IMPROVED MANAGEMENT AND MINIMISING UNCERTAINTY - DISCHARGE MEASUREMENT SOLUTIONS FOR IRRIGATION CHANNELS IN IRAN

AMELIORATION DE LA GESTION ET DIMINUTION DE L'INCERTITUDE – SOLUTIONS DE MESURE DE DEBIT POUR LES CANAUX D'IRRIGATION EN IRAN

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ABSTRACT

The accurate measurement of flow in irrigation network is of fundamental importance to the assessment and optimum management of Iran's irrigation water requirements. The Government of Iran through its Department of Water Resources Management (WRM), has embarked on a programme to improve the monitoring of flow in irrigation channels throughout the country. The Abtin Co, with technical support from Hydro-Logic Ltd. (UK), has been commissioned to assist with the design and implementation of flow measurement solutions. This paper outlines the flow measurement methods used, including technical background, the issues encountered with their implementation and an assessment of uncertainties in the computed discharge values.

In view of the range and variety of channel sizes and site conditions no single solution was applicable for all sites, even though the importance of standardisation was recognised. The recommended solutions consist of several techniques and technologies including rated sections (stage-discharge relationships), acoustic technologies, including bed-mounted ultrasonic Doppler and transit time systems, and the use of both existing and new flow measurement structures.

The potential uncertainties in discharge data were considered at the investigation and the design stage. It is generally believed that the network is capable of obtaining discharge data to uncertainty levels of within 10% at the 95% confidence level for the majority of the gauging stations. The development of the stage-discharge relationships and velocity index ratings will be required at rated section and acoustic installations. A range of gaugings will be undertaken at each of the discharge measurement sites for performance checking or

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calibration purposes. Calibration will be undertaken by conventional current meter gauging measurement techniques and supported by the use of Acoustic Doppler technology where appropriate. This gauging data can then be used to provide an estimate of the uncertainty in continuous discharge measurement for each site. The gauging station calibration and the determination of uncertainties are described in this paper.

Discharge data from each of the sites will be sent via GPRS telemetry, this data feed provides a means of remotely monitoring. Also, live data will be displayed at each station. The data hosting capabilities allow multiple users to access the data ensuring it can be quality checked and managed effectively.

Key words: *Irrigation canals, Discharge measurement, Uncertainty, Current meter, Doppler technology.*

RESUME

La mesure précise de débit dans le réseau d'irrigation est d'une importance fondamentale à l'évaluation et à la gestion optimale des besoins en eau d'irrigation en Iran. Le gouvernement de l'Iran à travers son Département des Ressources en Eau (WRM), a entrepris un programme visant à améliorer le suivi des flux dans les canaux d'irrigation à travers le pays. La compagnie Abtin, avec l'appui technique d'Hydro-Logic Ltd. (Royaume Uni), ont été commandés pour assister à la conception et la mise en œuvre de solutions de mesure de débit. Ce document décrit les méthodes de mesure du débit utilisée, y compris les connaissances techniques de base, les problèmes rencontrés pendant leur mise en œuvre et une évaluation des incertitudes dans les valeurs de débit calculées.

Vu l'étendue et la variété de tailles de canaux et les conditions du terrain d'échantillon, aucune solution n'a été trouvée qui aurait été valable pour tous les terrains, cependant l'importance de la normalisation a été reconnue. Les solutions préconisées comprennent de plusieurs techniques et technologies y compris les sections estimées (stade-débit), les technologies acoustiques, comme Doppler ultrasonique monté sur le billon et des systèmes du temps de transit, et l'utilisation des structures de mesure de débit, existantes et nouvelles.

Les incertitudes potentielles des données de décharge ont été examinées pendant l'enquête et la phase de conception. Il est généralement admis que le réseau est capable d'obtenir des données de décharge à l'incertitude de 10% contre la certitude de 95% pour la majorité des stations de jaugeage. Le développement des relations niveau-débit et les cotes de l'indice de vitesse seront exigés à la section nominale et les installations sonores. Une gamme de jaugeages sera menée sur chaque site de mesure de décharge pour vérifier les performances ou à des fins d'étalonnage. L'étalonnage sera entrepris par les techniques classiques de la mesure de jaugeage d'ampèremètre et il sera soutenu par l'utilisation de la technologie Acoustique de Doppler, le cas échéant. Ces données mesurées peuvent ensuite être utilisées pour fournir une estimation de l'incertitude dans la mesure de décharge continue pour chaque site. Ce document décrit la calibration de la station d'étalonnage et la détermination des incertitudes.

