

Evaluation of an indirect method for measuring irrigation water abstracted from rivers with centrifugal pumps

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Dissertation summary

Evaluation of an indirect method for measuring irrigation water abstracted from rivers with centrifugal pumps

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Although a wide range of flow measurement devices and methods already exist for the measurement of irrigation water, water users and water management officials still claim there is a need for more appropriate devices that are non-intrusive, reliable, easy to install and maintain, and cost effective. Meters that are typically used for irrigation water measurement were tested in a laboratory as an initial part of the research and measurement errors larger than $\pm 10\%$ of the actual discharge was recorded.

This study was aimed at evaluating an experimental measuring method that may meet the requirements of the users.

The experimental method is based on the unique relationship between the differential pressure and the discharge of a specific pump. By determining this relationship for a specific pump over a range of operating conditions (but for specific installation conditions), a curve similar to the pump curve as developed by the pump manufacturer can be established. If this relationship is inversed (into a discharge-differential pressure relationship), it can be used to calculate the discharge of the pump by measuring the differential pressure. The volume of water discharged by the pump over a period of time can then be determined by integrating the calculated discharge over time.

Laboratory tests were conducted to evaluate the validity of the proposed measuring method. The tests entailed the development of the discharge-differential pressure relationship for the specific pump being used, by simultaneously measuring the system discharge, and pressure at both the suction and delivery sides of the pump.

Once the relationship had been developed, a set of independent tests was conducted and the pressure measurements used to calculate the discharge through the system. The calculated discharge values were then compared with the measured values.

The experimental measuring method was also evaluated in the field through empirical testing of its application in the field. The necessary equipment was installed and calibrated at an irrigation system pump station at the Orange-Riet Water User Association, and data collected over a two week period.

The laboratory evaluation of the proposed measurement method produced favourable results, with the analyses showing that discharge can be “measured” with this method at errors smaller than $\pm 5.4\%$ of the reference reading within a specified range of flow rates, which is better than the errors produced by the conventional meters evaluated during the initial part of the research.

The field tests showed that the method can be applied successfully to monitor pump abstractions. The method’s results were compared to two reference measurements and it was found that the volume of water abstracted according to the experimental method was within $\pm 2.6\%$ of the reference measurements.

The field work also showed that from a practical application point of view, the method has definite advantages over the conventional meters, although it is not less expensive than other measuring devices. The advantages include easier installation, high turn-down ratios, low maintenance requirements, no additional head loss, and suitable for telemetric data collection.

Further work that is required include investigations on the use of a differential pressure transducer (rather than two separate suction and delivery side transducers), since this may reduce costs and the number of recorded data points, as well as evaluations of the validity of the discharge – differential pressure relationship over a long period of time, since it may change due to wear on the pump or motor.

Samevatting van verhandeling

Evaluasie van 'n indirekte metode vir die meting van besproeiingswater wat onttrek word uit riviere met sentrifugaal pompe

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Alhoewel daar alreeds 'n wye verskeidenheid van vloeimeters en meetmetodes bestaan vir die meting van besproeiingswater, beweer watergebruikers en waterbestuursbeamptes steeds dat daar 'n behoefte bestaan vir meer toepaslike toerusting, wat betroubaar, gebruikersvriendelik en bekostigbaar is. Die akkuraatheid van tipiese besproeiingswatermeters is in 'n laboratorium getoets, en daar is bevind dat die meters foute groter as $\pm 10\%$ van die ware vloeitempo registreer.

Hierdie studie het dit ten doel gestel om 'n moontlike nuwe meetmetode wat bogenoemde tekortkominge oorkom, te evalueer.

Die voorgestelde metode is gebaseer op die unieke verband wat daar bestaan tussen die differensiële druk en die vloeitempo van 'n spesifieke pomp. Hierdie verband kan voorgestel word deur 'n kromme wat soortgelyk is aan 'n konvensionele pompkromme soos deur pompvervaardigers verskaf. Die inverse van die verband (met ander woorde, 'n vloeitempo-differensiële druk verband) kan dan gebruik word om die vloeitempo te bereken indien die differensiële druk gemeet word. Om die volume water wat oor 'n periode van tyd gepomp is te bepaal, kan die berekende vloeitempo's ge-integreer word oor die periode.

Laboratoriumtoetse is uitgevoer om die geldigheid van die metode te evalueer. Toetse is uitgevoer om die vloeitempo-differensiële drukverwantskap te bepaal vir 'n spesifieke

pomp, deur die vloeitempo, suigkantdruk en leweringskantdruk gelyktydig te meet by 'n aantal dienspunte.

Nadat die verband bepaal is, is 'n nuwe toets uitgevoer en die gemete drukwaardes gebruik om die vloeitempo te bereken. Die berekende vloeitempo-waardes is met die gemete waardes vergelyk.

Die voorgestelde metode is ook deur middel van empiriese toetse in die veld ge-evalueer. Die nodige toerusting is geïnstalleer en gekalibreer by 'n pompstasie by die Oranje-Riet Watergebruikersvereniging, en data is versamel vir 'n periode van twee weke.

Die laboratoriumtoetse het positiewe resultate getoon. Na analisering van die data is daar bevind dat die metode gebruik kan word om die vloeitempo te bepaal binne ± 5.4 % van die ware vloeitempo, wat beter is as die konvensionele meters wat getoets is.

Die veldtoetse het getoon dat die metode wel suksesvol aangewend kan word om pomp onttrekkings te monitor. Die resultate van die eksperimentele meetmetode is vergelyk met twee verwysingsmeetmetodes, en daar is gevind dat die resultate binne ± 2.6 % van die ware gepompte volume was.

Die veldwerk het ook getoon dat die eksperimentele metode definitiewe voordele inhou in vergelyking met konvensionele meettoerusting wanneer dit kom by praktiese implementering.

Verdere aspekte wat aangespreek moet word, sluit die gebruik van een differensiële druksensor (in teenstelling met twee afsonderlike suig-en leweringskant sensors) in, aangesien dit die koste en datavolume kan verminder, asook die evaluering van die moontlike verandering van die vloeitempo – differensiële drukverwantskap met tyd, as gevolg van slytasie in die pomp en motor.

