

b > 0.1(m)

h < 2 (m)

Other flow measuring structures

Measuring structures standardised in British Standards (see Bibliography), but not commonly used in the UK include the following:

Round nose horizontal weirs
Rectangular profile weirs
V-shaped broad crested weirs
U-throated (round bottomed) flumes

Compound gauging structures (BS 3680 Part 4D)

These are common in the UK where one or more low flow sections are incorporated within divide walls. The compounding normally consists of the same structure types set at different levels but may also consist of different types of structures.

Discharge range for measuring structures

Table A7. 1 shows the actual discharge range that can be gauged for a selection of British Standard measuring structures.

2.3 The Ultrasonic gauge

The ultrasonic gauge (Fig A7. 17) is particularly applicable to rivers up to about 300m in width although a few gauges have been installed in wider rivers. It is used in situations where it is not possible to establish a stable stage-discharge relation or where a measuring structure is unsuitable. The gauge is therefore appropriate under conditions of backwater and very low velocities of the order of 0.005 m/s. There is no constriction to flow since the assemblies carrying the transducers are installed on the banks. Like the electromagnetic method, the ultrasonic method can measure reverse flow and provides a continuous measurement of discharge. Sound pulses are sent obliquely across the river in opposite directions from transducers fixed at chosen depths on each bank. The sound waves travelling downstream propagate at a higher velocity than those travelling upstream due to the component of stream velocity parallel to the acoustic path. The time taken for a pulse of sound to travel a measured distance between two reference points in one direction is compared to the time taken for pulses to travel between the same two points in the opposite direction and the difference observed is directly related to the average velocity of the elements of water in the 'flight path' and referred to as the 'path velocity'.

This basic principle, in combination with appropriate instrumentation, permits the discharge to be determined from the mean velocity component along each flight path, the average depth of flow and channel width (area of flow).

The ultrasonic gauges installed today are normally multipath systems and may incorporate several pairs of transducers controlled by a microprocessor. Electric power is required (240 volts) for continuous measurement, and stage, measured normally by solid state recorder combined with a shaft encoder, is related to the area of flow and keyed into the software. Battery operated versions are now available.

Referring to Fig A7. 17, the time taken (t_1) for a pulse to travel from A to B is:

$$t_1 = \frac{L}{C + v_p}$$

Similarly the time taken (t_2) for a pulse to travel from B to A is

$$t_2 = \frac{L}{C - v_p}$$

From which the simplified equation for deriving line velocity in a direct flight path is

$$\overline{v} = \frac{L}{2\cos\Theta} \left(\frac{1}{t_1} - \frac{1}{t_2}\right)$$

The velocity is measured in a similar manner at several levels between the surface and bed and the flow computed in various slices by the mid-section method by multiplying the velocity by the width and thickness of the slice. The total discharge is computed by summing these separate measurements.

If the angle Θ between flight path and direction of flow is not known accurately ('oblique flow') 'crossed paths' are used and both paths combined to leave only a small residual error.

Reflector systems are also available where the transducers are installed on one bank only.

2.4 The electromagnetic gauge

The electromagnetic gauge (Fig A7. 18) operates on a principle similar to that of an electric dynamo. If a length of conductor moves through a magnetic field, a voltage is generated between the ends of the conductor. In the electromagnetic gauge, a vertical magnetic field is generated by means of an insulated coil located either above or beneath the channel. The conductor is formed by the water which moves through the magnetic field; the ends of the conductor are represented by the channel walls or river banks. The very small voltage generated is sensed by electrodes on the channel banks, and these are connected to the input of a sensitive voltage measuring device. The faster the velocities, the greater is the voltage generated.

The basic physical relationship between the variables is:

$$E = \bar{v}\, bH$$

where E is the voltage generated in microvolts (µv);

$\bar{v}$ is the average velocity of the conductor (water) (m/s);

b is the length of the conductor (water) and is equal to the width of the channel (m); and

H is the magnetic field strength (amp turns/m).

The discharge Q (m^3/s) is then

$$Q = \bar{v}\, A$$

$$= \bar{v}bd$$

where d is the depth of flow (m); therefore

$$Q = \frac{E.d}{H}$$

The electromagnetic gauge therefore requires the measurement of the emf at the electrodes, the coil current and the water level, from which the depth of flow is directly derived. A source of electrical power is required (110 or 240 volts) and an on-site current meter calibration. However, empirical tests have shown that a provisional calibration equation may be keyed into the gauge software and subsequently modified after on-site calibration. The gauge requires sophisticated electronics in the field of signal detection and data processing but an important feature is its ability to provide a continuous measurement of discharge in rivers with low velocity with significant weed growth or silty or moving beds. Due to cost considerations the maximum width of river for operational purposes is about 50m.

2.5 Dilution method

Principle

The dilution method is generally used for purposes of calibration or for spot gaugings mainly because of the costs of performing a gauging and a chemical analysis of the tracer samples. Nevertheless the method can often provide very accurate results given a suitable reach of river. The outstanding advantage of the dilution technique is that it is an absolute method because discharge is computed from volume and time only. Tracer concentrations need be determined only in dimensionless relative readings. In rock-strewn shallow streams, the dilution method may provide the only effective means of estimating flow. The main disadvantages of the method are the difficulties in obtaining complete mixing of the tracer without loss of tracer (the method is therefore unlikely to be suitable for rivers with low velocities) and the problem of obtaining permission to inject tracers into rivers. There are two basic injection techniques, several sampling techniques and a large number of possible tracers of three main types - chemical, fluorescent and radioactive. The technique is normally carried out by specially trained personnel and although the method is mostly used for smaller rivers,1 discharges of up to 2000m^3/s have been measured with confidence.

The basic principle of the dilution method is the addition of a suitably selected tracer to the flow. Downstream of the injection point, when dispersion throughout the flow is effected, the discharge of the flow may be calculated from the determination of the dilution of the tracer.

Theory

(i) Constant Rate Injection Method

A concentrated homogeneous solution of an indicating substance is discharged to a stream at a constant rate and samples are taken from a downstream cross-section, at a position where mixing of the injected solution and the stream are complete. The following equation gives the amounts of indicating material passing the injection point and the sampling point during unit time:

$$QC_o + qC_1 = (Q + q)C_2$$

where Q is the discharge of the stream (m^3/s), q is the discharge of the injected solution (m^3/s), C_o is the concentration of the injected substance naturally present in the stream (mg/litre), C_1 is the concentration of the injected substance (mg/litre) and C_2 is the concentration of the substance at the sampling point (mg/litre).

$$Q = \frac{(C_1 - C_2)}{(C_2 - C_o)} q$$

This equation can usually be simplified if $C_o = 0$ and if C_1 is large compared to C_2 then:

$$Q = \frac{C_1}{C_2} q$$

where C_1/C_2 is known as the dilution ratio.

(ii) Integration (Gulp) Method

A known volume (V) of the indicating substance is injected quickly (or slowly) and samples are taken at regular intervals of time and the concentrations determined so as to draw a concentration time curve. Then:

$$(C_1 - C_o) V = Q \int_o^T (C_2 - C_o) dt$$

$$\text{and } Q = V \frac{(C_1 - C_o)}{\int_0^T (C_2 - C_o) dt}$$

$$\text{or} \quad Q = \frac{VC_1}{\int_0^T (C_2 - C_o) dt}$$

This equation holds for both intermittent sampling and for continuous sampling at a constant rate. In the former case, the integral $\int_o^T (C_2 - C_o) dt$ is evaluated graphically, and in the latter case $(C_2 - C_o)$ is determined by analysis of the mixed sample. In this special case the equation is reduced to:

$$Q = \frac{VC_1}{T(\bar{C}_2 - C_o)}$$

During a gauging by the integration method, the concentration at the sampling cross-section will not be uniform across the section, except under conditions of exceptional turbulence. Sampling should, therefore, be at fixed points at each of which the value of $\int_o^T (C_2 - C_o)\, dt$ should be the same.

Figure A7.19 shows typical curves for constant rate and gulp injection methods. The former may be considered as a large number of small gulp injections made at equal intervals of time. If the pulse from a gulp injection is drawn for each small gulp injection at the appropriate time and the resulting curves summed vertically, the shape of the curve for the constant rate injection is obtained.

2.6 The slope area method

The most important use of the slope-area method is for the determination of flood discharge, either directly or after the flood has passed. It may also be used, however, where the flow is affected by backwater but the method is not applicable for low velocity measurement. The method consists of the estimation of three basic factors:

(a) the area of flow of the average cross-section in a longitudinal reach of channel of known length;

(b) the slope of the water surface or the slope of the energy gradient in the same reach of channel; and

(c) the character of the stream bed so that a suitable roughness factor may be chosen.

When these factors are known, the mean velocity of the stream may be computed by either the Chezy equation or the Manning equation:

Chezy: $\bar{v} = CR^{1/2} S^{1/2}$ (m/s)

Manning: $\bar{v} = \frac{1}{n} R^{2/3} S^{1/2}$ (m/s)

where $\bar{v}$ = mean velocity of stream (m/s);

R = hydraulic radius = $\bar{A}/P$ where $\bar{A}$ (m^2) is the mean cross section area of flow and P the wetted perimeter (m);

S = slope or energy gradient:

n = Manning roughness coefficient.

Generally the Manning equation is preferred in practice because it is simple to apply and many years of experience in its use have shown that it produces acceptable results.

The product of the mean velocity so obtained from either of the above equations and the area $\bar{A}$ of the average cross-section provides an estimation of the discharge.

If the mean velocity does not remain constant from section to section along the reach of channel, the surface slope may not coincide with the energy gradient, and for those conditions the energy gradient is used instead of the surface slope.

The Manning equation, like the Chezy equation, was developed for conditions of uniform flow in which the water surface slope and energy gradient are parallel to the stream bed, and the area, hydraulic radius and depth remain constant throughout the reach. For lack of a better solution, it is assumed that the equations are also valid for non-uniform reaches if the water surface gradient is modified by the difference in velocity head between the cross-section. A schematic definition of slope area is shown in Figure A7. 20

2.7 The stage-fall-discharge method

Several factors can cause the scatter of discharge observations about the stage-discharge relation at current meter stations. Backwater is one of these factors, whereby the velocity is retarded so that a higher stage is necessary to maintain a given discharge than would be necessary if the backwater were not present. Backwater is caused by constrictions such as narrow reaches of a stream channel or artificial structures downstream, such as dams or bridges or downstream tributaries. All of these factors can increase or decrease the energy gradient for a given discharge and cause variable backwater conditions.

If, however, the backwater caused by a fixed obstruction is always constant at any given stage, the discharge rating is a function of stage only. Constant backwater, as caused by section controls for example, will not adversely affect the simple stage-discharge relation. The presence of variable backwater, on the other hand, does not permit the use of simple stage-discharge relations for the accurate determination of discharge.