Les données sur la décharge de chacun des sites seront envoyées via télémétrie GPRS, ce flux de données permet de surveiller à distance. De plus, les données en direct seront affichées à chaque station. Les capacités d'hébergement de données permettent à plusieurs utilisateurs d'accéder aux données. C'est pour assurer que la qualité des données peut être contrôlée et gérée de façon efficace.

***Mots clés:** Canaux d'irrigation, mesure de débit, incertitude, ampèremètre, technologie Doppler.*

1. INTRODUCTION

Only a small proportion of Iran has sufficient rainfall for the cultivation of crops. The rest of the country has arid or semi arid climate. Therefore, it is necessary to establish a large irrigation network to provide valuable water resources. Iran has undertaken a large investment in water resources and irrigation infrastructure with a series of dams and channels to maximise its utilisation. Significant works in this regard have been accomplished since the middle of the 20th century that has helped deliver water management and developed agribusiness.

Effective monitoring of flow in the irrigation channels is important to enable timely and proactive management of the available water resource. The Iranian Department of Water Resources Management (WRM) have identified locations throughout the country where reliable, good quality flow data is required. Abtin Co in association with Hydro-Logic Ltd has been involved with the provision of flow monitoring facilities at a number of these sites. The work undertaken has included site surveys and the selection of the most appropriate flow measurement methodology for each location.

Many of the flow measurement sites identified are in newly constructed channels, while others have been used for irrigation purposes for some time. At some of the sites, flow monitoring infrastructure already existed, while at other locations no monitoring had previously been undertaken. Earlier monitoring work had included spot flow measurements from cableways and bridges using conventional rotating element current meters and the derivation of some stage (water level) - discharge relationships.

Several different flow monitoring techniques have been identified and applied based on specific site conditions. The use of a range of flow measurement techniques means that a wide range of conditions can be measured in the most accurate and cost effective manner.

2. SITE CONDITIONS

2.1 Background

The conditions of both the physical properties of the channel and the flowing body of water can have a significant impact on the ability to undertake a reliable and accurate flow measurement. These impacts can include factors such as skewed flow, entrained air, silt and weed. Some of the key issues faced and their potential impacts are indicated below.

2.2 Channel conditions

Conditions in the irrigation channels in Iran presented a range of different flow measurement challenges. Reported flows at the sites under consideration ranged from prolonged dry conditions to 90 m3s-1. As some channels were only used for limited periods the flow measurement methods selected had to be sustainable throughout prolonged dry periods so there are no problems in data quality when channels start to flow. Stage (water level) ranges at some sites were up to 7 m presenting further challenges for accurate measurement techniques throughout the range of flows. An example of a large irrigation channel is shown in Fig. 1

Fig. 1. Large irrigation Channel

The majority of the flow monitoring stations were on channels constructed for the purpose of irrigation and formed from concrete with a graduated longitudinal fall. Generally the sites were rectangular or trapezoidal concrete channels and in excellent repair, providing good flow measurement conditions.

2.3 Velocity distribution

Poorly distributed velocities or highly turbulent flow can introduce uncertainty into flow measurements. The use of field surveys prior to site and method selection is important in ensuring that reliable flow measurement can be achieved throughout the full flow range. To ensure a good velocity distribution at the point of measurement most flow measurement techniques require an optimum straight length of approach, ideally a minimum of 10 times the width of the channel.

2.4 Entrained air

Sluice gate systems particularly at dam discharge points cause a large volume of entrained air in the discharged body of water (Fig. 2), this can also occur at natural falls or at discharge points. The presence of too much air within the body of water can cause errors in velocity estimation, or complete failure when using some acoustic flow measurement technologies. In particular this applies to transit time/time of flight systems. Conversely, Doppler devices will operate well with some air in the water as long as this is not excessive.

Fig. 2. Entrained air

2.5 Silt and suspended solids

A build up of silt can impact flow measurement. In high energy systems the silt particles are held in suspension in the water and carried along with the flowing body of water. If the water is slowed down by a backwater effect then the suspended material can drop out and form a layer of silt, affecting flow measurement. Upstream of one of the measurement points a number of settlement tanks had been constructed to remove sediment from suspension in the water body before passing onto the network (Fig. 3). A build up of silt may block bed mounted ultrasonic Doppler systems and cause a change in the area or even obscure lower paths in a transit time (time of flight) system. Build up of silt at gauging structures with discharge controls can also significantly impact on the reliability of a defined rating. The occurrence of high levels of suspended solids at transit time gauging stations can cause system failure as the sound pulses may not reach their target destination.

Fig. 3. Silt settlement tanks

2.6 Non Modularity and variable backwater

If using a structure to create a stage discharge relationship or derive a theoretical flow it is important to ensure that modular flow is maintained. Modular flow means there is a change from sub-critical to super-critical flow at the structure, as the flow moves over the control. This means that the upstream water level is independent of the downstream conditions.