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List of Symbols

$E_{\%CS}$	Error in percent comparison standard discharge	%
$E_{\%FS}$	Error in percent full scale discharge	%
g	Gravitational acceleration	m/s^2
H	Pump head	m
H_o	Pump head at $Q = 0$	m
H_{opt}	Pump head at optimum discharge point	m
Δp	Pump differential pressure ($p_d - p_s$)	Pa
p_d	Discharge pressure gauge reading	Pa
p_s	Suction pressure gauge reading	Pa
Q	System discharge	m^3/h
Q_i	Indicated discharge from device being tested	m^3/h
Q_{CS}	Comparison standard discharge as measured with another device of known accuracy	m^3/h
Q_{FS}	Full scale or maximum discharge of the device being tested	m^3/h
v_d	Velocity in discharge branch, m/s	m/s
v_s	Velocity in suction branch, m/s	m/s
Z_d	Elevation of discharge gauge above datum elevation, m	m
Z_s	Elevation of suction gauge above datum elevation, m	m

List of acronyms

ASME	American Society of Mechanical Engineers
CMA	Catchment Management Agency
DWAF	Department of Water Affairs and Forestry
NPSH	Net Positive Suction Head
NWA	National Water Act (Act 36 of 1998)
NWRS	National Water Resources Strategy
WMP	Water Management Plan
WRC	Water Research Commission of South Africa
WUA	Water User Association

1. Introduction

1.1 Background

Irrigated agriculture accounts for almost 60 % of water used in South Africa (Department of Water Affairs and Forestry, 2002), compared to 25 % used for urban requirements and the remaining 15 % used by the mining, industrial, power generation, afforestation and rural sectors. The direct contribution by the agricultural sector to the GDP is only about 4.5 %, of which an estimated 25 to 30 % is from irrigated agriculture. Furthermore, employment by the agricultural sector accounts for 11 % of the total national employment, but only 10 to 15 % of this is in the irrigated agricultural sector. Therefore, the economic impact of the water used for irrigation is considered very low compared to other sectors, and industrialists often consider irrigation as a waste of water and not economically justifiable.

Farmers obtain irrigation water in various ways. Water can be abstracted from rivers or boreholes, or run-off collected in farm dams by individual farmers. Alternatively, farmers on irrigation schemes may share a diversion structure and canal or pipeline to receive their water. The infrastructure may have been developed by the farmers themselves, in which case it would have been managed by an irrigation board consisting of farmers, or by government, in which case the Department of Water Affairs and Forestry would have been responsible for management.

In order for the Department of Water Affairs and Forestry to monitor the abstracted volume, a variety of flow measurement devices and methods have been developed and used since irrigation water measurement became compulsory in 1984 (Kriek, 1986). The readings taken from these devices were generally used as basis for water accounts sent to farmers, who reputedly developed many ingenious ways of reducing the accuracy of the devices (in their favour) by tampering with the mechanisms in ways that could be interpreted as "accidents".

1.1.1 Legal requirements

In 1998, the previous water law was replaced by the National Water Act (Act 36 of 1998), which is to be implemented through the National Water Resources Strategy (NWRS), which makes provision for, amongst others, the establishment of Catchment Management Agencies (CMAs) and Water User Associations (WUAs) in

each of the 19 water management areas in the country, as declared in Government Notice 1160 in October 1999 (Department of Water Affairs and Forestry, 2000).

The CMAs are statutory bodies, established by Government Notice, with jurisdiction in a defined water management area. The functions and responsibilities of the CMAs include the development of catchment management strategies, management of water resources and co-ordination of water-related activities, and any other functions delegated by the Minister.

WUAs are co-operative associations of individual water users who wish to undertake water-related activities at a local level for their mutual benefit. They operate in terms of a formal constitution and are expected to be financially self-supporting from water use charges paid by members. A WUA falls under the authority of the CMA in whose area it operates, if the agency has received powers from the Minister to operate the WUA's activities. According to Schedule 5 of the Act, one of the functions of a WUA can be "to supervise and regulate the distribution and use of water from a water resource according to the relevant water use entitlements, by erecting and maintaining devices for measuring and dividing, or controlling the diversion of the flow of water".

Through the constitution and business plan it must be shown how "the WUA makes progress towards measuring the quality and quantity of inflows and outflows, losses and water supplied to its customers, and towards the use of acceptable measuring devices or techniques." (Department of Water Affairs and Forestry, 2000)

Further provisions for monitoring and information systems for water resources, and responsibilities for providing water-related information, are provided in Chapter 14 of the Act. The Act empowers the Minister to require any person to provide data and information, either on an ad hoc or regular basis, for the national monitoring and information system, to facilitate the management and protection of resources (Department of Water Affairs and Forestry, 2002).

The strategy and implementation of the business plans are currently being tested through three pilot studies on the development of water management plans for the Gamtoos, Orange-Riet and Orange-Vaal WUAs. The Water Management Plans that will be the results of the project should reflect the current and expected water demand as well as proposed water conservation measures. At all three WUAs,

water measurement is considered of fundamental importance for water management, but the cost of providing and installing the necessary infrastructure causes concern amongst the farmers as well as the water management staff.

1.1.2 Practical measuring requirements

Except for the legislative reasons for measuring irrigation water, many other benefits related to practical water management, are derived from upgrading water measurement programs and systems, some of which are the following (United States Bureau of Reclamation, 1997):

- Accurate accounting and good records help allocate equitable shares of water between competitive uses both on and off farm.
- Good water measurement practices make record keeping possible, resulting in fewer problems and easier operation.
- Accurate water measurement provides the on farm decision-maker with the information needed to achieve the best use of the irrigation water available while minimising negative environmental impacts.
- Installing canal flow measurement structures reduces the need for time consuming current metering, which is frequently needed after making changes of delivery and to make seasonal corrections for changes of boundary resistance caused by weed growth, sectional bank slumping or sediment deposits.
- Instituting accurate and convenient water measurement methods improves the evaluation of seepage losses in unlined channels. Thus, better determinations of the cost benefits of proposed canal and ditch improvements are possible.
- Permanent water measurement devices can also form the basis for future improvements, such as remote flow measurement and canal operation automation.
- Good water measurement and management practice prevents excess run-off and deep percolation, which can damage crops, pollute ground water with chemicals and pesticides, and result in drainage flows containing contaminants.
- Accounting for individual water use combined with pricing policies that penalise excessive use, can be implemented.

1.1.3 Current status

In order to review the measurement situation in terms of the new National Water Act, a three-year research project funded by the Water Research Commission of South Africa was initiated in 2001 and is currently being conducted by the Department of Civil and Biosystems Engineering of the University of Pretoria together with the Agricultural Research Council's Institute for Agricultural Engineering and NB Systems (Van der Stoep, Benadé & Smal, 2002). The main objective of the project is to develop guidelines for the choice, installation and maintenance of water measurement devices by the WUAs for canal, pipeline and river distribution systems.

As part of the project, more than 30 groups of stakeholders in some of the prominent irrigation areas in South Africa were interviewed and sites visited to establish what the current status of irrigation water measurement is. It was found that despite the legislative and practical reasons for measuring irrigation water as well as the availability of measuring devices for irrigation water, it has been poorly implemented and was usually reverted to as a last resort to solve water management problems. This reluctance was motivated by claims of high cost of devices and installations, as well as poor reliability and accuracy of available devices.