Regulated streams may have variable backwater virtually all of the time, while other streams will have only occasional backwater from downstream tributaries or from the return of overbank flow. A complex situation arises when all of the above factors are present plus scour and deposition of the bed. Many of these sites can be operated by the so-called stage-fall-discharge method using a reference gauge (base gauge) at which stage is measured continuously and current meter measurements are made occasionally, and an auxiliary reference gauge some distance downstream where stage is also measured continuously. when the two reference gauges are set to the same datum, the difference between the two stage records is the water surface fall and provides a measure of water surface slope. The shorter the slope reach, the closer the relation between fall and water surface slope. On the other hand, the longer the slope reach, the smaller the percentage uncertainty in the recorded fall.

Precise time synchronisation between base gauge and auxiliary gauge is important if stage changes rapidly, or when fall is small. Reliable records can usually be computed when fall exceeds about 0.1m. Timing and gauge height uncertainties which may be negligible at high flows become significant at very low flows. Stage-fall-discharge relations can be conveniently divided into two broad categories of constant-fall ratings and variable-fall ratings. In both cases the fall is used as a third parameter to produce a series of rating equations from which discharge may be computed. Because the velocities require to be measured by current meter at the base station, the method is unsuitable where low velocities persist. An example of the stage-fall-discharge method is shown in Figure A7. 21.

2.8 Moving-boat method

The moving-boat method is of comparatively recent origin and was introduced by the United States Geological Survey to gauge some of the world's largest rivers. The highest discharge gauged by the method was 250 000 cumecs on the Amazon in 1972. The main difference from the current meter method is in the method of data collection.

A propeller type current meter is suspended from a boat at about 1 metre below the surface and the boat traverses the channel normal to the streamflow. During the traverse an echo sounder records the geometry of the cross-section and the continuously operating current meter records the resultant of the stream and boat velocities. A vertical vane aligns itself in a direction parallel to the movement of water past it and an angle indicator, attached to the vane assembly, indicates the angle between the direction of the vane and the true course of the boat. The velocity v_b of the boat is the velocity at which the current meter is being pushed through the water by the boat. The force exerted on the current meter is a combination of two forces acting simultaneously: one force resulting from the movement of the boat through the water and the other a consequence of the streamflow. The velocity measurement taken at each of the sampling points (verticals) in the cross-section is a vector quantity which represents the relative velocity past the vane and meter. This velocity v_v is the vector sum of v, the component of stream velocity normal to the cross-section at the sampling point and v_b.

A rate indicator unit is used in conjunction with a current meter rating table to obtain v_v while the angle reading α, representing the angle the vane makes with the cross-section path, defines the direction of the vector (Fig A7. 22).

Stream velocity, v, perpendicular to the boat path at each vertical, can be determined from:

$$v = v_v \sin \alpha$$
$$b = \int v_v \cos\alpha \, dt$$

where b is the distance that the boat has travelled along the true course between two consecutive verticals. It can be assumed that α is approximately uniform over the relatively short distance between verticals and can be treated as constant. The equation then becomes:

$$b = \cos\alpha \, v_v \, dt$$
and
$$\int v_v \, dt = b_v$$

where b_v is the relative distance through the water between two consecutive verticals, as represented by the output from the rate indicator and counter:

then
$$b = b_v \cos\alpha$$

Finally, d, the stream depth at each vertical, is obtained from the echo sounder chart and, upon obtaining v, b and d for each vertical across the measuring section, the midsection method of computation is used to obtain the discharge. Since the method uses a current meter measurement at about 1m below the surface (sub-surface method) the computed discharge requires to be multiplied by a coefficient. In rivers over about 3m deep it is found that the vertical velocity profile is usually vertical for most of its depth and a single coefficient is normally satisfactory. This coefficient, from measurements in several of the world's rivers, has been found to vary between about 0.90 and 0.95. Normally at least 6 runs are made, each with 30 to 40 verticals, and the results averaged.

The limitations of the moving-boat method concern the minimum width and depth of channel, and the shape of the vertical velocity curve. The channel width should preferably be of the order of at least 100m, the depth at least 3m, and the velocities above about 0.15m/s to get the best results. Because of these limitations the method is not used in the UK. The vertical velocity curve should be stable for an individual run and the vertical distribution of velocity should be such as to be able to estimate the sub-surface coefficient with acceptable uncertainty.

2.9 Float Gauging

When it is impractical to use a current meter because velocities are too low or too high, or if floating debris is present during floats, it is sometimes necessary to estimate velocities by means of floats. Timing floats was probably man's first attempt to measure stream velocity but their use today is avoided if at all possible unless for spot gaugings in preliminary surveys. The velocity as determined by timing a float over a measured distance is neither a local point velocity nor an instantaneous one for the mean velocity in time, t, over a distance, L, is:

$$v = \frac{L}{t}$$

Floats may consist of surface floats, canister floats or rod floats. Surface floats are the most convenient to use but wind effect can significantly affect their course. Canister floats consist of a closed can connected by a line to a surface float. The can dimensions and its immersion depth are chosen so that the float velocity is equal to the mean velocity in the vertical. Rod floats are cylindrical rods weighted so that they float vertically in still water with only the top protruding above the surface. Rod lengths are selected so that they extend through the stream depth without the lower end touching the bed. Ideally, three cross-sections are selected - one at the beginning of the reach, one midway and one at the end of the reach. The float should be released far enough above the first cross-section. The time at which the float passes the final cross-section, and the midway cross-section, if used, is noted.

This procedure is repeated with floats at different distances from the bank. The calculation of discharge is carried out by dividing the width of the channel into a suitable number of segments either of equal width or of equal discharge. The discharge is calculated by multiplying the mean area of flow of the segments by the estimated mean velocity in each segment; that is:

$$Q = \sum_{1}^{N} q$$

$$= \sum_{1}^{N} \bar{v} \bar{A}$$

where $\bar{v}$ is the mean velocity in each segment and $\bar{A}$ is the mean area of flow of each segment.

A travel time of at least 20 seconds is recommended in the standards but a shorter time may be used for streams with high velocities when it may not be possible to find a straight reach of channel having adequate length. As a guide, the distance between the upstream and downstream cross-sections should be about four or five times the width of the midway section or the average width of the river reach.

More recent methods, but not yet included in standards, are the rising air float technique and the aerial float technique where, for large rivers, the floats are dropped from aircraft. In the latter method either the paths of the floats are traced by aerial photography or floats are dropped containing oil which, in impact with the bed, release the oil. The oil traces the distribution of velocities as in the rising air float method.

In the rising air float technique the 'floats' are a succession of air bubbles produced by a specially manufactured pipe laid across the channel bed. This produces a semi-continuous envelope of air bubbles on the water surface. In the limited number of field tests carried out by the former water authorities the main problems were the assumed laboratory value of the bubble rise velocity and the method of data collection.

2.10 Recent advances in flow measurement

Methods which have recently been the subject of innovation but not evaluated in rivers and possibly having application in low velocities are:

Doppler velocity sensor (eg Detectronics + Warren Jones)
Sensanet flow system (Aqua Data Systems)
Arx ultrasonic look-up level measurement (Scan Group)
Ultrasonic portable velocity meter (Ferranti and Sarasota)
Electromagnetic current meter (eg ADS and Valeport, see page 11)

2.11 Guide to the selection of methods

A guide to the selection of methods is given in Tables A 7.2 and A 7.3. The following methods are considered suitable for low velocity flow measurement.

1. Velocity area using electromagnetic current meter (see page 11)
2. Weirs and flumes, where sufficient head is available
3. Ultrasonic
4. Electromagnetic

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Part 4E, 1990: Rectangular broad crested weirs
Part 4F, 1990: Round nose horizontal crest weirs
Part 4G, 1990: Flat V weirs
Part 4H, 1986: Guide for the selection of a measuring structure
Part 4I, 1986: V shaped broad crested weirs
Part 5, 1970: Slope area
Part 6, 1973: Tidal channels
Part 7, 1971: Measurement of stage
Part 8A, 1989: Current meters
Part 8B, 1983: Sounding and suspension equipment
Part 8C, 1980: Current meter calibration
Part 8D, 1980: Cableway system
Part 8F, 1986: Hydrometric data transmission - general

Part 8G, * : Hydrometric data transmission - requirements
Part 9A, 1971: Pressure actuated instruments
Part 9B, 1981: Float operated water level recorders
Part 10A,1977: Sediment load samples
Part 10B,1980: Measurement of suspended sediment
Part 10C,1980: Bed material sampling
Part 10D,1986: Determination of concentration, particle size and relative density
Part 10E, * : Measurement of sediment in reservoirs
Part 10F, * : Bed load discharge
Part 10G, * : Gravel bed materials

BS 7022, 1988: Geophysical logging of boreholes
BS 6316, 1983: Test pumping water wells
BS 5844, 1980: Estimation of the uncertainty of a flow rate measurement
BS 7118/1,1990:Uncertainty in linear calibration relation
BS 7118/2,1989:Uncertainty in non-linear calibration

TABLE A7. 1 Range of discharge for various types of weir and flume

Type	Size and geometry			Discharge range	Remarks
Thin-plate, full-width weir	b	P_1			
	0.15m	0.2m		0.8 l/s-100 l/s	Upper limit depends on P_1
	1.0m	0.5m		5.4 l/s-2.7 m^3/s	Upper limit depends on P_1
	10m[a]	1m		50 l/s-77 m^3/s	
Thin-plate, side -contracted weir	b	P_1			
	0.15m	0.2m		1.4 l/s-67 l/s	Upper limit depends on P_1
	1.0m	0.5m		9.5 l/s-1.7 m^3/s	Upper limit depends on P_1
	10m[a]	1m		90 l/s-49m^3/s	Upper limit depends on P_1
V-notch weir	θ=20°			0.2 l/s-330 l/s	Other angles are permissible
	θ=90°			1.1 l/s-1.8 m^3/s	
Triangular-profile (Crump) weir 1:2/1:5	b	P_1			
	0.3m[b]	0.2m		3 l/s-350 l/s	Upper limit depends on P_1
	1.0m[b]	0.5m		10 l/s-4.6 m^3/s	Upper limit depends on P_1
	10m[c]	1m		0.3 m^3/s-130 m^3/s	Upper limit depends on P_1
	100m[a,c]	1m		3 m^3/s-1300 m^3/s	Upper limit depends on P_1
Triangular-profile weir, 1:2/1:2	b	P_1			
	0.3m[b]	0.2m		3 l/s-300 l/s	Upper limit depends on P_1
	1.0m[b]	0.5m		11 l/s-3.9 m^3/s	Upper limit depends on P_1
	10m[c]	1m		0.3 m^3/s-110 m^3/s	Upper limit depends on P_1
	100m[a,c]	1m		3 m^3/s-1100 m^3/s	Upper limit depends on P_1
Triangular-profile, compound weir					Compounding could link minimum of one of above geometries with maximum of next larger, for example
Flat-V weir,	$P_1P_2P_U$	Slope	b		
1:2/1:5	0.2m	1:10	4m	14 l/s-5.0 m^3/s	
	0.5m	1:20	20m	27 l/s-180 m^3/s	Assumed H_{1max}= 3m
	1m[a]	1:40	80m	55 l/s-630 m^3/s	Assumed H_{1max}= 3m
Flat-V weir,	$P_1P_2P_U$	Slope	b		
1:2/1:5	0.2m	1:10	4m	15 l/s-2.5 m^3/s	
	0.5m	1:20	20m	30 l/s-65 m^3/s	
	1m[a]	1:20	40m	30 l/s-330 m^3/s	Assumed H_{1max}= 3m