Sluices and controls located downstream of a measurement section may create a variable backwater effect. This in turn means that relationships between stage and flow are unstable. This issue can also occur with vegetation, as during seasons of growth there will be an increase in head for the same flow compromising any relationships between stage and flow.

2.7 Temperature

In Iran a considerable range of temperatures is experienced both in air and water. Air temperatures can vary from -20 to 60 °C. Instrumentation specifications should match the temperature ranges experienced. Cabinets with good ventilation and suitable colour coat are designed to minimise the impact of temperature extremes and to provide a safe and secure housing for equipment.

2.8 Impact of pumps

Pump systems are placed in many of the irrigation channels for water abstraction. Flow measurement should take place away from the turbulence and eddy impact zones of pumping to ensure flow measurement accuracy.

2.9 Gauging and location of suitable infrastructure

It is important to ensure that calibration and check gauging can be undertaken throughout the full range of flows. When possible flow monitoring stations should be located close to existing bridges or cableways to assist with current meter gauging. Where flow measurement structures are located in channels they should be placed close to channel crossing to allow access to both banks and help with the maintenance of stations and calibration.

3. FLOW MONITORING TECHNIQUES

3.1 Background

The range of site conditions has meant that to ensure cost effective and accurate flow measurement at the sites several different flow measurement techniques have to be employed. The number of selected techniques have been kept to a minimum so that operators are not required to be proficient with a large and diverse range of flow measurement techniques. The techniques used include:

1. Purpose built flow measurement structures that comply with the relevant International Standard: Both rectangular thin plate weirs and existing Parshall flumes presented suitable flow measurement techniques. Provided these are well maintained, constructed in accordance with the relevant standard and operated within their design range, flow measurement structures are capable of producing good quality flow data. However, the design process requires that the modular limit is maximised while the amount of afflux is minimised.
2. Rated Sections i.e. stage (water level) – discharge relationships derived by current meter gauging. These are low cost and low impact and can provide excellent means of continuous data. The problem with rated sections is that they require considerable gauging effort and the stage-discharge relationships can be unstable due to seasonal changes in vegetation growth and other variable backwater affects such as the operation of sluices.
3. Acoustic techniques: In recent years acoustic stream flow monitoring technologies have been used more extensively throughout the world as alternatives to the more conventional techniques. These can represent a cost efficient method of accurate flow measurement. They have been utilised for a range of sites and can operate in variable backwater conditions. Key methods employed in the irrigation project include both bed mounted ultrasonic Doppler devices and time of flight/transit time ultrasonic technology. The ‘time of flight’ or transit time method also has benefits in terms of reduced calibration effort.

For all flow measurement solutions good hydrometric practice must be employed to ensure recording good quality data. A key element is the accurate measurement of stage. A staff gauge should be correctly installed at all the measurement sites, these should be manufactured according to the guidelines contained in Hydrometry – Water level measuring devices (ISO 4373: 2008). As a number of the measurement locations are in trapezoidal channels sloping staff gauges can be used to provide an accurate reference check water level measurement. Sloping staff gauges need to be manufactured to suit each individual site i.e. the manufacture is dependent on an accurate survey of the slope of the channel sides.

3.2 Flow Measurement Structures

Flow measurement structures are not so widely used for new sites as they used to be since there are now more effective lower cost solutions available. However where purpose built structures are already in existence, or where existing structures can be modified, flow measurement structures can provide a robust and effective means of flow measurement at a site. The uncertainty in flow determinations for a well located and maintained site should be of the order of 5% at the 95% confidence level. Due to the nature of a structure, calibration is not usually necessary within the design flow range. In part of the project area Parshall flumes were already in place. A further thin plate weir modification was also recommended for improving an existing channel control structure.

Both of these types of structure have appropriate International Standards describing their design application and use, namely:

1. Rectangular thin plate weirs (ISO 1438:2008);
2. Parshall flumes (ISO 9826: 1992)

Rectangular thin plate weirs: The rectangular thin plate weir is a commonly used structure for providing accurate flow measurement in small open channels. The key parameters and installation and maintenance requirements are outlined in the International Standard ISO 1438: 2008. One of the main requirements for a thin plate weir is that there is good aeration of the nappe.

Fig. 4. Example of thin plate weir gauging structure

Parshall flumes: The Parshall flume is one of a large class of open channel primary structures known as critical flow Venturi flumes. It has a rectangular cross section and a unique rating based on the size of the flume. A distinguishing characteristic of the Parshall flume is the downward sloping invert of the throat. This feature gives the Parshall flume its ability to operate at higher ratios of downstream to upstream head than any other such device. The three stages of the flume include a level approach with a downward sloping throat and a diverging outlet that slopes upwards. The Parshall flume acts a short throated flume with the control located near the end of the level floor in the converging section. A Parshall flume is shown in Fig. 5.