1.1.4 Pumped irrigation abstractions

One of the applications of irrigation water measurement that was found to be a major concern to WUAs and DWAF, is the measurement of pumped abstractions from rivers. On most of the country's larger rivers there are farmers who abstract water individually with mostly centrifugal pumps. If the flow in the river is destined for water users lower down the river, there may be restrictions on water abstractions and the pumps need to be monitored. According to DWAF (Bosman, 2001) on the Vaal River between the Vaal Dam and the confluence of the Vaal and Orange Rivers, it is estimated that there are at least 3000 river pumps being operated. The middle and lower parts of the Orange River (downstream of the Vanderkloof Dam) is also considered a problem area, although some attempts are now being made to control new developments through monitoring irrigated areas with satellite imagery.

Measuring individually owned pumped water abstractions have been done mostly with mechanical flow meters up to now, but problems are often encountered and

there is a general lack of faith in the instruments amongst water management staff and water users. Some of the causes of the failures are described below.

1.1.5 Available measuring devices and their shortcomings

1.1.5.1 Direct measuring methods

There are presently mainly two types of meters generally used for measuring pipe flow on irrigation schemes, i.e. mechanical rotor type meters and electromagnetic flow meters.

The mechanical rotor type meters are widely used on irrigation schemes, being the most affordable option and not requiring electricity for operation. However they are easily affected by physical obstructions, accidentally or intentionally. The two most commonly encountered meters were manufactured by Sparling and SA Liquid Meters in the 1980s, but neither are in production any longer and spare parts are unavailable.

Electromagnetic meters are probably the most ideally suited for irrigation water measurement, with no moving parts that can wear out and no obstructions in the flow path of the water. However, these meters require electricity to operate and can cost up to 10 times as much as a mechanical meter (Van der Stoep, Benadé & Smal, 2002).

The factors that complicate the installation and management of devices for the measurement of water abstraction at remote points along a river can be summarized as the following:

- *Quality of the water*

One of the constraints mentioned most often by water management staff of the WUAs, is the problems caused by physical and chemical impurities in the water. Physical impurities include water grass, sticks, frogs, sand, silt, or any other object or substance that can be conveyed by the water. The larger objects can get stuck in the rotor of a flow meter, and sand or silt can cause excessive wear of the meter's mechanisms or casing, thereby affecting meter accuracy and necessitating expensive maintenance.

The chemical quality of irrigation water abstracted from rivers is often poor due, firstly to groundwater return flows containing a large amount of salts that have been leached from the irrigated fields adjoining the river, and secondly from reduced natural flow in the river caused by diversion structures or upstream control (limited releases from a dam in the river). Poor quality water also causes excessive wear of the meter mechanisms and casing, or it may cause precipitation and chemical reactions in the meter.

- *Cost of the measuring device*

In all discussions with water users or management staff on water meters, the issue of cost is brought up. A major concern is the initial cost of the meter and installation; although a commercially available meter can be bought and installed for less than R10000.00 on most irrigation pipe systems (usually smaller than 300 mm in diameter), most farmers use more than one pump, at different sites, to abstract water. For example, at the Orange-Vaal WUA in the Northern Cape, the average number of pumps operated per farmer is four. It is estimated that on the Vaal River part of the WUA control area there are at least 400 pumps, meaning that the initial cost of supplying and installing meters in this area alone could be as high as R 4 million. Since the meters will be the property of the WUA, the initial cost will have to be carried by it through a loan and then recovered from the water users (Van der Stoep et al, 2002).

Although this cost could be discounted over a number of years to make it more affordable, the water users have indicated during interviews that they do not feel that the installation of meters would have any effect on their water use (increasing efficiency) and they could not see how the cost of the meters would be recovered, therefore feeling that the expense of measuring water use at farm level could not be justified in the first place. Measurement of the bulk water abstracted for the WUA as a whole catchment management purposes was considered to be a more sensible investment.

If meters were to be installed at individual pumps, it would also require regular maintenance and calibration, which would mean further cost to the WUA. Some other constraints include the following:

- *Existing pipe systems*

Most of the meter installations required at pumped river abstractions are at existing pumping systems. In order for the meter to operate correctly, most flow meters require a straight section of pipeline of at least 5 (preferably 10) times the diameter of the pipe in front of the meter, and at least 3 (preferably 5) times the diameter after the meter to ensure a fully developed turbulent flow profile in the meter. At most pipeline systems these requirements cannot be met without major changes in the existing pipeline, which often requires construction at the pump station.

The installation of a flow meter increases the head loss in the system, and if a reduction in pipe diameter is required, this may also affect the duty point of the pump and influence the pressure available at the irrigation system at the end of the pipeline. It may be the case that the pump cannot meet the additional pressure head requirements and the installation will then influence the efficiency of the irrigation system.

1.1.5.2 Alternatives to direct measuring methods

In a quest to overcome the above-mentioned constraints and other limitations, water management staff at WUAs have developed methods to determine water use by measuring a parameter that is related to the pumping system and deriving the discharge from a predetermined or calibrated relationship between the system discharge and the measured parameter.

The most common application of this method is where the WUA monitors the pump hour or kilowatt-hour meters on the pumps' motors. The power-discharge relationship is determined by measuring discharge with a portable flow meter (typically an acoustic transit time or Doppler meter) and simultaneously measuring the power consumption of the motor. The method however is not very accurate since the relationship may vary at a single pump depending on the water level on the suction side of the pump, the discharge rate, the head loss in the system, etc. Due to all the variables that are not taken into consideration, previous investigations by MBB Consulting Engineers (1997) have shown that errors of up to 50 % can occur.

The advantages of the indirect measurement methods include that they are usually non-intrusive, therefore not causing any obstruction in the flow path, and can more

easily be added to an existing system without major construction or alteration to the pipeline. However, disadvantages include the fact that the devices are electrically operated and still not 100 % tamper-proof.

1.1.6 Experimental measuring method

A possible alternative method that could overcome some of the constraints which conventional meters are subject to, is based on the unique relationship between the discharge and differential pressure of a specific pump. The pump differential pressure is the increase in pressure that takes place between the suction and the discharge branches of the pump (SIHI Group, 1985).

By performing a pump test where the discharge or flow rate (Q) and differential pressure (Δp) can be measured simultaneously, the data which is obtained can be used to determine the discharge – differential pressure relationship for a specific pump for a range of operating conditions (but for specific installation conditions, such as the positioning of the pressure transducers). If this relationship can be described by a mathematical function where the discharge is a function of the differential pressure, the function can be used to calculate the discharge from a differential pressure measurement. The volume of water discharged by the pump over a period of time can then be determined by integrating the calculated discharge over time.

The experimental measuring method is described in detail in section 2.4.