TABLE A7. 1 (Cont) Range of discharge for various types of weir and flume

Rectangular-profile weir	b	P_1	L		
	0.3m	0.2m	0.8m	8 l/s-180 l/s	
	1m	0.5m	2m	90 l/s-2.3 m^3/s	Compounding is permissible
	10m[a]	1m	2m	1.5 m^3/s-65 m^3/s	
Round-nosed horizontal-crested weir	b	P_1	L		
	0.3m	0.15m	0.6m	8 l/s-34 l/s	
	1m	0.15m	1m	25 l/s-740 l/s	Compounding is permissible
	10m	1m	5m	1 m^3/s-82 m^3/s	
	100m[a]	1m	5m	10 m^3/s-820 m^3/s	
Long-throated flumes	b	m	L		
	0.5m	0	1m	9 l/s-300 l/s	Rectangular flume
	0.1m	1	1m	3 l/s-290 l/s	Trapezoidal flume
	1m[a]	5	4m	270 l/s-41 m^3/s	Trapezoidal flume
Parshall flumes	b				
	25.4mm			0.1 l/s-5 l/s	Specified throat width defines all other dimensions
	0.305m			3 l/s-450 l/s	
	2.438m			0.1 m^3/s-3.9 m^3/s	
	15.24m			0.75 m^3/s-93 m^3/s	
U-flumes	D	L			
	0.3m	0.6m		2.4 l/s-70 l/s	
	1m[a]	2m		19 l/s-1.4 m^3/s	

Sample sizes of structure are considered. Intermediate sizes and other geometric ratios are permissible, and this will effect discharge range

[a]There is no upper limit specified for the size of these structures

[b]Lower limit of head assumed to be 0.03m for smooth crest section

[c]Lower limit of head assumed to be 0.06m for concrete crest

TABLE A7. 2 Guide to the selection of methods - limiting conditions (after B.S. 3680 Part 3G)

Method			Criteria						Uncertainty	
No		British Standard 3680	Width	Depth	Velocity	Sediment load	Approach channel	Time factor	Attainable (Percentage)	Comment
1	Velocity-area, by wading	PART 3A	L,M,S	S	S,M		b,c,d	J,K	±5	A,B
2	Velocity-area, from bridge	PART 3A	M,L	M,L	M,L		b,c,d	K	±5	A,B,C,D
3	Velocity-area, cableway	PART 3A	M,L	M,L	M,L		b,c,d	K	±5	A,B,C
4	Velocity-area, static boat	PART 3A	M,L	M,L	M,L		b,c,d	K	±5	A,B,C,E
5	Velocity-area, moving boat	PART 3D	L	M,L	M,L		b,c,d	K	±10	A,B,E
6	Velocity-area, floats	PART 3A	M,L	M,L	M,L,S		b,c,d	K	±10	F
7	Slope-area and stage-fall	PART 5	M,L	M,L	M,L		b,c,d	K,N	±10	Q
8	Ultrasonic	PART 3E	M,L	M,L	M,L,S,v	R	b,c,d	G,J,H	±5	
9	Electromagnetic	PART 3H	M,S	S,M	S,M,v		b,d	G,H,J	±5	T
10	Dilution, chemical, continuous injection	PART 2A	S,M	S,M	S,M		c,g,k	K,N	±5	
11	Dilution, chemical, sudden injection	PART 2B	S,M	S,M	S,M		c,g,k	K	±5	
12	Dilution, radioactive tracer, sudden injection	PART 2C	S,M	S,M	S,M		c,g,k	K	±5	
13	Dilution, radioactive tracer, continuous injection	PART 2C	S,M	S,M	S,M		c,g,k	K,N	±5	
14	Tidal channels	PART 6						K	±10	H
15	Thin-plate weirs, sharp crest, v-notch	PART 4A	S	S	M,S,v	I	a,b,e,j	J,G	±1	
16	Thin-plate weirs, sharp crest, rectangular, suppressed	PART 4A	S	S	M,S,v	I	a,b,e,f,j	J,G	±1	
17	Thin-plate weirs, sharp crest, rectangular	PART 4A	S	S	M,S,v	I	a,b,e,f,j	J,G	±1	
18	Weirs, broad-crested with sharp upstream edge	PART 4E	M,S	S	M,S,v	I	a,b,e,h,j	J,G	±5	
19	Weirs, broad-crested with rounded upstream edge	PART 4F	M,S		M,S,v	I	a,b,e,h,j	J,G	±5	
20	Weirs, triangular profile	PART 4B	M,S	S	M,S,v	I	a,b,e,j	J,G	±5	
21	Weirs, triangular profile, flat-V	PART 4G	M,S	S	M,S,v	I	a,b,e,j	J,G	±5	
22	Weirs, V-shaped, broad-crested	PART 4I	M,S	S	M,S,v	I	a,b,i	J,G	±5	
23	Flumes, rectangular	PART 4C	M,S	S	M,S,v	I	a,b	J,G	±5	
24	Flumes, trapezoidal	PART 4C	M,S	S	M,S,v	I	a,b	J,G	±5	
25	Flumes, U-shaped	PART 4C	M,S	S	M,S,v	I	a,b,i	J,G	±5	

TABLE A7. 3 Explanation of symbols used in table A7.2

Symbol	Definition
a	Flow should be subcritical
b	Flow should have no cross-currents
c	Channel should be relatively free from vegetation
d	Channel should be fairly straight and uniform in cross-section
e	Channel should be fairly straight and symmetrical in cross-section for about 10 channel widths upstream
f	Channel should have vertical walls and a level floor for a distance upstream of not less than 10 times the width of the nappe at maximum head
g	Flow in the channel should be turbulent (even including a hydraulic jump) to ensure mixing
h	Channel should be rectangular for a distance upstream of at least twice the maximum head
i	Channel should be nearly U-shaped
j	Velocity distribution should be fairly uniform
k	Channel should be free from recess in the banks and depressions in the bed
A	For velocity-area method, with velocity observed at 0.6 times the depth, or with two-point method, the minimum uncertainty may be up to 5%
B	For velocity-area method, with velocity observed at surface, the minimum uncertainty may be up to 10%
C	Corrections may be required because of distance or air and wet-line effects
D	Major error can be caused by pier effects
E	Major error can be due to drift, obstruction of boat and heaving action
F	This method is recommended for use only when the effect of the wind is small and where no other will serve. Such conditions are likely to be so variable that no representative accuracies can be quoted, but usually the accuracy of this method is lower than conventional methods using current-meters and higher than the slope-area method
G	Method suitable for more frequent discharge measurements
H	Method suitable for tidal waterways
I	Heavy sediment concentration not permissible
J	Quick method (less than 1h)
K	Slow method (1 to 6h)
L	Large width (more than 50m) or high velocity (more than 3m/s) or large depth (more than 5m)
M	Medium width (between 5 and 50m) or medium depth (between 1 and 5m)
N	Very slow method (more than 6h)
Q	Approximate method used when velocity-area method not feasible and slope can be determined with sufficient accuracy
R	Suspended material concentration should continue to be low in order to avoid too large a loss of acoustic signal; for the same reason, the flow should be free from bubbles
S	Narrow width (less than 5m) or shallow depth (less than 1m)
T	May be used in rivers with weed growth and moving bed material
v	May be used in rivers with low velocities (less than 0.030m/s)