Fig. 5. Parshall flume

Unlike long throated flumes (ISO 4359: 1983 {revised edition to be published in 2012}), the formula/stage-discharge relationships for which are based on hydraulic theory, Parshall flumes are based on laboratory testing. They come in a number of sizes which have been the subject of detailed hydrometric assessment under laboratory conditions. Therefore, a new construction has to be built in exact accordance with a specified size. The head measuring device is located in the converging throat of the flume at the exact position specified in the ISO standard. Check gauging is recommended to ensure that the structure is performing correctly.

3.3 Stage-Discharge Relationships

The stage discharge technique relies on a natural or artificial control that provides a fixed and stable relationship between the discharge and the upstream water level (stage). By undertaking a range of calibration gaugings the relationship between an observed stage and its corresponding flow can be defined. A good fall was noted at a range of the sites providing ideal conditions for this solution.

The principles of the stage discharge technique are outlined in the International Standard ISO 1100-2 :1998 –Measurement of liquid flow in open channels- Part 2 : Determination of the stage discharge relationship. A new version is due to be published in 2011. This will outline the minimum requirements for accurate flow measurement using this technique. ISO 1100-2 recommends that a minimum of 15-20 gaugings are undertaken to define the stage-discharge relationship. The stage-discharge relationship is often defined by one or more shifted power law equations of the form:

$$Q = (h - a)^{\beta} \qquad \text{Equation (1)}$$

Where, Q = discharge (m^3s^{-1}), h = stage (m) and C, a, β are constants.

In order to undertake the stage measurement, the most cost effective and robust means was to install a pressure sensor appropriate for the design stage range, paired with a data logging device.

3.4 Acoustic Flow Measurement Techniques

3.4.1 General

In challenging hydrometric conditions there can be significant advantages in utilising acoustic flow monitoring techniques. There are four main categories of acoustic technologies that are currently used for velocity, and thus flow, determination.

Acoustic flow monitoring techniques include:

1. Bed mounted devices that are based on the Doppler shift principle – these only sample a portion of the channel. The portion sampled is usually unknown.
2. More sophisticated range gated devices based on acoustic Doppler current profiler (ADCP) technology
3. Echo correlation devices - these look like bed mounted Dopplers but are based on a somewhat different principle.
4. Time of flight/transit time ultrasonic.

Following the investigations of site details it was decided that the use of both time of flight / transit-time ultrasonic and bed mounted Doppler devices would be appropriate for some of the sites.

3.4.2 Transit time / time of flight ultrasonic

Transit time ultrasonic river gauging is based upon the principle that the time taken for sound pulses to be transmitted through flowing water over a known distance, is different to the time taken for the pulse to travel the same distance when that water is stationary (ISO6416:2004). When pulses are transmitted at an angle to the direction of flow the speed of the pulse in the downstream direction will be enhanced by the flow of water whilst, returning in the upstream direction, the speed of the pulse will be impeded by the flow. The difference in the travel times in each direction between the same points will be proportional to the component of water velocity along the "flight path" taken by the signal. The timing difference referred to is very small (of the order of millionths of a second) but can be measured accurately electronically and the resolved component of mean velocity of water along the flight path calculated. A level sensor is also incorporated into the system. This technology has been successfully used in stream flow measurement since the nineteen seventies.

Using such systems velocities can be measured at different levels or paths. If there are sufficient paths operating within the cross-section and these are well distributed throughout the water column these devices are capable of returning accurate determinations of flow with little calibration effort. They work particularly well in clear water which is a problem with some of the Doppler technologies which require particles or reflectors in the water to function. These systems are ideally suited to installation in the concrete channel sections seen throughout the majority of the irrigation sites. These provide excellent fixing points and for the trapezoidal channels a bespoke fixing bracket allows the paths to be configured accurately. An example of the probes used is shown in Fig. 6.

Where flow measurement is required in sections with skewed flow, downstream of bends in the irrigation system, a cross path system has been specified. This measures velocity in both directions across the channel width and therefore provides a more accurate determination of flow by removing bias. The paths are offset to measure a range of levels through the vertical section, maximising measurement accuracy.

A further application was used installing the time of flight system in much smaller sites than usually applied. This involved the use of a single pair of transducers measuring velocity along a single path. As water level varies what this single path represents in the vertical section will change and therefore it is necessary to undertake a velocity index calculation based on a series of flow gaugings under different conditions (see Section 3.5).