1.2 Problem statement

Due to legislative requirements and greater pressure on available water resources for primary use, the use of measuring devices by irrigation water users have become imperative. Although a wide range of flow measurement devices and methods already exist for the measurement of irrigation water, water users and water management officials claim that there is a need for more appropriate devices that are non-intrusive, reliable, easy to install and maintain, and cost effective. Alternative methods of estimating irrigation water use do exist, but are generally more suitable as planning tools or rely on flow-related parameters that may vary over time.

DWAF and WUAs needs to monitor and control the diversion of water at numerous abstraction points from surface water sources where unlawful abstractions can lead

to water shortages in other areas. The cost of supply, installation, monitoring and maintenance of mechanical flow meters is seen as major constraint by many WUAs. Furthermore, previous use of these type of meters have been largely unsuccessful due to the devices' susceptibility to damage (intentional and unintentional), leading to a general lack of faith by both water users and water management staff in the devices' output.

A possible alternative method to measure pumped abstractions is to make use of a discharge – differential pressure relationship for a specific pumping system that have to be determined through in-field measurements. By integrating the discharge over a specific period of time, the volume of water pumped during the period can be determined. The method needs to be evaluated to determine whether it is valid and whether it can work in practice.

1.3 Objectives

The overall objective of the study was to evaluate the experimental measuring method , as described in section 1.1.6 above, in terms of its validity and usefulness in practice.

The specific objectives of the study are the following:

- To conduct a literature study on devices used for irrigation water measurement and related research conducted on the subject in South Africa and internationally
- To evaluate the principle of the experimental measuring method through laboratory tests
- To evaluate the experimental measuring method under field conditions
- To identify advantages and disadvantages of the experimental method, and evaluate the feasibility of applying the method in practice
- To compile a report on the project findings and make recommendations for further work

1.4 Scope of the study

The application of the experimental measuring method is limited to raw water being pumped by a centrifugal pump into a pipe line leading to an irrigation system where it is discharged under pressure. The pump can be operated at more than one duty point, but all possible duty points have to be considered when determining the discharge – differential pressure relationship. This relationship will be unique for every pump, and also for the same pump at different installations. The relationship and duty points may change over time due to wear of equipment or changes to the irrigation system.

Laboratory tests were conducted to evaluate the validity of the discharge – differential pressure relationship and its application for volumetric flow measurement purposes. No long-term tests were conducted in the laboratory.

1.5 Methodology

1.5.1 Literature study

A literature review on the conventional measurement methods presently being used for this specific application were performed.

The theory and principles of the experimental measuring method are described in detail. As background for the experiments that were undertaken, an overview of standards and norms for centrifugal pump system testing and pump differential head measurement were completed.

The issues related to measurement accuracy and uncertainty were also addressed in the literature study.

1.5.2 Materials and methods

The experimental work that was conducted during a two year period as part of the study consisted of five phases, of which an overview is presented in section 3.1. The results of the principle laboratory and field evaluations are presented in the main report while the results of work conducted during the earlier stages of the project are attached in Appendices A, B and C.

1.5.3 Analysis and report

The data from the laboratory and field evaluations was analysed and is presented in Chapter 4 of this report. Conclusions and recommendations based on the technical results are presented in Chapter 5.

2. Literature study

2.1 Introduction

2.1.1 Flow meter definition

All fluid meters consist of two distinct subunits: a primary device that interacts with the fluid and the secondary element that translates the interaction into flow quantities (volumes or weights) or discharge (quantity per unit time) that can be observed and acted on by a human operator or by control equipment (Replogle, Clemmens & Bos in Hoffmann, 1991).

The Instrument Society of America (ISA) gives the following definitions related to flow meters (Miller, 1989):

Flow meter: A device that measures the rate of flow or quantity of a moving fluid in an open or closed conduit. It usually consists of both a primary and secondary device.

Flow meter primary device: the device mounted internally or externally to the fluid conduit which produces a signal with a defined relationship to the fluid flow in accordance with known physical laws relating the interaction of the fluid to the presence of the primary device.

Flow meter secondary device: the device that responds to the signal of the primary device and converts it to a display or to an output signal that can be translated relative to the discharge or quantity.

Both the primary and secondary devices can consist of one or more elements to perform its specific function.

2.1.2 Flow meter classification

Flow meters can be classified in various ways, for example according to the principle upon which the meter operates, or the primary device, or the output it produces (discharge or quantity), or the application (natural waterways, open channels, or closed conduit).

Miller (1989) suggests classifying meters as either square-root (differential producer) or linear meters because, he argues, that all meters for which the flow is not a function of the square-root of the differential pressure are essentially linear meters.

Differential producer flow meters' operation is based on a physical phenomenon in which a restriction in the flow line creates a pressure drop that bears a relationship to the discharge. This phenomenon is based on fluid dynamics principles described by the continuity equation, and Bernoulli's equation (Crabtree, 2000).

Examples of the primary elements used in differential-producer flow meters are orifice plates, venturis and flow nozzles. These flow meters have along history of use in many industrial process measurement and control applications, and are renowned for their simplicity and accuracy. For irrigation water measurement applications, however, these meters are seldom used, mainly because it usually contains an element that obstructs the flow, or because air gets trapped in the lead lines to the pressure measurement devices.

In the case of the linear flow meters, the primary element of the meter produces an output signal of which the frequency or magnitude increases linearly with the flow velocity (and therefore also with the discharge).

Linear meters can be grouped as pulse-frequency type and linear-scale type meters (Miller, 1989). Turbine and vortex shedding flow meters are examples of the pulse-frequency type, and produce a signal with a frequency proportional to the flow velocity. Most irrigation meters presently in use are propeller or turbine type meters. Linear-scale type meters include magnetic and ultrasonic (acoustic) flow meters, which both have the advantage of measuring flow without obstructing the flow path, but are considerably more expensive than the other types of meters.

2.1.3 Flow measurement units

Flow meters can produce output in either discharge or volumetric units. Most mechanical (pulse-frequency linear) type meters display measurement in volumetric units; therefore only the volume of water that had passed through the meter since the previous reading is known, and not when it was abstracted and at which rate.

Although the volumetric readings form the basis of most WUAs' water pricing strategies, the abstraction rate and timing is of importance for water management in some cases, and can provide useful information for the WUA.

In order to obtain discharge data from pulse-frequency type meters, it has to be fitted with a frequency converter or other device that can record the number of pulses and when they occur. These devices usually require an external electrical power source.

In order to obtain volumetric data if discharge readings are taken, the discharge has to be measured and recorded at short intervals, in order to integrate the flow over time, producing the volume.

2.1.4 Meter calibration

Most flow meters are supplied as a pre-calibrated independent unit with installation requirements to ensure that the meter operates as intended. Since it is an independent unit, it can be calibrated in a flow laboratory according to acceptable national or international standards.