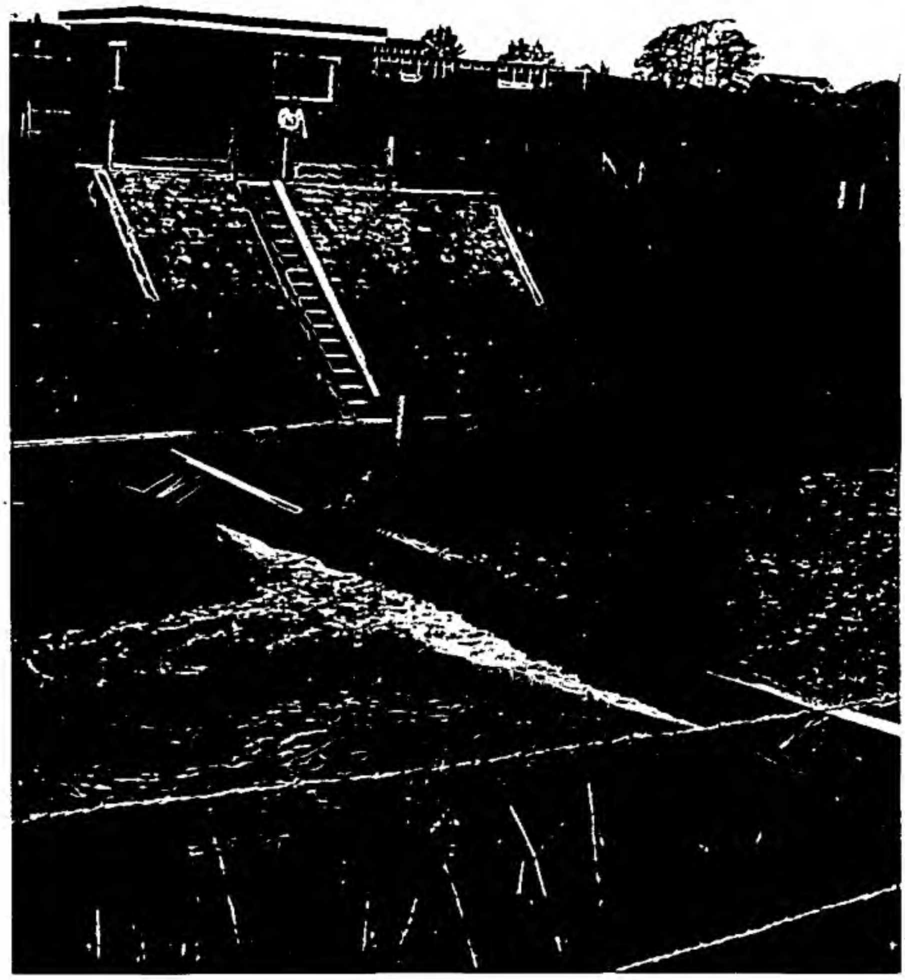


Fig A7.1 Velocity area gauging station with low flow control

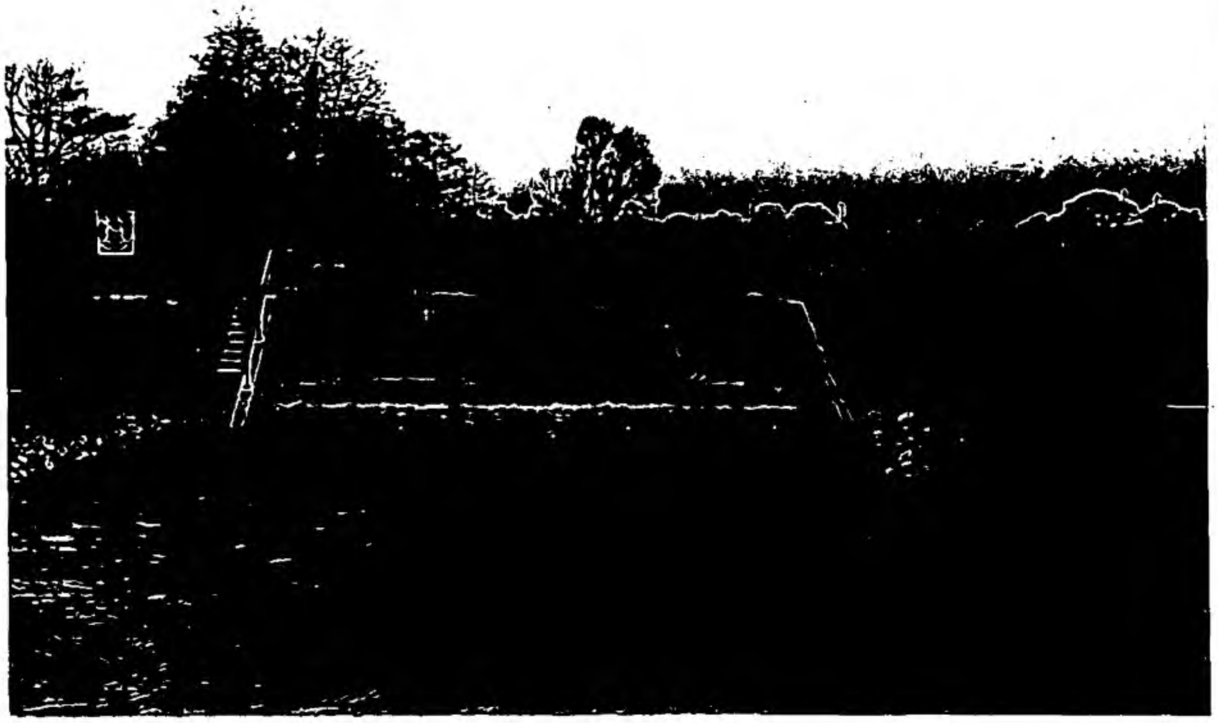


Fig A7.2 Weir

Fig A7.3 Flume

Fig A7.4 Transducers at an Ultrasonic gauging station

Fig A7.5 Electromagnetic gauging station

Fig A7.6 Dilution gauging: Tracer injection point

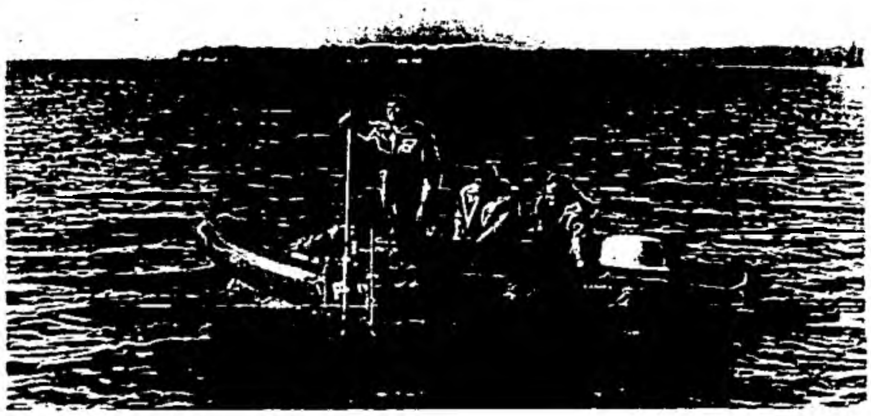
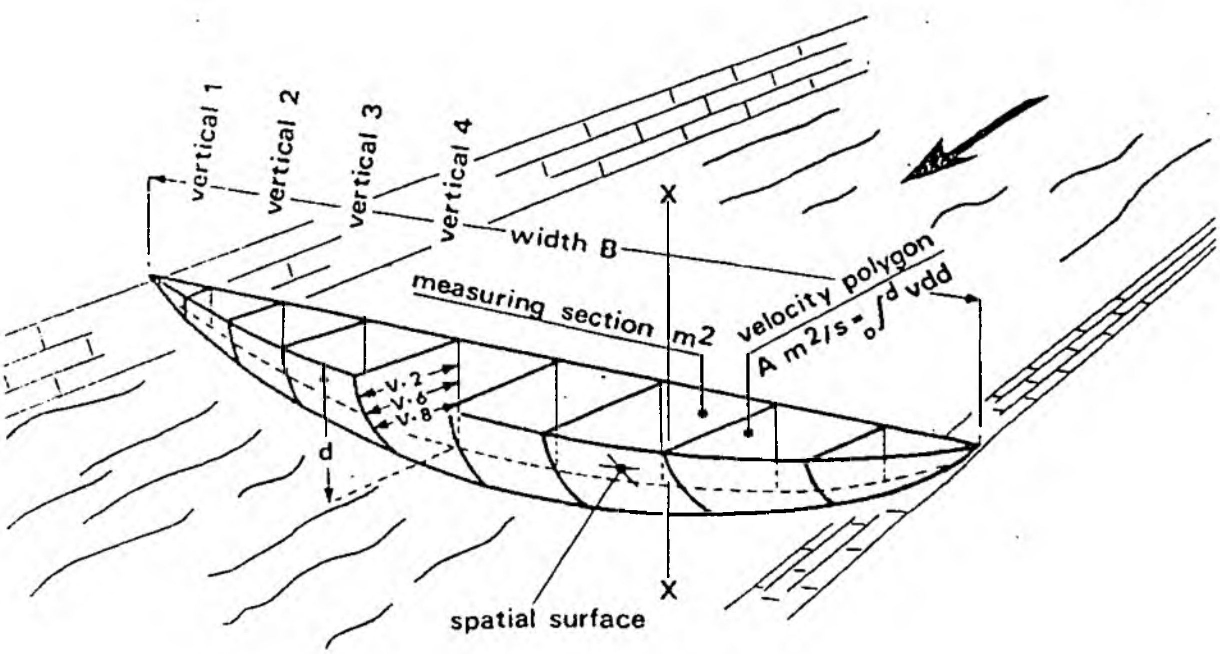


Fig A7.7 Moving boat gauging



The measuring section

Volume of water per second $= \int_0^b A\,db = \int_0^d \int_0^b V\,dd.\,db = Q\ m^3/s$

This volume is bounded by:
a) the measuring section
b) the water surface
c) the bed
d) the spatial surface

MIDSECTION METHOD OF COMPUTATION

THE PARTIAL DISCHARGE, qx AT ANY VERTICAL x is:-

$$q_x = V_x \left[\frac{b_x - b_{(x-1)}}{2} + \frac{b_{(x+1)} - b_x}{2}\right] d_x = V_x \left[\frac{b_{(x+1)} - b_{(x-1)}}{2}\right] d_x$$

where q_x = discharge through partial section x
V_x = mean velocity at location x
b_x = distance from initial point to location x
$b_{(x-1)}$ = distance from initial point to preceding location
$b_{(x+1)}$ = distance from initial point to next location
d_x = depth of water at location x

eg the discharge through partial section 3 is: $q_3 = V_3 \left[\frac{b_4 - b_2}{2}\right] d_3$