Fig. 6. Time of flight probe

3.4.3 Doppler devices

The Doppler method is based on the principle named after Christian Doppler 1843 (ISO 15769:2010). Sound is transmitted from the device and reflected from particles in the water column, the reflected sound is measured by a receiver on the instrument. The transmitter and receiver have overlapping fields and the angle of this enables a shift in frequency to be measured that is used to infer the velocity of the particle and therefore the water body carrying the particle. The ultrasonic Doppler flow meters were originally developed for use in sewer systems where they have been widely and successfully used for a number of years. It is only more recently that they have been used in larger open channels and natural watercourses. Most ultrasonic Doppler systems will only sample velocity in a portion of the open channel. The size of the portion sampled is dependent on several factors. These include the spread and angle of the acoustic beam (a torch beam is a good analogy), the other design characteristics of the sensor e.g. how the sound is transmitted, received and processed and the physical characteristics of the channel e.g. the dimensions of the channel and the amount of suspended solids. Some simpler systems have failed when used in clear streams during periods when there are very few suspended particles in the flowing water.

One of the main problems in using these systems is ascertaining what portion of the channel has been sampled. Therefore, it is often necessary to derive a relationship between the measured and the mean velocity in the cross-section. This requires current meter gauging, which can be used as an index velocity to determine the mean velocity in the measuring section. This is sometimes referred to as the velocity index technique. These systems also generally have an in-built water level sensor. The profiling range of the velocity sensor is limited and may be reduced by changes in suspended material. For example if there is an increase in sediment the acoustic beam will penetrate less of the vertical velocity profile as the signal is restricted by the particle matter in the water.

These bed mounted devices were used on sites within the irrigation project where there was insufficient depth for a transit time system or a suitable stable control to develop a stage-discharge relationship. In order to achieve a critical minimum depth water level can be raised by means of a downstream control structure.

3.4.4 The use of velocity index rating techniques

Velocity index techniques, such as those required when using the Doppler technology, are velocity area methods. Discharge is therefore determined using the continuity equation,

$$Q = \overline{V} \times A \qquad \text{Equation (2)}$$

Where

Q = discharge (m^3s^{-1})

= mean velocity at instrument measuring section (ms^{-1})

A = cross-sectional area at instrument measuring section (m^2)

For many installations the velocity determined by the instrument will not be the same as the mean velocity in the measuring section since in most channels the instrument will not sample the whole of the flowing cross-section. The mean velocity is determined by using a relationship between the mean velocity and the instrument velocity, usually referred to as the index velocity. Velocity index relationships can take the following general forms:

$$\overline{V} = fn(V_i) \qquad \text{Equation (3)}$$

$$\overline{V} = fn(V_i, h) \qquad \text{Equation (4)}$$

Where

Vi = instrument/index velocity (ms^{-1})

h = stage (m)

The cross-sectional area is determined using a relationship between stage and cross-sectional area. This can be determined by cross-sectional survey.

The computation process is summarised as follows:

1. Mean velocity is determined from the velocity index rating, using the measured velocity and, for more complex ratings, also the stage;
2. The cross-sectional area is determined from the stage via a stage area relationship, look-up table or direct calculation from cross-sectional survey data directly input into the instrument;
3. The corresponding mean velocity and cross-sectional are multiplied to obtain the discharge.

4. DATA MANAGEMENT

4.1 Background

The effective management of the irrigation network across Iran is supported by the timely feed of flow data from the monitoring points to the operational control centre. This has been achieved by using a suite of Isodaq GPRS data enabled loggers. These transfer data from the sites on a daily basis to a central holding database system. The system is web based. Therefore, data can be accessed by any user who has the unique sign in name and password. This data handling site allows graphical display and download of the sites to ensure that the irrigation network can be measured effectively. Live displays through the processing device or the logger are also made available at each site for data quality assessment.

4.2 Logging Systems

Two types of logger have been utilised at the sites depending on the flow measurement methodologies used. Where an alternative display is available on a primary system e.g. a transit time processing unit a GPRS logger with no display is used to transfer data. At stage discharge and structure sites where no display is available from the sensor system a logger with integrated display has been used Fig. 7. This has a display screen and the facility to incorporate a stage-discharge relationship table into the logger so that discharge can be displayed on site. Where possible these logging systems are located in a control room to improve security and functionality.

Fig. 7. Logging devices at a Parshall Flume gauging station

All data is logged at 15 minute intervals, this has been globally adopted as an appropriate time interval in obtaining a representative flow in surface water applications. Groundwater systems are generally logged at an hourly interval. It is possible to alter all these systems logging intervals to ensure an appropriate degree of data is issued at all times.

4.3 Data Interface

The data interface used allows users to interact with the data and display graphs and data from the gauging station network. This can be shown in a map format for easy identification and management. The interface with the loggers allows remote configuration, helping to effectively manage field sites remotely. The operation of the irrigation network can be assisted by a series of alarm thresholds that can trigger text and email alarms when key parameters rise or fall through a defined threshold.