The two standard methods used for liquid flow meter calibration, are the weighing (mass) and volumetric methods. According to Miller (1989), these methods are described in ISO 4185 (1985) and ISO DIS 8316 (1987) respectively, but it is also briefly described here.

The weighing method includes both a static and a dynamic method.

In the static method, the flow is diverted into a collection tank located on a weighing mechanism at the start of the test, and then diverted from the tank after a certain time. The difference in mass in the tank between the end and the start of the test is equal to the mass that had passed through the meter.

The dynamic method requires the mass measurement to be made under steady discharge conditions.

The accuracy of these methods is determined through an uncertainty analysis taking into account bias and random errors.

The volumetric calibration method involves the measurement of the volume of liquid that had passed through the meter, either under static or dynamic conditions, through diversion of the liquid into a calibrated vessel.

2.1.5 Factors influencing flow meter selection

In irrigation systems, water measurement at pumped abstractions are dependent on a number of site-specific factors that can influence the selection of a suitable flow meter.

In its Water Measurement Manual, the United States Bureau of Reclamation (1997), identifies and discusses the following 18 factors for consideration:

- Accuracy requirements
- Cost
- Legal constraints
- Range of discharge
- Head loss
- Adaptability to site conditions
- Adaptability to variable operating conditions
- Type of measurements and records needed
- Operating requirements
- Ability to pass sediment or debris
- Longevity of device for given environment
- Maintenance requirements
- Construction and installation requirements
- Device standardization and calibration
- Field verification, troubleshooting and repair
- User acceptance of new methods
- Vandalism potential
- Impact on environment

During discussions with water management officials and farmers in South Africa, the factors probably mentioned most often were the need for robustness and durability of the device together with the ability to pass debris; secondly cost, and thirdly resistance against vandalism (Van der Stoep et al, 2002).

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Factors that were found to be often overlooked until installation of a device were head loss, construction and installation requirements, and field verification of the meter readings.

2.2 Measurement accuracy

Accuracy can be defined as “the closeness of agreement between the result of a measurement and the true value of the measurand” (Miller, 1989). It is therefore the interval within which the true value of the measured quantity can be expected to lie within a stated probability (usually 95 % unless otherwise specified).

Users of water measurement devices generally depend upon manufacturers to calibrate meters and provide assurances of accuracy, since few users have the facilities to check the condition and accuracy of flow meters.

Miller (1989) and the United States Bureau of Reclamation (1997) describe how the accuracy of a meter is specified by the manufacturer over a flow range, which is defined between a certain minimum and maximum discharge where the meter produces acceptable performance. The accuracy is usually determined through error analysis of data obtained from simultaneous measurements taken with the meter being tested and another measurement device of known accuracy.

These kinds of comparison tests enable manufacturers of meters to develop “accuracy envelopes” within which a meter is said to have specified accuracy under reference conditions. An example of an accuracy curve and envelope is shown in Figure 2.1.

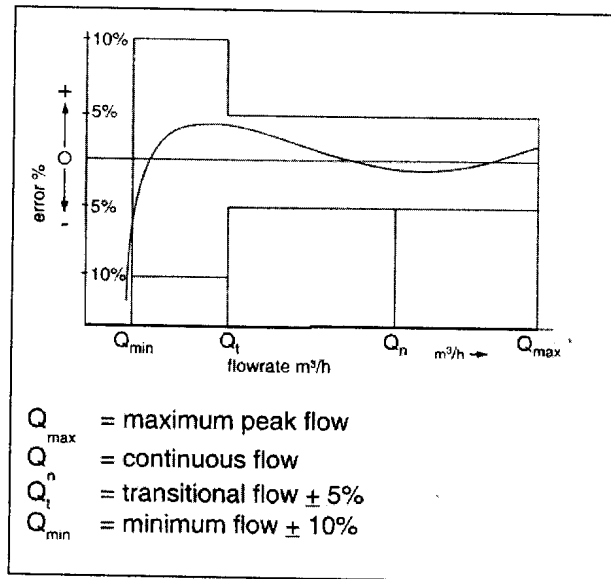


Figure 2.1 Example of a meter accuracy curve (Meinecke Meters, 2001)

In this example the manufacturer specifies that the meter's maximum measurement error will be $\pm 5\%$ of the real value if the meter is operated within the flow range between the transitional discharge, Q_t , and the maximum discharge that the meter can handle, Q_{max} . If the discharge is between the minimum recordable discharge, Q_{min} , and Q_t , the measurement error will be less than $\pm 10\%$.

2.2.1 Factors that influence measurement accuracy

Dunnicliff (1988) identified seven types of measurement errors that may occur:

- Gross error
- Systematic error
- Conformance error
- Environmental error
- Observational error
- Sampling error
- Random error

Miller (1989) and the United States Bureau of Reclamation (1997) defined three broader categories of error which includes the seven types recognized by Dunnicliff (1988). Different terms are used by the two sources to describe the same types of error, as shown in Table 2.1.

Table 2.1 Equivalent terms for types of error (USBR ,1997 and Miller, 1989)

Type of error		Possible cause of error	Effect on recorded data
USBR (1997)	Miller (1989)		
Spurious	Outlier	Incorrect reading taken by operator	Data points falls well outside the expected random statistical distribution about the mean
Systematic	Bias	Device used for comparison gives incorrect readings	The mean of the data points falls on one side of the true value
Random	Precision	Device used for comparison not read precisely	Data points are randomly scattered about the mean

If the results of a test can be represented as marks on a target as shown in Figure 2.2, a systematic (bias) error would result in a distribution of marks as shown in Figure 2.2 (a), and a random (precision) error in a distribution as shown in Figure 2.2 (b).

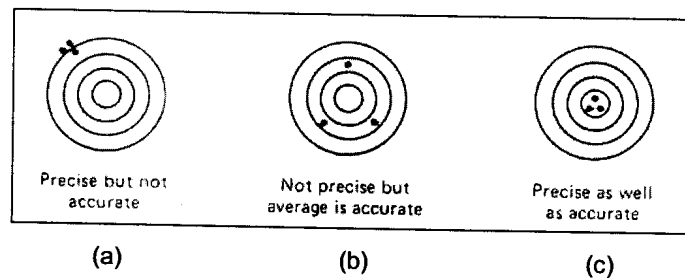


Figure 2.2 Difference between systematic and random errors (Dunnicliff, 1988)

Errors may be due to a number of factors, which can be related to the equipment used or the operator (or a combination), including nonlinearity, hysteresis, incorrect calibration, incorrect installation, bias, and reading, recording or computing mistakes.

The total error of importance for manufacturers is the result of the combination of systematic and random errors caused by components of the entire measurement system.