and total discharge is $Q = q_1 + q_2 + q_3 + q_4 + \text{----} q_n$

Fig A7.8 Diagrammatic view of current meter measuring section

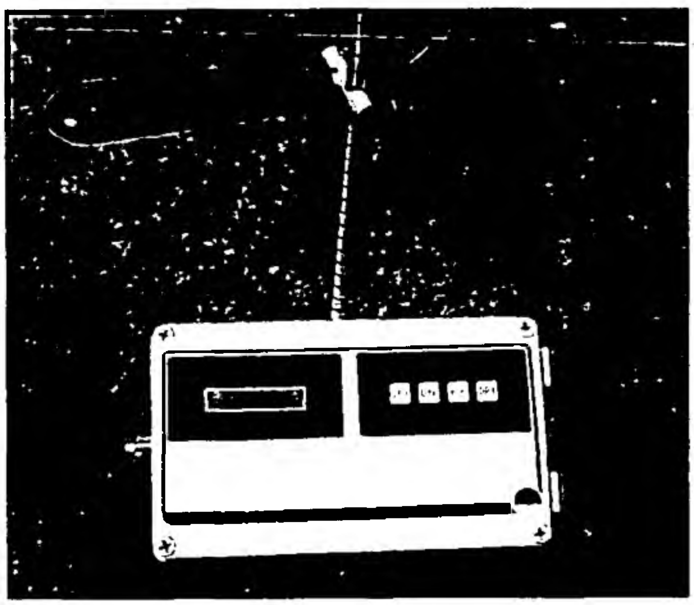


Fig A7.9 The solid state electromagnetic current-meter, range 0.000 to 4.000m/s

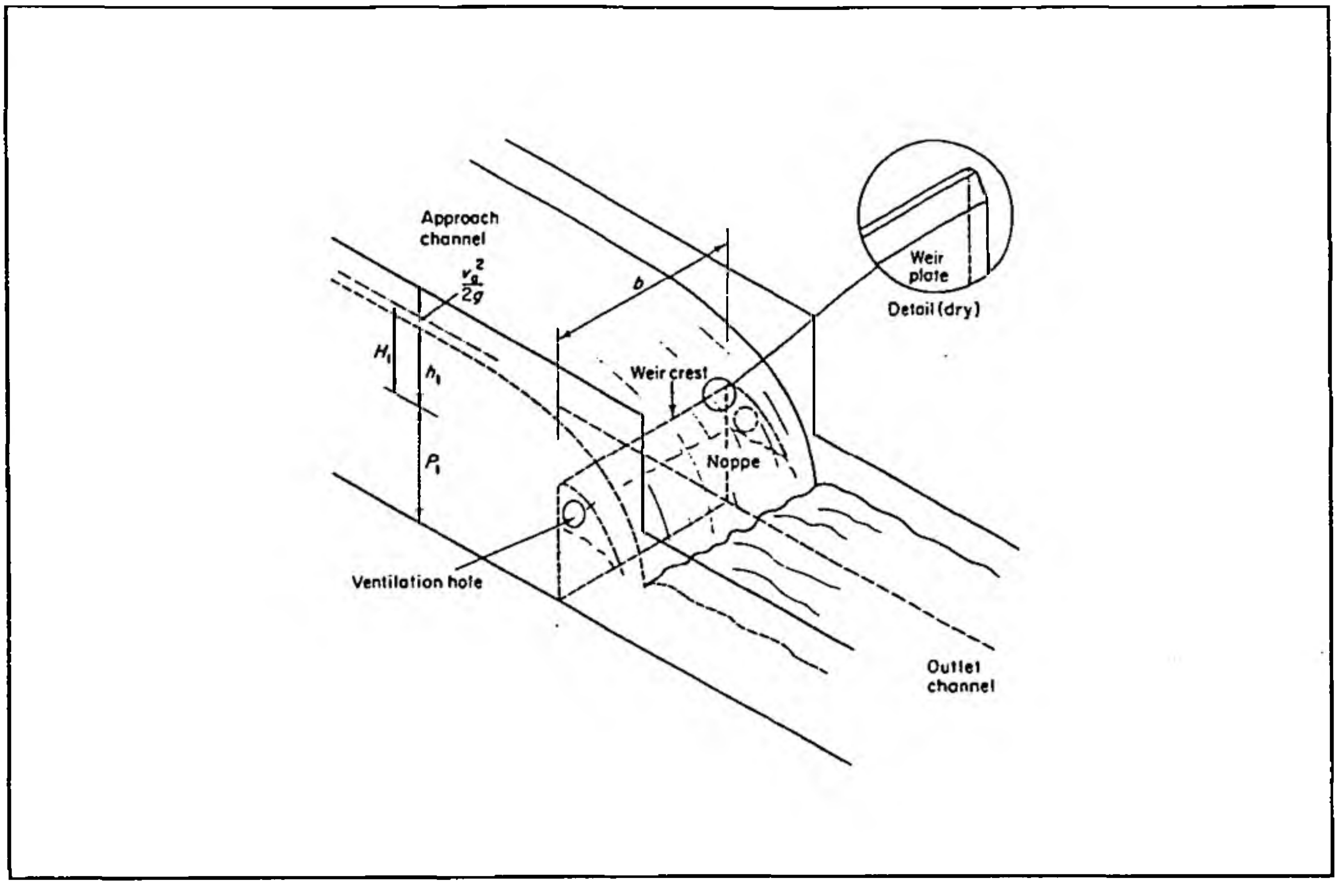


Fig A7.10 Full-width thin-plate weir

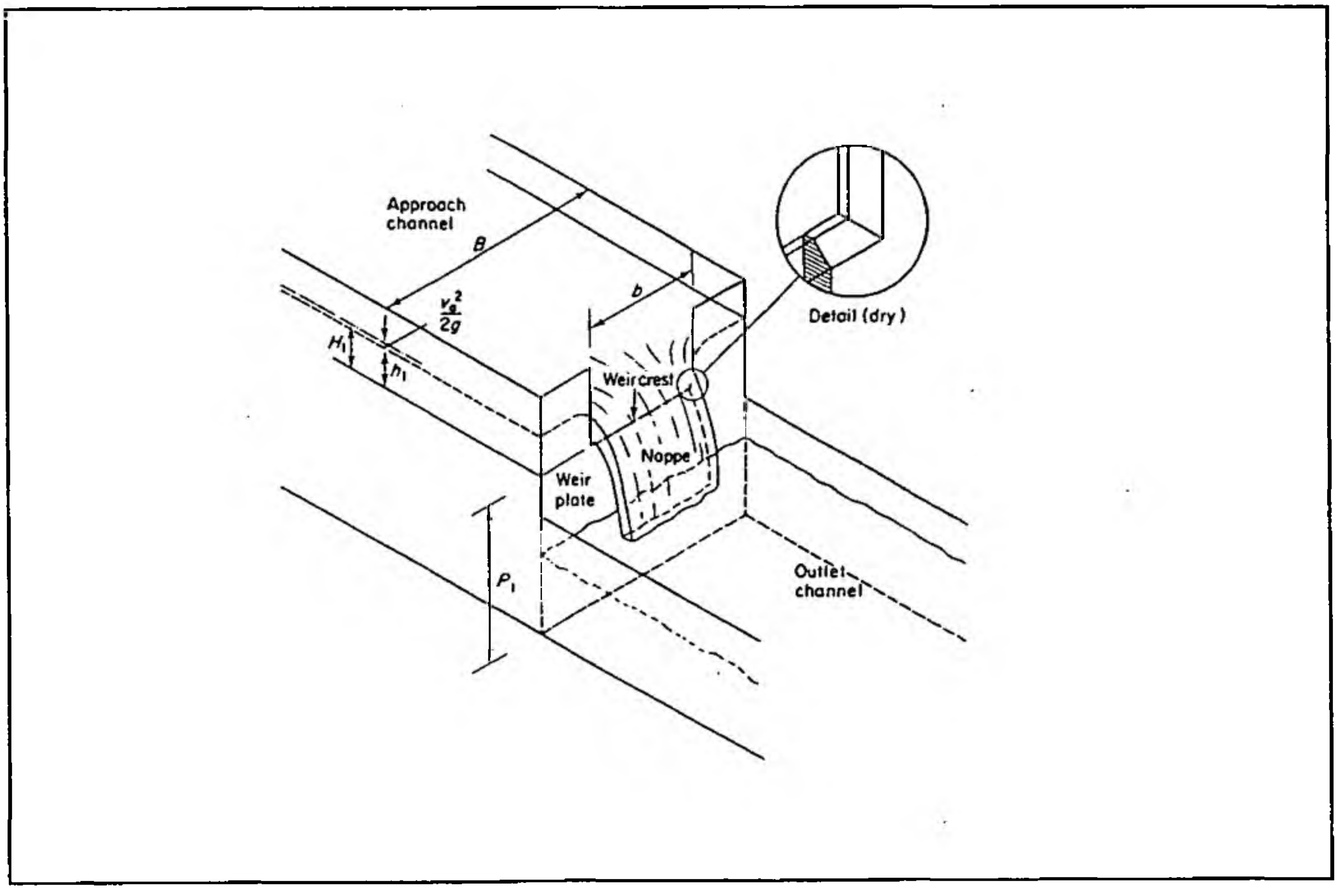