Data can be viewed on time series graphs that can be scaled over a range of time periods to help identify trends in data and ensure that the water resource is being monitored effectively. Data can be exported from the data management software in a range of formats for further data interpretation and archiving on operational databases.

A typical plot of the daily feed of flow data from the sites is shown below. This data is from the two Parshall flume structures and shows head (upstream water level), tail (downstream water level) and calculated flow.

Fig. 8. Typical data presentation

5. UNCERTAINTIES

5.1 Background

All hydrometric measurements are subject to errors. Error is the difference between the true value and the measured value. As the true value is unknown, it is not possible to determine the error. Therefore, the uncertainty of a measurement is estimated which is the range in which the true value is expected to lie. Normally the uncertainty is estimated at the 95% confidence level (two standard deviations). This means that there is a 95% probability that the true value will lie within the estimated uncertainty limits.

As stated in the EN ISO 25377:2007 'Hydrometric Uncertainty Guidance'

"All measurements of a physical quantity are subject to uncertainties.....The result of a measurement is only an estimate of the true value of the measured quantity and therefore is only complete when accompanied by a statement of its uncertainty."

And

"The discrepancy between the true and measured values is the measurement error. The error, which cannot be known, causes uncertainty about the correctness of the result."

Hydrometry is not a precise science and it is important that the users of hydrometric data are made aware of the uncertainties in the flow determinations. The uncertainty in a stream flow measurement is a combination of a number of individual measurement and assumption uncertainties. The individual uncertainties are normally combined in quadrature.

The ISO recommends that uncertainties should be estimated in the first instance, at the 68% confidence level (1 standard deviation). However, for most hydrometric applications uncertainties are expressed at the 95 % confidence level (2 standard deviations).

5.2 Uncertainties in Flows Derived using Measurement Structures

The uncertainty (U^*_c) for a flow measurement structure is a combination of the combined uncertainties in the discharge coefficient (C_e), the structure geometry and the stage. The uncertainty in the geometry for a rectangular notch is the uncertainty in the width (b). For a v-notch the uncertainty in the geometry is the uncertainty in tan(α/2) where α equals the notch angle. The stage uncertainty (he) is a combination of instrument and gauge zero uncertainties and can be estimated as follows:

$$u^*_{he} = 100\frac{\sqrt{u(h_e)^2 + u(E)^2}}{h_e} \qquad \text{Equation (5)}$$

Where u(he) is the absolute uncertainty in the instrument measurement and u(E) is the absolute uncertainty in the stage zero for a given stage he.

The overall uncertainty for rectangular notch is given by the following equation:

$$U^*_c(Q) = \sqrt{u^*(C_e)^2 + u^*b^2 + (1.5u^*(h_e))^2} \qquad \text{Equation (6)}$$

An uncertainty curve for a full width rectangular notch 3 m wide and 0.5 m high, operating within its design range, is shown in Figure 9. It has been assumed that the uncertainty in the stage measuring instrument is 2 mm and the gauge zero uncertainty is 1 mm at the 68% confidence level. The minimum recommended operating stage for a rectangular notch is 30 mm which corresponds to a discharge of 0.029 m^3s^{-1} for which the estimated uncertainty at the 95% confidence level is about 12.3 %.