2.2.2 The effect of installation on accuracy

Common installation guidelines usually prescribe that a straight section of pipe, 8 to 10 times the pipe diameter in length, be installed directly upstream from a flow meter, and a straight section 3 to 5 times the diameter in length downstream from the meter, to reduce errors due to excessive turbulence, and to ensure that there is a fully developed velocity profile in the pipe. However, it is often found that these guidelines are not adhered to with irrigation systems, especially when pumping plants are constructed by farmers, or where a meter have been installed some time after the rest of the piping had been put in place.

Hanson & Schwankl (1998) investigated the error in discharge measurements under nonoptimal conditions caused by a 90 degree elbow, a non-return valve and a partially open butterfly valve. The flow meters that were used included two turbine type meters, two differential head meters (pitot tube type), two impeller type meters, and an ultrasonic meter. Results showed that the turbine type and differential pressure type meters were the least affected by excessive turbulence, with all the meters strongly affected by the partially open butterfly valve.

Zimmermann (1999) investigated the effect of disturbed flow on a differential head (orifice plate) meter, and recorded deviations of up to 31 %. Replogle (1999) also recognised that installation guidelines were often not adhered to with irrigation water meter installations.

Cipindu & Wantenaar (2000) investigated the effect of various installation deviations on inferential meters for domestic water measurement, and found that if meters that were meant to be installed horizontally, were installed at an angle of 45 degrees instead, errors greater than 10 % of the real values were recorded at low discharges. They also reported inaccuracies can be due to problems with the counter (totalisers) of the meters.

2.2.3 Accuracy calculations

The accuracy of a water measurement device is commonly expressed as a error percentage of either the comparison standard discharge (or the actual discharge),

measured with another device of known accuracy, or the upper range value (URV or also called the full scale value) of the device being tested.

In the first case, the measurement error can be mathematically expressed as:

$$E_{\%CS} = \frac{100(Q_i - Q_{CS})}{Q_{CS}} \dots\dots\dots(1)$$

where

- $E_{\%CS}$ = error in percent comparison standard discharge
- Q_i = indicated discharge from device being tested
- Q_{CS} = comparison standard discharge as measured with another device of known accuracy

Comparison standard discharge is also sometimes called the actual discharge, but it is an ideal value that can only be approached by using a much more precise and accurate method or device than the one being tested.

The error as a percentage of full scale can be calculated from:

$$E_{\%FS} = \frac{100(Q_i - Q_{CS})}{Q_{FS}} \dots\dots\dots(2)$$

where

- $E_{\%FS}$ = error in percent full scale discharge
- Q_{FS} = full scale or maximum discharge of the device being tested

2.3 Measurement methods currently being used

The current practices for the measurement of irrigation water resulted from an instruction issued in 1984 by the then Department of Environmental Affairs, that all new irrigation water abstraction works had to be fitted with flow meters. The implementation of this instruction was done according to guidelines set out by a water meter committee consisting of the section engineers of the Department of Water Affairs (Kriek, 1986).

In the report Kriek (1986) evaluated differential head, positive displacement, electromagnetic, acoustic and mechanical rotor type (inferential) meters, finding only

the last two types suitable for irrigation water measurement, but recommended that the mechanical rotor type meter was the most appropriate since the other two methods require electricity to function. The devices and methods currently being used are briefly described here.

2.3.1 Inferential (mechanical rotor type) meters

Inferential meters have rotor-mounted blades in the form of a vaned rotor or turbine which is driven by the water at a speed proportional to the discharge. The number of rotor revolutions is proportional to the total flow through the meter and monitored by either a gear train, or by a magnetic or optical sensor (Crabtree, 2000).

Distinction can be made between turbine (Woltman) meters, propeller meters and impeller meters, based on the orientation of the vaned rotor in relation to the flow.

2.3.1.1 Turbine meters

The turbine meter usually comprises of an axially mounted bladed rotor running on bearings or a bush and mounted concentrically within the flow stream by means of support struts.

The axle may be positioned either horizontally or vertically as shown in Figure 2.3. The vertical turbine is said to be subject to less bearing friction and is therefore more sensitive. However, it provides more obstruction to the flow through the meter is more likely to be affected by physical impurities often found in irrigation water.

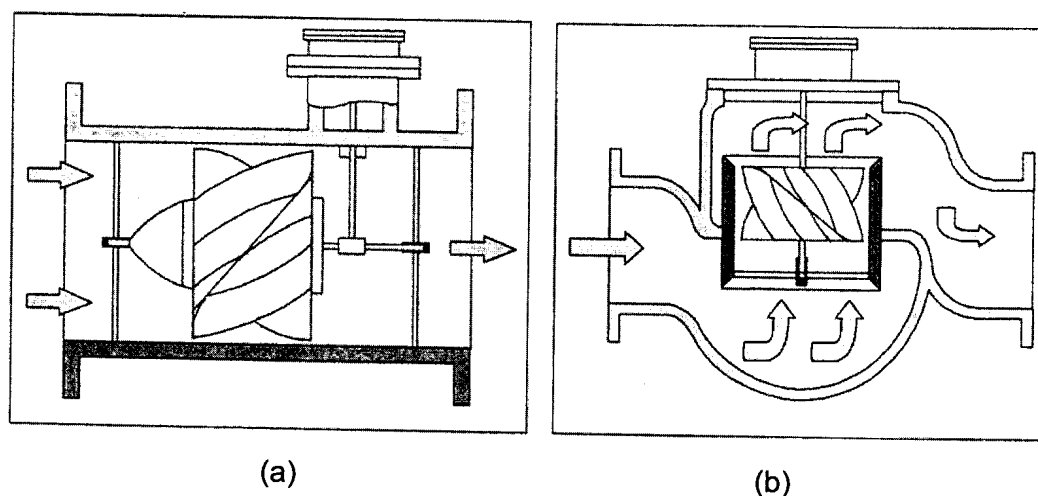


Figure 2.3 (a) Horizontal and (b) vertical turbine meters (Crabtree, 2000)

The measurement of the turbine's rotation can be done by means of either a magnet, fitted within the rotor assembly which produces a single pulse per revolution in an externally mounted pick-up coil, or a low friction gear train connecting the axle to the totaliser.

2.3.1.2 Propeller type meters

This type of meter incorporates a long axle at the end of which the propeller is mounted, with the body of the meter at the other end of the axle and out of line of the flow stream, as shown Figure 2.4. The working part of the meter can be removed easily without dismantling the whole installation, but the meter's performance is lower than the turbine type meters usually due to the position of the measuring element relative to the flow profile in the conduit (Crabtree, 2000).