Fig A7.11 Rectangular thin-plate weir with side contractions

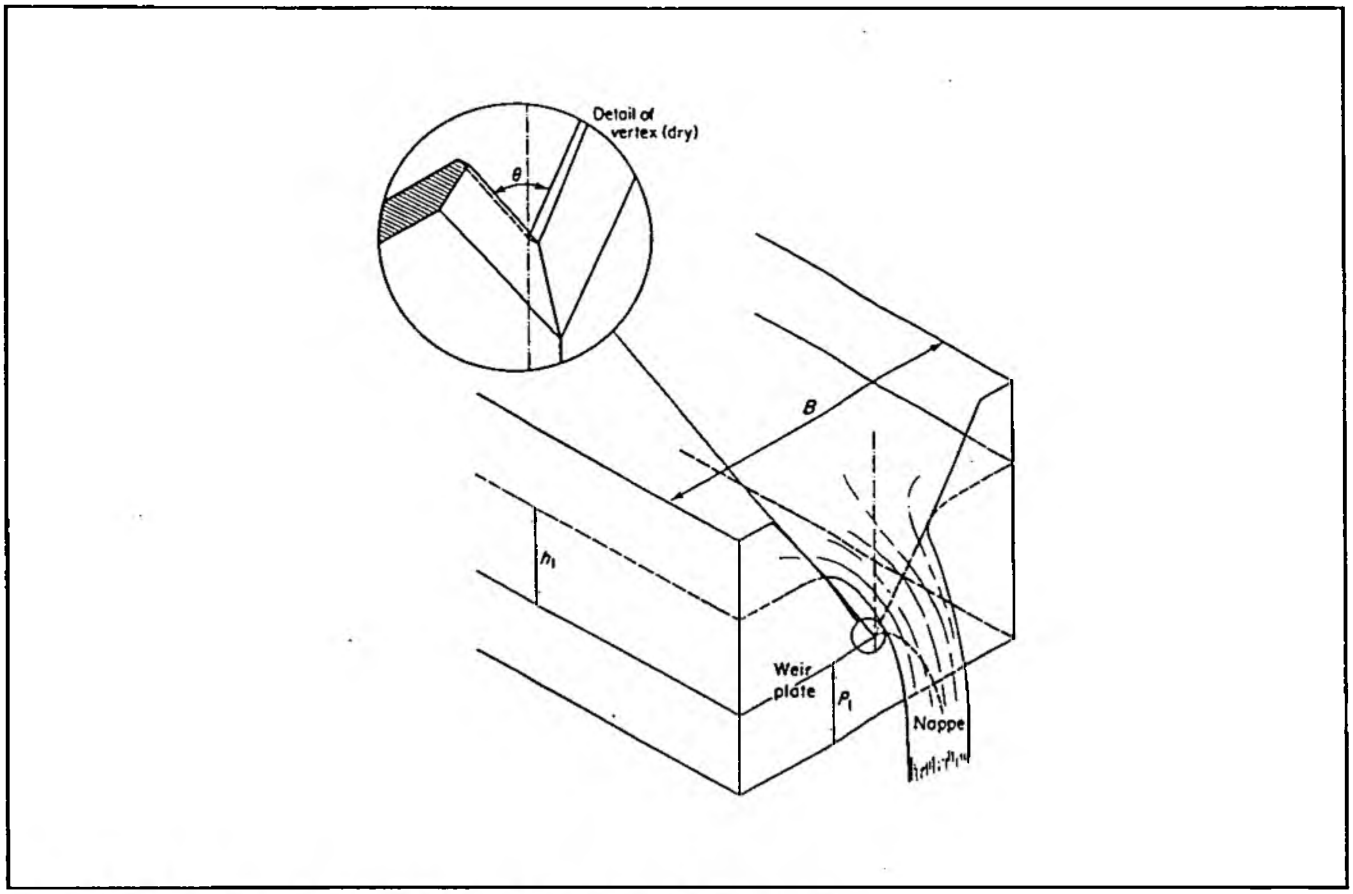


Fig A7.12 V-notch: triangular thin-plate weir

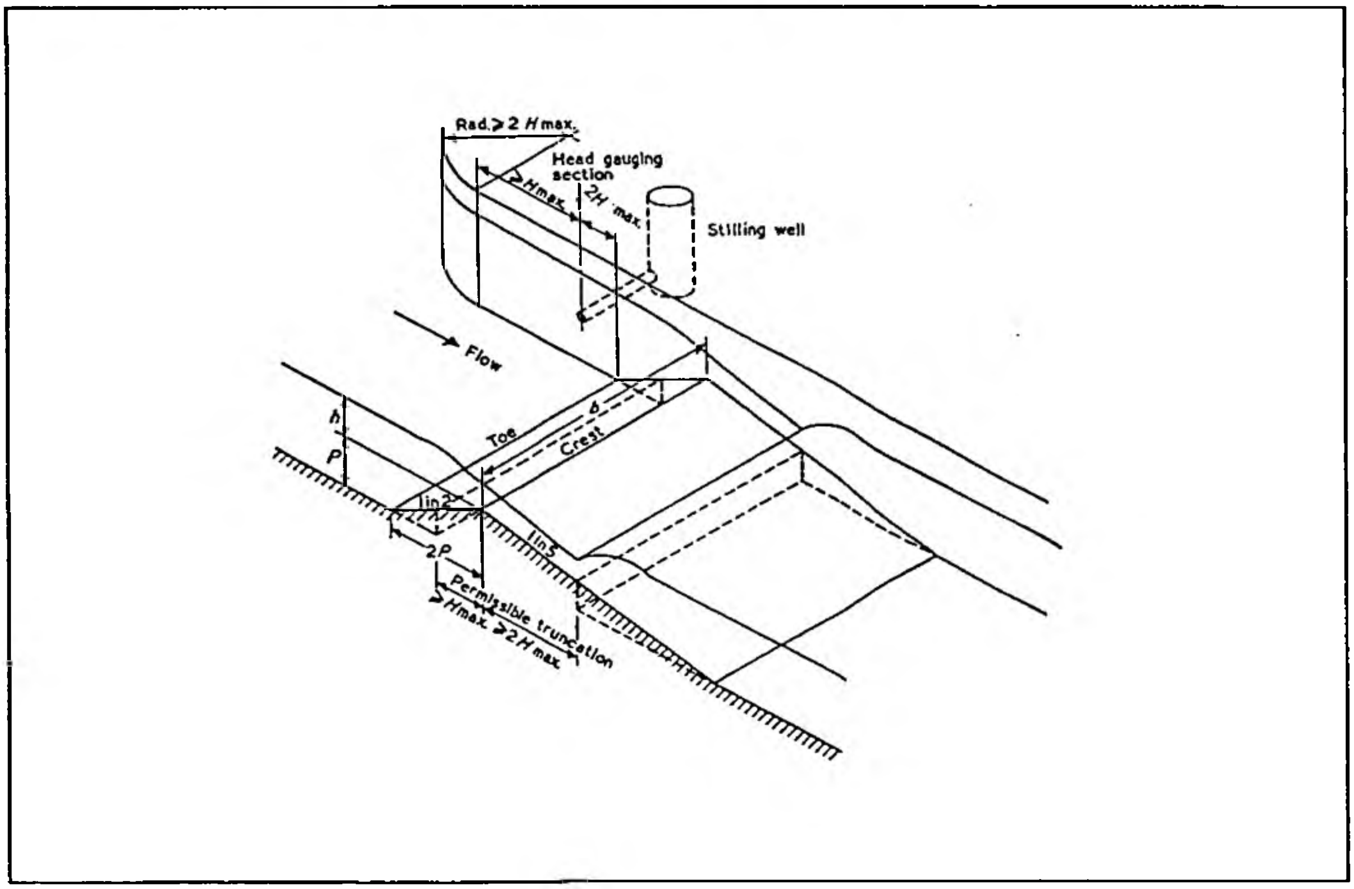


Fig A7.13 Diagrammatic illustration of the triangular profile (Crump) weir

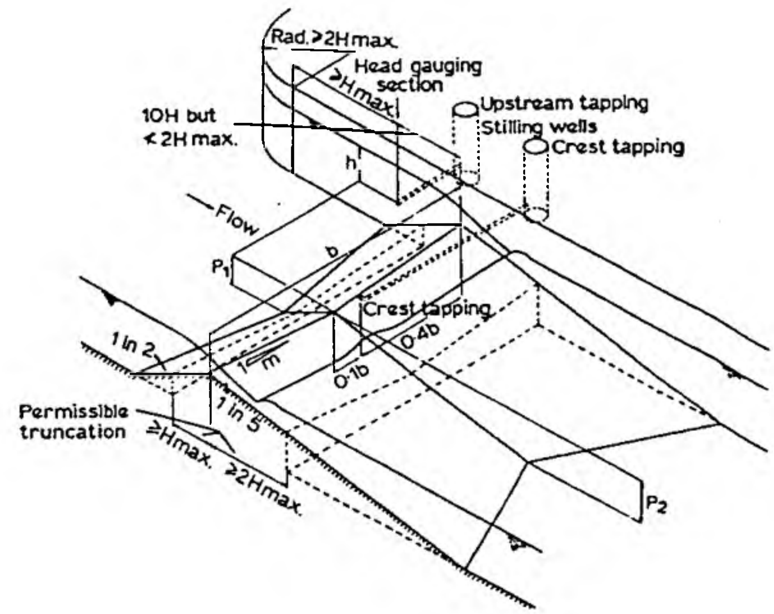


Fig A7.14 Diagrammatic illustration of the flat V weir (courtesy of BSI/ISO)