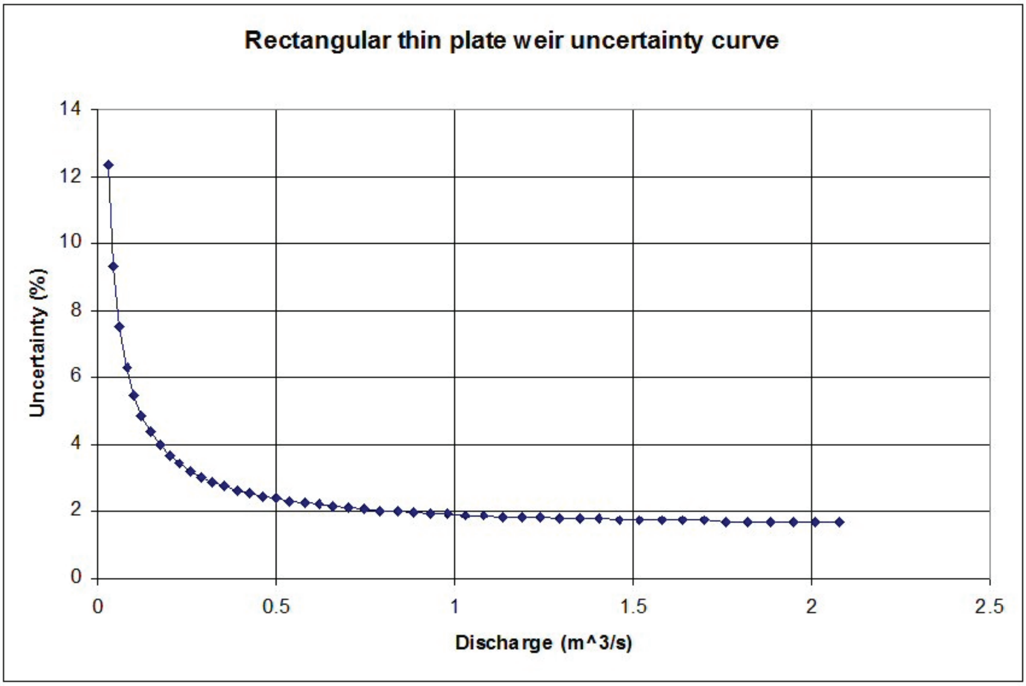

Fig. 9. Example of an uncertainty curve for a thin plate weir

By far the most significant source of overall uncertainty is the uncertainty in the stage measurement. At the majority of the sites good quality low range, pressure transducers/transmitters are used. If the level range of the pressure transmitter is not greater than 3 m, these should be capable of measuring water level to 3 mm when set-up correctly.

Generally a well constructed and maintained flow measurement structure operating within its design range should be capable of delivering flow data to within 5 – 10% at the 95% confidence level (two standard deviations).

5.3 Uncertainties using Other Techniques

5.3.1 Velocity index techniques

The overall uncertainty can be obtained by combining the component uncertainties in quadrature. The component uncertainties are those related to the velocity index rating, the index/instrument/measured velocity, the cross-sectional area/stage area relationship and the overall uncertainty in the stage. The largest source of uncertainty is generally in the velocity index rating. Provided this is relatively stable and is defined by a reasonable amount of gaugings (min. 10 – 15) over the target flow range, it should be possible to determine discharge to within 10%.

5.3.2 Time of flight/transit time ultrasonic

The overall uncertainty is a function of uncertainties due to the limited number of paths (pairs of transducers) and their distribution in the vertical, the instrument calculated velocity, the width measurement and the stage or depth measurement. The largest source of uncertainty is likely to be the former. However, with a four path system with a well distributed array of transducers it should be possible to determine discharge at the 95% confidence level to within 5 – 10%.

5.3.3 Rated sections

The uncertainties associated with rated sections are a function of the stability and sensitivity of the control, the number of gaugings that have been used to derive the stage-discharge relationship and the overall uncertainty in the stage measurement. For stable controls a minimum of 15 gaugings is usually recommended (ISO1100-2:1998) over the target flow range. For stable controls it should be possible to determine discharges to within 10% but where variable backwater occurs due to variations in seasonal weed growth the uncertainties could be significantly larger. However, as most of the sites in the Iranian irrigation channels where stage-discharge relationships have been used are very good controls, uncertainties of 5 – 10% are readily achievable.

6. CALIBRATION AND MAINTENANCE

6.1 Background

To achieve good quality reliable data attention must be given to high quality calibration and maintenance in the field. If a solution requires calibration this must be done over the full flow range to minimise errors through extrapolation. Maintenance is recommended on a routine basis, with monthly visits considered good practice.

6.2 Current Meter Gauging

The key method of calibrating or checking a station is by gauging the flow with a current meter. A number of different methods of flow gauging have been adopted in hydrometry. The most applicable methods for the channels encountered in Iran are rotating element current meters or Acoustic Doppler Current Profilers (ADCPs).

Current meter gauging has been, and still is, undertaken using rotating element current meters (cup/bucket and impeller meters). These determine the velocity at the point where the instrument is placed in the measuring section. In recent years, electromagnetic and ultrasonic Doppler meters have been increasingly used by some organisations. Spot flow gauging is undertaken using the velocity area method, where a cross-sectional area is defined and velocities are measured at a number of verticals (positions across the measuring section). Flow is a product of velocity multiplied by area. Under low flow gaugings in smaller channels current meters are deployed by wading. In larger channels and for higher discharges, bridges and cableways (see Figure 10) are used.

Fig. 10. Gauging cableway

The procedures for current meter gauging are outlined in the International Standard ISO:748: 2007. The recommended number of verticals for channel widths is shown in Table 1.