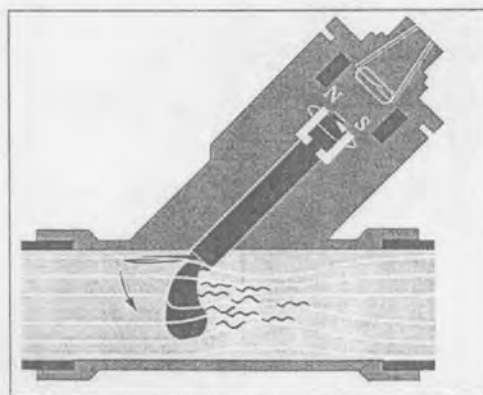


Figure 2.4 Propeller type meter with magnetic totaliser sensor (Crabtree, 2000)

Meters found on irrigation schemes are usually fitted with a mechanical gear train connecting the axle to the totaliser.

2.3.1.3 Impeller type meters

The rotating blades of the impeller meter are perpendicular to the flow, making it inherently less accurate than the turbine meter. At low discharge readings, it is possible that the water cannot maintain the force needed to overcome bearing friction, impeller mass inertia and drag, and at high readings, cavitation can occur and cause readings that are higher than the actual discharge.

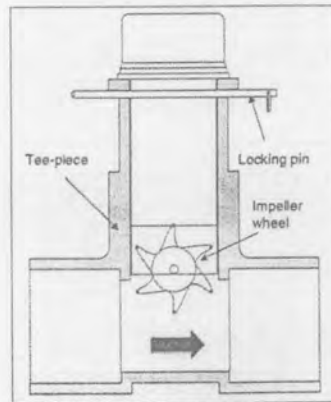


Figure 2.5 Impeller type meter (Crabtree, 2000)

The most common form of impeller meter is shown in Figure 2.5, with the impeller wheel mounted at the top of the pipe section. Although the meter provides minimal head loss in the system, the top end of the section is also the first place that air will accumulate.

2.3.2 Electromagnetic meters

The principle of the meter is based on Faraday's law of induction. In the electromagnetic flow meter, a magnetic field is produced across a cross-section of the pipe, with the water forming the conductor. Two sensing electrodes set at right angles to the magnetic field, are used to detect the voltage which is generated across the flowing water, and the strength of which is directly proportional to the discharge in the pipe. A schematic lay-out of the meter's components are shown in Figure 2.6.

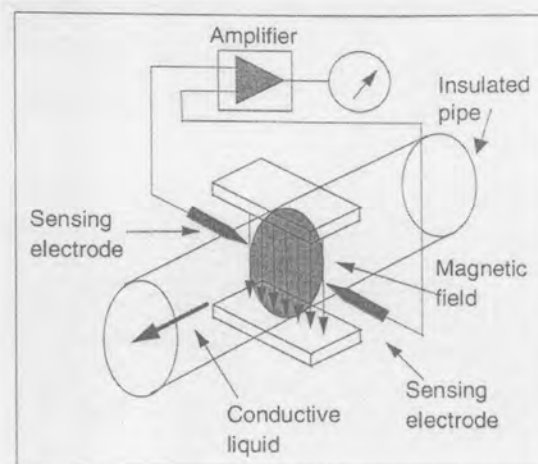


Figure 2.6 Schematic lay-out of the components of an electromagnetic flow meter (Crabtree, 2000)

The electromagnetic meter's characteristic that makes it ideal for irrigation water measurement is the fact that the meter causes no obstruction in the flow path of the water. Furthermore, it has no moving parts, is relatively insensitive to flow profile changes, and can record discharge readings with errors less than $\pm 0.5\%$ of reading (Crabtree, 2000).

However, the disadvantages include the high cost of the meter (approximately 5 – 10 times the cost of inferential meters), and the fact that it requires electricity to record readings.

2.3.3 Acoustic (ultrasonic) devices

Like the electromagnetic meters, ultrasonic flow meters are non-intrusive devices that can measure flow at high accuracies ($\pm 1\%$ of reading), and fall in the same price range. The biggest application of these meters in irrigation water measurement is the use of portable clamp-on models for in-field verification of other meters.

There are three types of ultrasonic meters that each use a different facet of the principle for measurement: the Doppler method, the time of flight method and the frequency difference method.

2.3.3.1 The Doppler method

These meters operate on the basis of the Doppler effect, which is the change in frequency that occurs in a sound wave when the source and receiver of the wave move either away or towards each other.

The meter transmits an ultrasonic signal with a frequency in the order of 1 to 5 MHz at an angle into the water flowing in the pipe. Some of the energy of the signal is reflected back to the meter by particles (impurities) that are present in the water and is detected by the receiver. Since the particles are moving towards and past the meter, the reflected signal has a different frequency than the original one, and the frequency difference (Doppler shift) is directly proportional to the velocity of particles. A schematic representation of an insertion type Doppler meter is shown in Figure 2.7, showing the velocity of the medium (v), velocity of sound (c), the transmitted frequency of the signal (f_i) and the angle at which it is transmitted (θ).

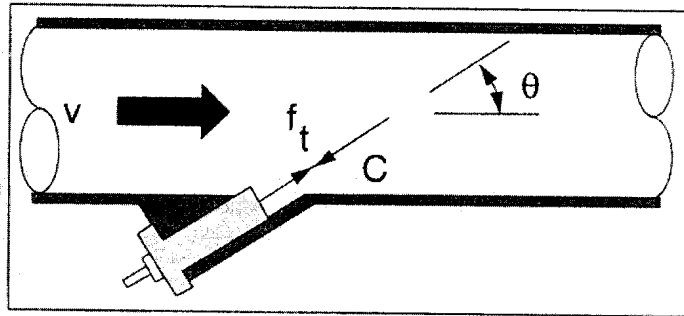


Figure 2.7 Schematic diagram of an insertion type Doppler meter

The Doppler meter has only one probe or transducer which houses both the source and receiver of the signal. The water has to contain reflective particles of a diameter that is at least one tenth of the wavelength of the signal in the water, otherwise it can not be detected by the meter.

Since it is possible that the particles are not always moving at the same velocity as the water, the Doppler meter's can produce measurement errors of $\pm 10\%$, which is considered relatively high, especially when one considers the relative high cost of the meter.

2.3.3.2 The transit time (time of flight) method

The principle of the transit time meter is that the flowing water will reduce the propagation speed of an ultrasonic signal traveling against the direction of flow, and increase the propagation speed of a signal traveling in the same direction as the water flow. It does not rely on the presence of particles in the fluid and is more suitable for measurement water flow than the Doppler method.

The meter comprises of two transducers (A and B in Figure 2.8), mounted at an angle to the flow and with a path length, L , each acting as a transmitter and receiver. The transit time of the signal is measured in both directions between the transducers and then compared. The flow velocity is directly proportional to the difference in transit time in the two directions.