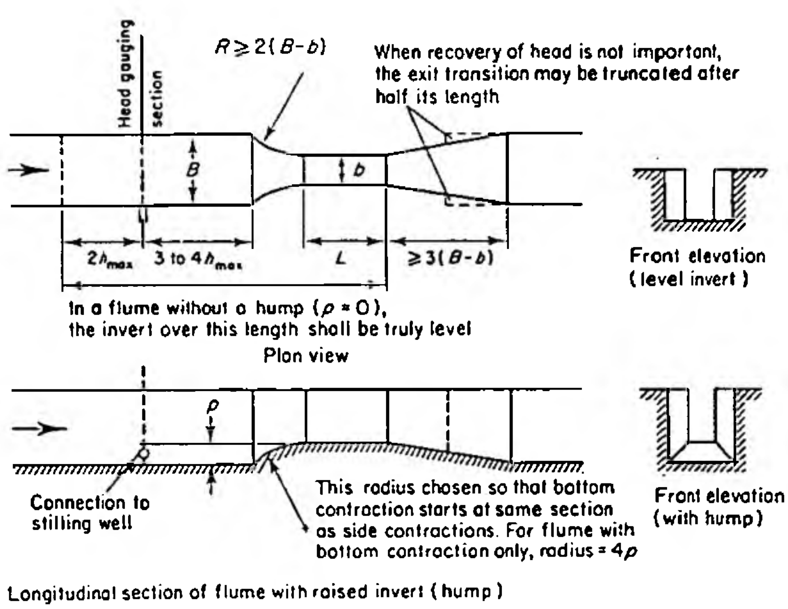


Fig A7.15 Diagrammatic illustration of the rectangular flume

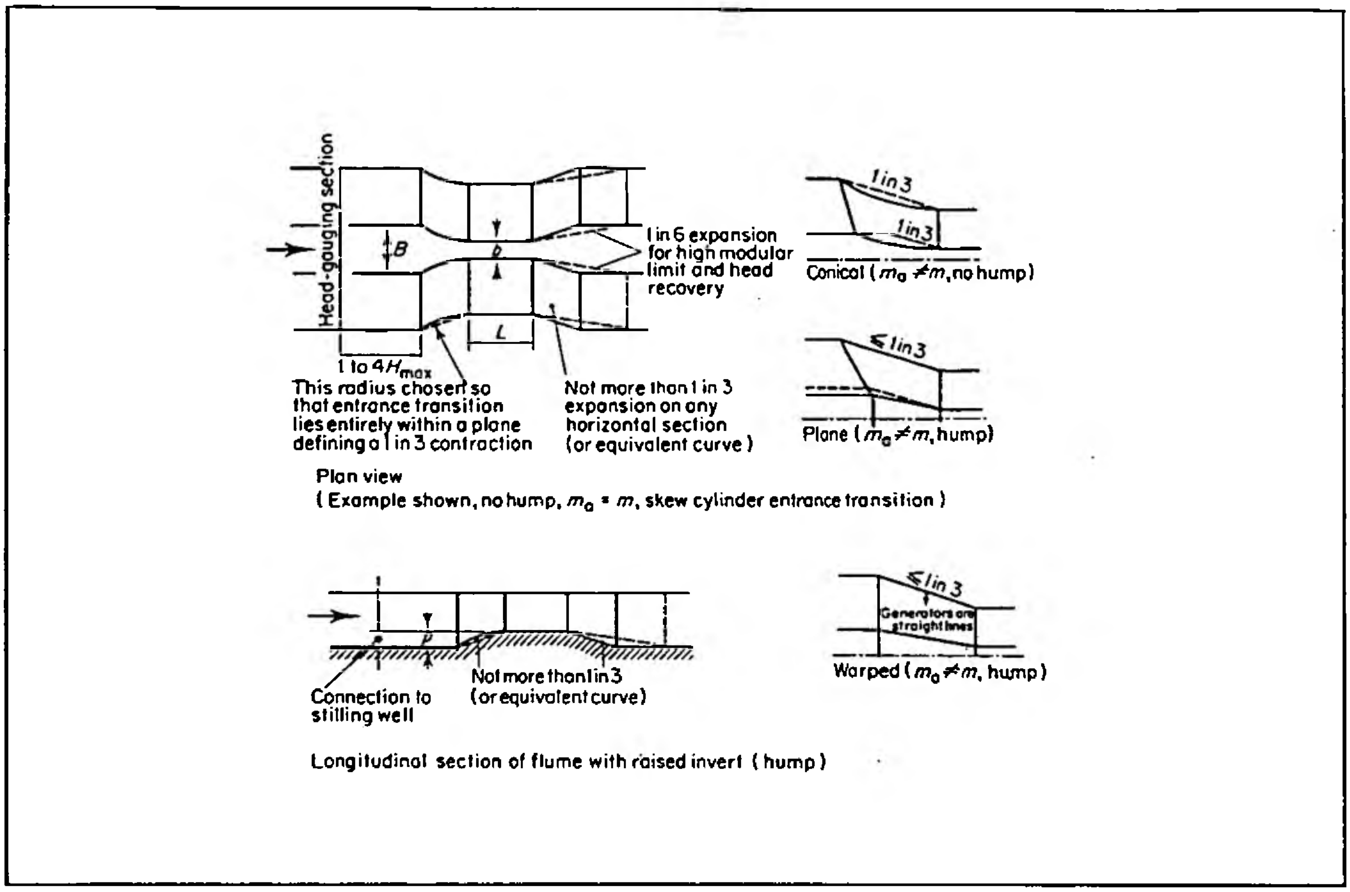


Fig A7.16 Diagrammatic illustration of the trapezoidal flume

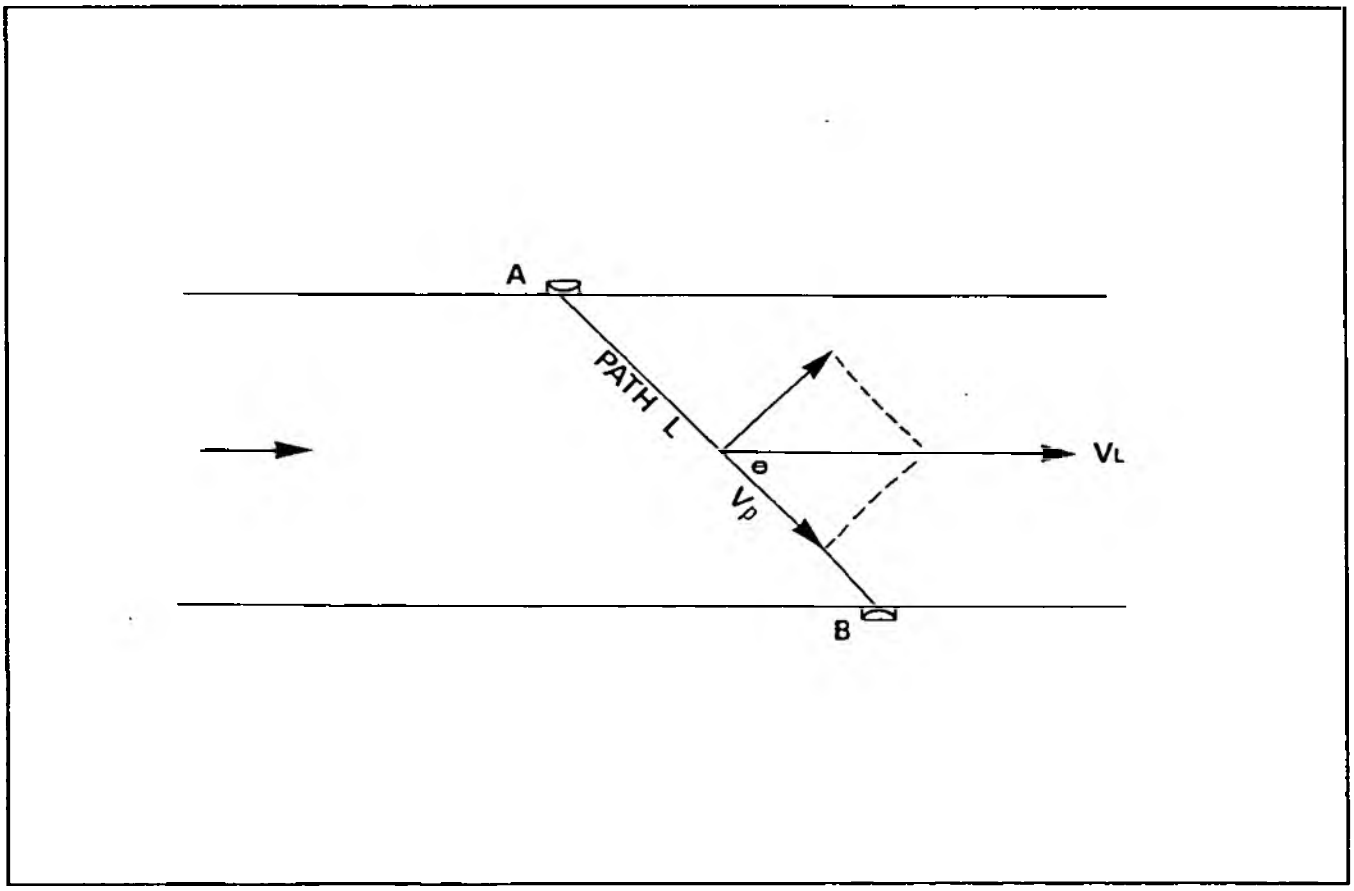


Fig A7.17 Ultrasonic method: velocity components

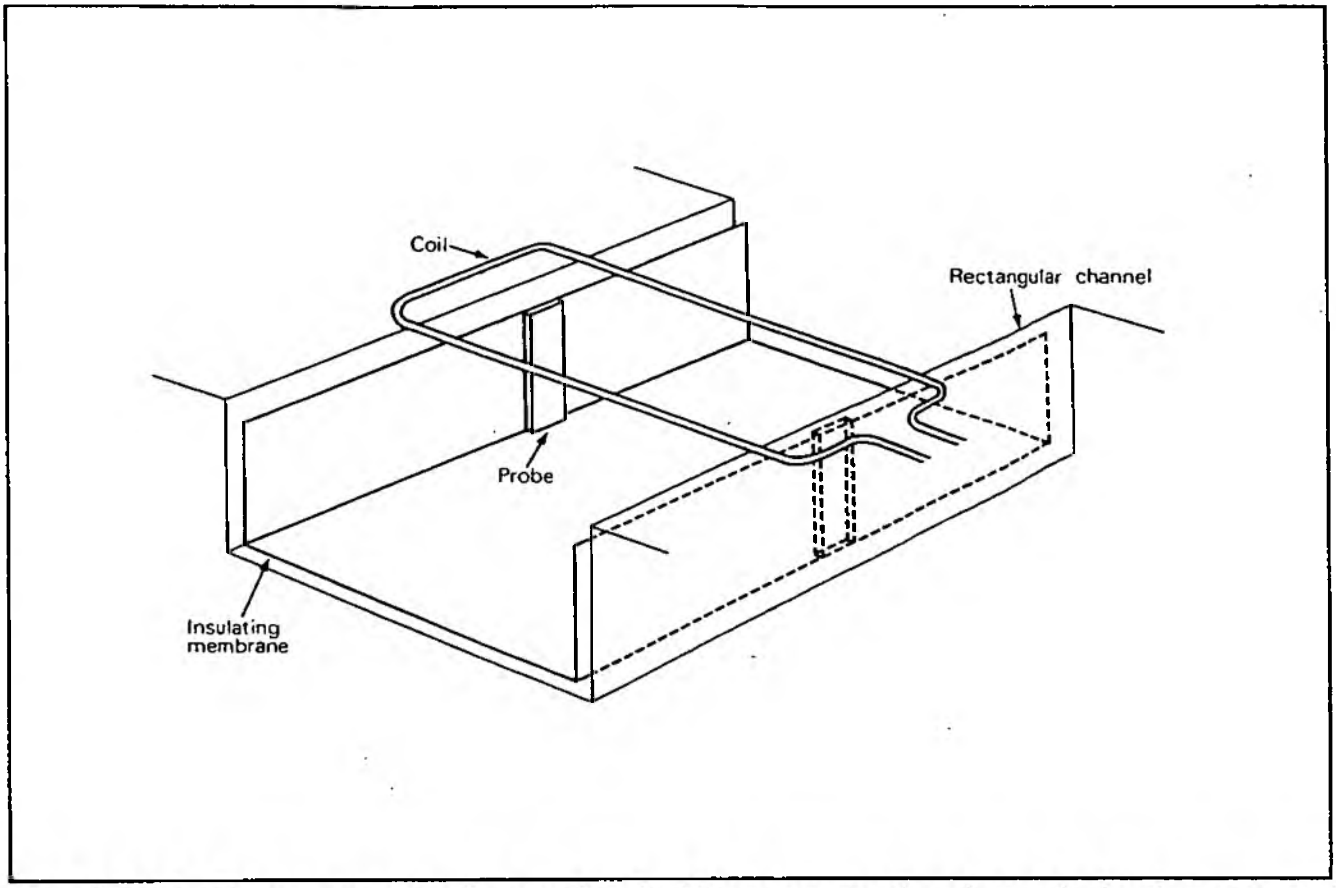


Fig A7.18 Electromagnetic method: Diagrammatic view of electromagnetic gauging station having coil installed over an insulated channel