Table 1 Recommended number of verticals for current meter Gauging (Source: ISO 748: 2007)

Channel width (m)	ISO 748: 2007
>0 & <0.3	5 to 6
>0.3 & <0.5	5 to 6
>0.5 & < 1	6 to 7
>1 & < 3	7 to 12
> 3 & < 5	13 to 16
>5 & < 10	≥22
> 10	≥22

6.3 Acoustic Doppler Current Profilers (ADCPs)

A more recent method of gauging open channels is the Acoustic Doppler Current Profiler (ADCP). The ADCP uses a similar principle to a bed mounted device by reflecting acoustic signals from particles carried in the water column. The instruments are mounted on a small boat or floating platform and are moved slowly across the surface of the water between the two banks. Through a phased array of four transducers the instrument will measure velocity in a conical sphere below the sensor face. The instrument will also measure direction and depth providing a cross-sectional area. ADCP technology remains relatively expensive and limits are in place regarding its distribution. It does however represent the most, robust and cost efficient means of flow gauging in many of the larger channels seen in the irrigation network, particularly those carrying significant volumes of water where health and safety becomes an issue.

6.4 Flow Validation

A key element of ongoing data quality assessment is confirming that the flow measurement method is still providing accurate measurement. This involves undertaking a flow gauging and confirming that the reported flow from the station is within acceptable limits. If measurements lie outside the acceptable limits then possible causes such as changed controls or maintenance issues must be examined.

6.5 Ongoing Maintenance

A key factor in the quality of hydrometric data is the maintenance of a gauging station. This includes checking for sensor drift against a fixed datum and ensuring that the station is clean and well maintained.

The presence of silt has been noted at a number of sites in Iran. If this is dropped from suspension in the water column and deposited on the bed then measurement accuracy can be affected. This can change the area of a site, obscure sensors and make gauging more challenging thereby increasing uncertainties. High quality routine maintenance must be undertaken at all flow measurement sites to ensure that they are operating within their hydrometric limits.

Fig. 11. The problem of silt accumulation and vegetation growth

Algal build up on a flow measuring structure can introduce significant errors in calculated flow. This impact is particularly critical on the sites where a concrete structure is used to provide a control for stage discharge rating assessment. In addition seasonal vegetation growth can make stage-discharge and velocity index ratings very unstable. Crests of control structures and gaugeboards should be cleaned on a routine bases to ensure that they do not impact on measurement accuracy and introduce errors or uncertainties to a data set.

7. STANDARDS

It is essential that both continuous and spot flow calibration measurements are undertaken in accordance with sound hydrometric practice. This can be achieved if the design, installation, operation and maintenance of the gauging stations and undertaking of calibration gaugings are in accordance with the relevant International Standards. There are appropriate standards for all the techniques described in this paper and used on the Iran irrigation network flow monitoring project with the exception of the application of ADCPs. However, a draft standard on the use of ADCPs will hopefully be published in 2012.

The relevant standards are summarised in Table 2:

Table 2: Summary of relevant International standards

ISO Standard No.	Subject matter	Reference No.
748	Current meter gauging	3
1100-2	Stage-discharge relationships	4
1438	Thin plate weirs	5
4373	Water level measuring devices	6
6416	Time of flight/transit time ultrasonic gauges	7
9826	Parshall Flumes	8
15769	Continuous flow measurement using acoustic technologies other than time of flight and velocity index ratings	9
24578 (draft)	Application of ADCPs	Pub. 2012
25377	Hydrometric uncertainty	11

ISO hydrometric standards have been drafted by committees with expert representation from a number of countries and provide good guidance on hydrometric practice. However, the authors are of the opinion that standards are a compromise between practices in different countries. As such they should generally be used as the norm or the minimum requirement and not as rigid guides.

8. SUMMARY

The rehabilitated irrigation channel flow monitoring network consists of a mixture of flow measurements structures, rated sections, time of flight ultrasonic and other acoustic gauging stations. This network should be capable of providing flow data with uncertainties of within 5 – 10% at the 95% confidence level at all but the most extreme flows provided the stations are operated in accordance with good hydrometric practice. However, in order to achieve this level of uncertainty it is essential as for all hydrometric networks a regular maintenance programme is agreed and implemented

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ISO 748:2007 Hydrometry – Measurement of liquid flow in open channels using current-meters or floats

ISO1100-2: 1998 Measurement of liquid flow in open channels- part 2: determination of the stage-discharge relationship

ISO 1438:2008 Hydrometry – Open channel flow measurement using thin plate weirs

ISO 4373:2008 Hydrometry – Water level measuring devices

ISO 6416:2004 Hydrometry – Measurement of discharge by the ultrasonic (acoustic) method

ISO 9826: 1992 Measurement of liquid flow in open channels -- Parshall and SANIIRI flumes

ISO 15769 2010: Hydrometry – Guidelines for the application of acoustic velocity meters using the Doppler and echo correlation methods

EN ISO TS 25377:2007 Hydrometric Uncertainty Guidance