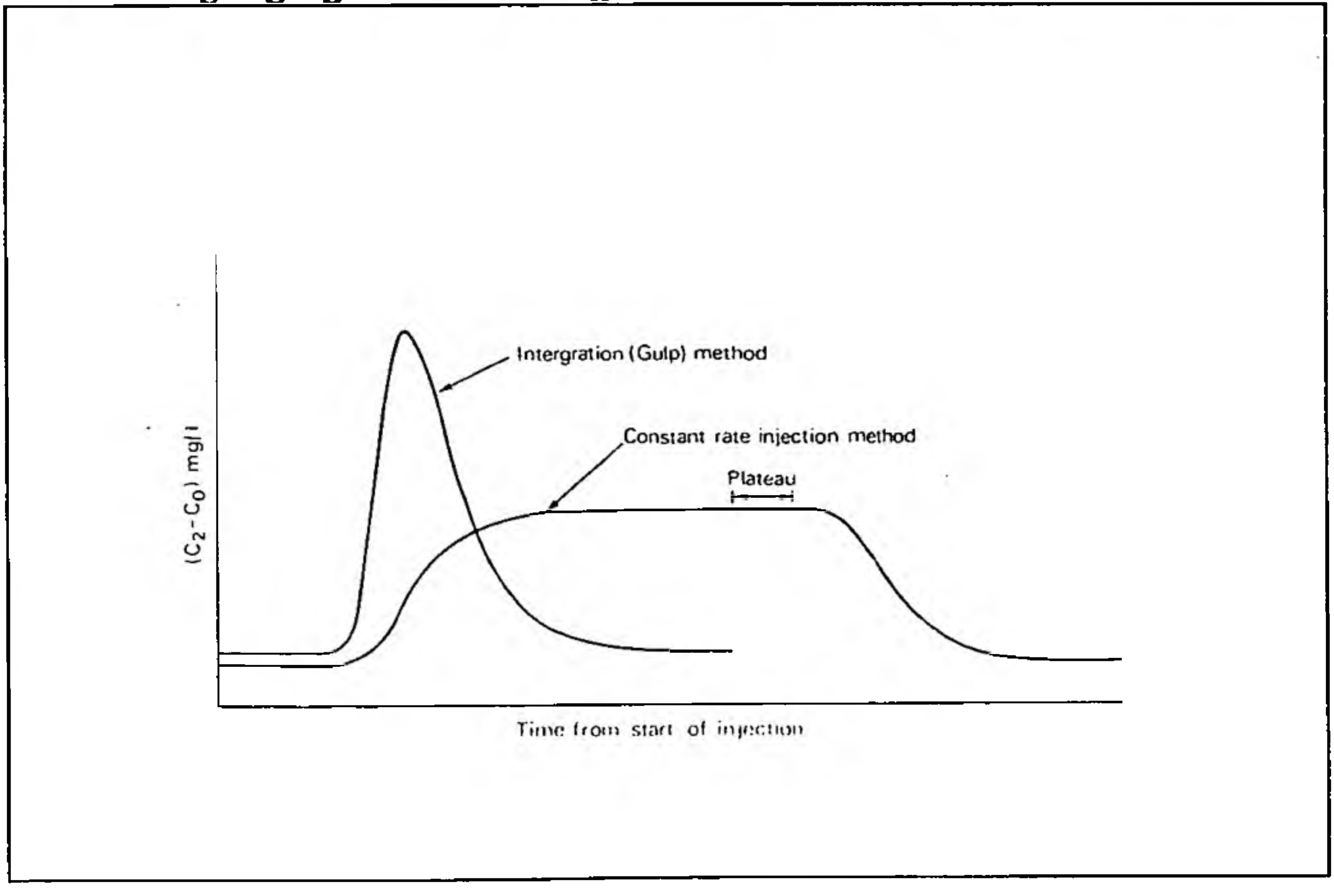


Fig A7.19 Dilution method: Typical pulse shapes for integration (gulp) method and constant rate injection method

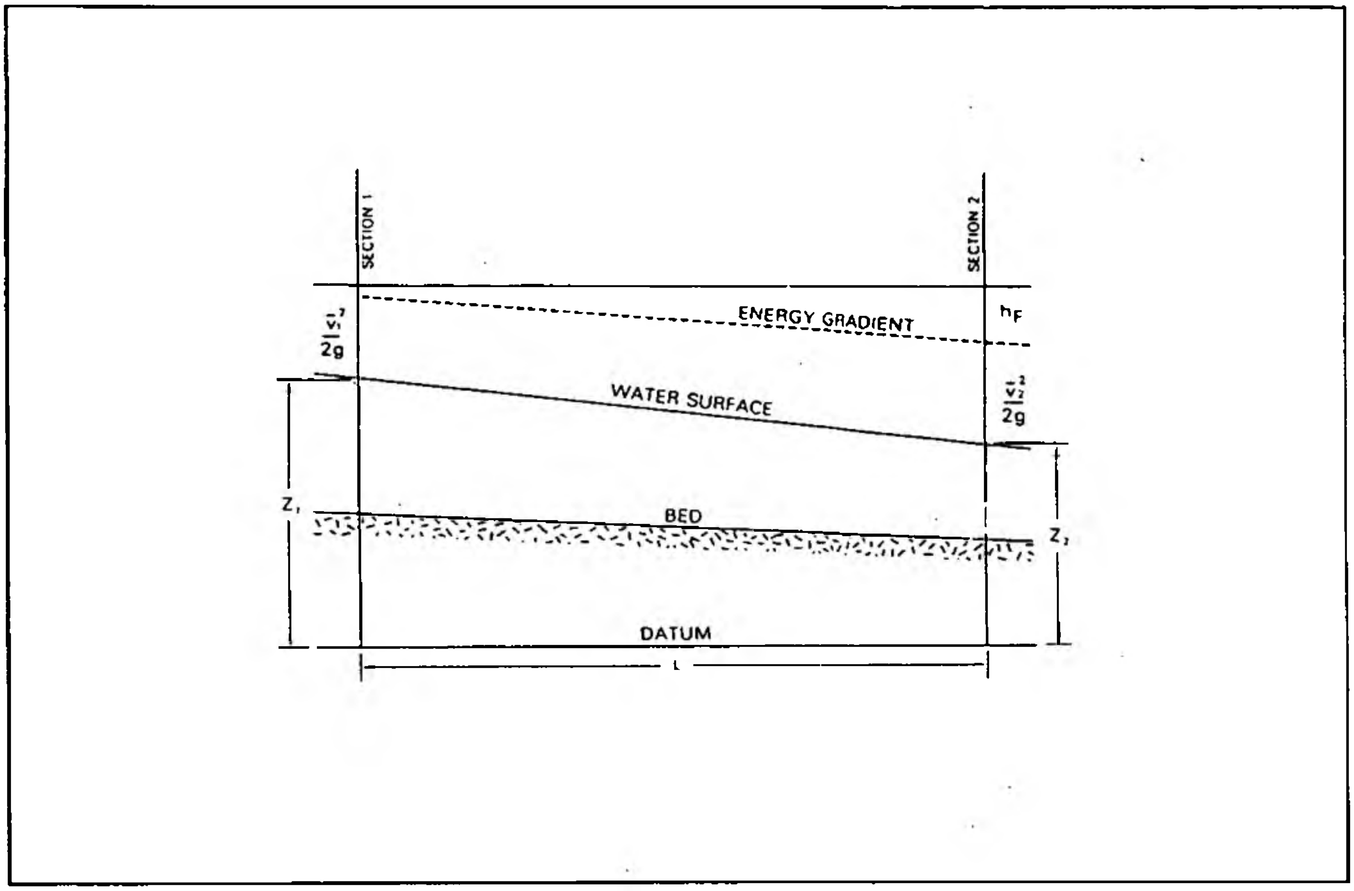


Fig A7.20 Schematic definition of a slope-area reach

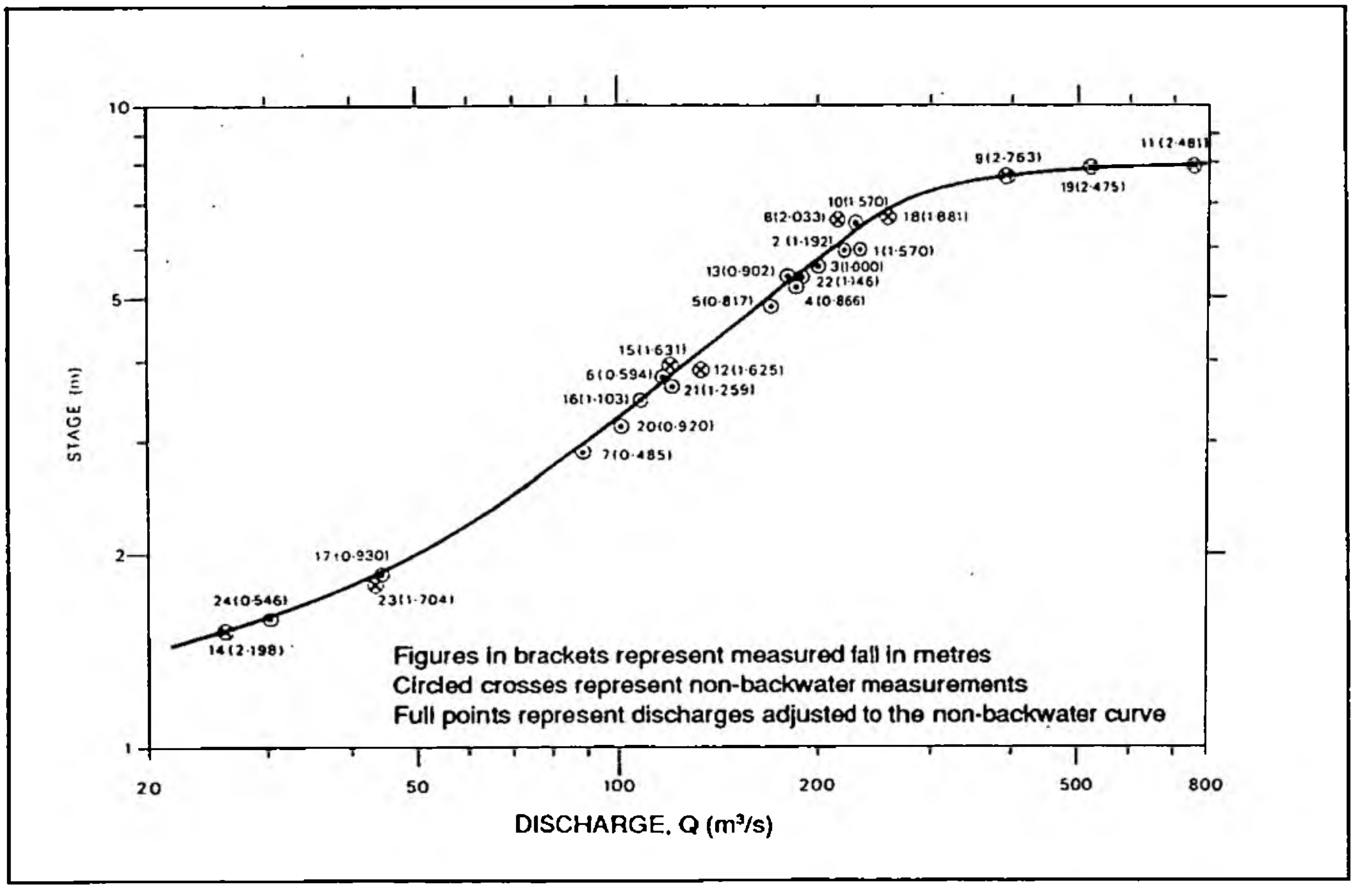


Fig A7.21 Example of stage-fall discharge rating: plot of measured discharges against stage

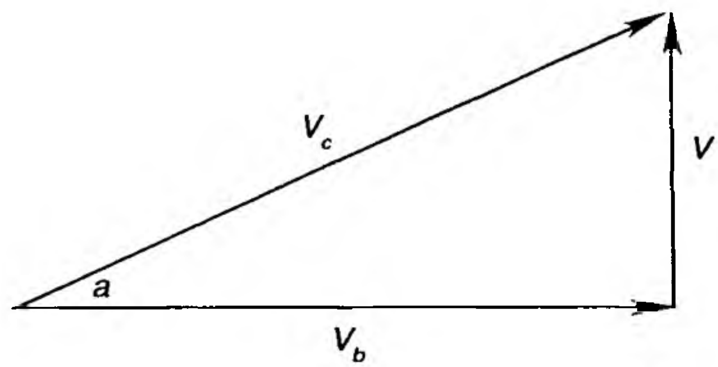


Fig A7.22 Velocity components, moving-boat method