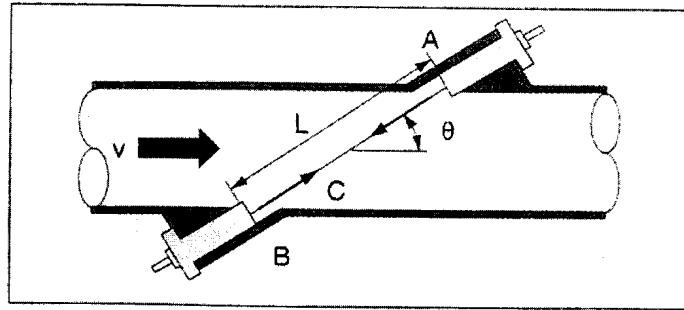


Figure 2.8 Schematic lay-out of transit time meter components (Crabtree, 2000)

The meter is suitable for a wide range of pipe diameters (50 mm to >3 m), with the only limitation being in the case of the small pipe diameters when the path length becomes short and the transit time differences very small. This problem can be overcome by allowing the signal to traverse the pipe more than once, thereby increasing the path length, as shown in Figure 2.9, and improving the measurement accuracy.

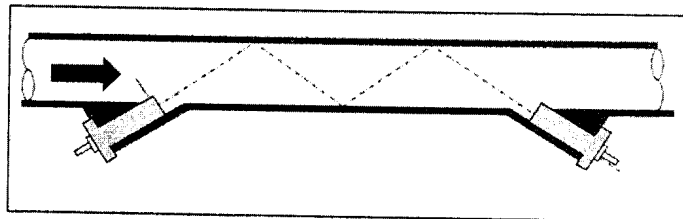


Figure 2.9 Increased path length through multiple traverses (Crabtree, 2000)

Disadvantages of the transit time method include high cost of the equipment and electricity dependence.

2.3.3.3 The frequency difference method

The frequency difference meter consists of four transducers, two sets of two transducers, A1-B1 and A2-B2, as shown in Figure 2.10. Each set of transducers' measuring path operates on the principle that the arrival of a transmitted signal at a receiver triggers the transmission of a next signal back to the other transducer. As a result, two pairs of transmission frequencies are set up, one for the upstream direction and another for the downstream direction. The difference in frequencies in the two directions is proportional to the flow velocity.

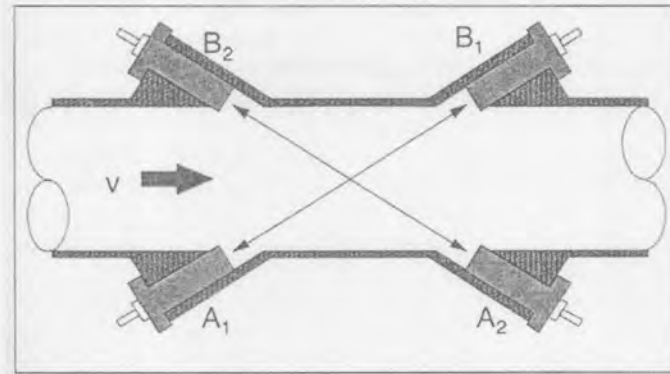


Figure 2.10 Lay-out of transducers for the frequency difference meter

2.3.4 Kilowatt-hour meters

It is a common practice in kwaZulu-Natal for WUAs to determine farmers' water usage on the basis of their electricity accounts (Van der Stoep et al, 2002). The method usually entails a once-off "calibration" procedure where a flow meter is temporarily installed at a specific pump station, and electricity consumption (in kWh) and the discharge be measured simultaneously for a short period of time. A calibration factor is determined that describes the relationship between electricity consumption and the volume of water pumped. The flow meter is then removed, and water usage calculated on the basis of the electricity account received from the national electricity supplier (ESKOM) and the calibration factor.

Although the method gives some indication of usage, it cannot be considered an accurate measurement method. Investigation by MBB Consulting Engineers (1997) at the Theewaterskloof Dam in the Western Cape showed that measurement errors between ± 25 to 50 % of the real usage can be made.

A refined method based on this principle using a custom made power consumption monitoring system is currently being investigated (MBB Consulting Engineers, 2003).

2.3.5 Summary of methods

Some of the characteristics of the methods described in this section are summarised for comparison in the following table:

Table 2.2 Summary of flow meter characteristics

Method	Special installation conditions (hydraulic)	Requires electric power	Accuracy (relative)	Sensitive to dirty water	Cost (including installation)
Inferential	Yes	No	Moderate	Yes	<R10000
Electromagnetic	Yes	Yes	High	No	R10000 - R30000
Acoustic	Yes	Yes	High	No	>R30000
kiloWatt-hour	No	Yes	Low	No	<R2500

During the initial phase of the research field tests were done to evaluate meters currently being used by WUAs to measure abstractions by individual farmers. Three randomly chosen meters (one electromagnetic and two inferential types) were evaluated in the field using a portable ultrasonic flow meter. These tests were aimed at verifying allegations that the available meters are unreliable and inaccurate.

Although errors of between -20 % and + 63 % of reading were found during the measurements, the sample size was too small to be able to make any scientific deductions about reliability of meters in general. However, it provided valuable insight into the lay-out of typical farm-level abstraction points, as well as the perspectives and expectations of farmers and water management officials.

Although these field evaluations contributed to the research project, it is not considered a main part of this project, but an overview of the methodology and results, as it was presented as part of the research at an earlier stage of the project, is attached in Appendix A.

2.4 The experimental measuring method

2.4.1 Introduction

Based on the literature study and practical experience, the specific constraints that need to be overcome by a suitable device or method for the measurement of pumped irrigation water abstracted from a surface source (canal or river) are the following:

- It must be affordable
- It must be simple and inexpensive to install (with little or no cutting, drilling or welding)
- There must be no moving parts in contact with the water that can be affected by impurities
- It must be reliable with little maintenance requirements
- The measurements must be within $\pm 5\%$ of the real value

A possible alternative method that could comply with all of these requirements, is based on the unique relationship between the discharge and differential pressure of a specific pump. The pump differential pressure is the increase in pressure that takes place between the suction and the discharge branches of the pump (SIHI Group, 1985).

By performing a pump test where the discharge or flow rate (Q) and differential pressure (Δp) can be measured simultaneously, the data which is obtained can be used to determine the discharge – differential pressure relationship for a specific pump for a range of operating conditions (but for specific installation conditions, such as the positioning of the pressure transducers). If this relationship can be described by a mathematical function where the discharge is a function of the differential pressure, the function can be used to calculate the discharge from a differential pressure measurement. The volume of water discharged by the pump over a period of time can then be determined by integrating the calculated discharge over time.

To apply the principle for volumetric measurement, a pump will need to be fitted with two pressure transducers (one on the suction side and one on the delivery side of the pump), or a differential pressure transducer, and a datalogger to record the differential pressure over the pump at short intervals when the pump is being operated. The previously established discharge – differential pressure relationship can be used to calculate the discharge per interval, and the volume of water pumped per interval can be determined by multiplying the discharge with the interval length.

The actions required are shown schematically in Figure 2.11.

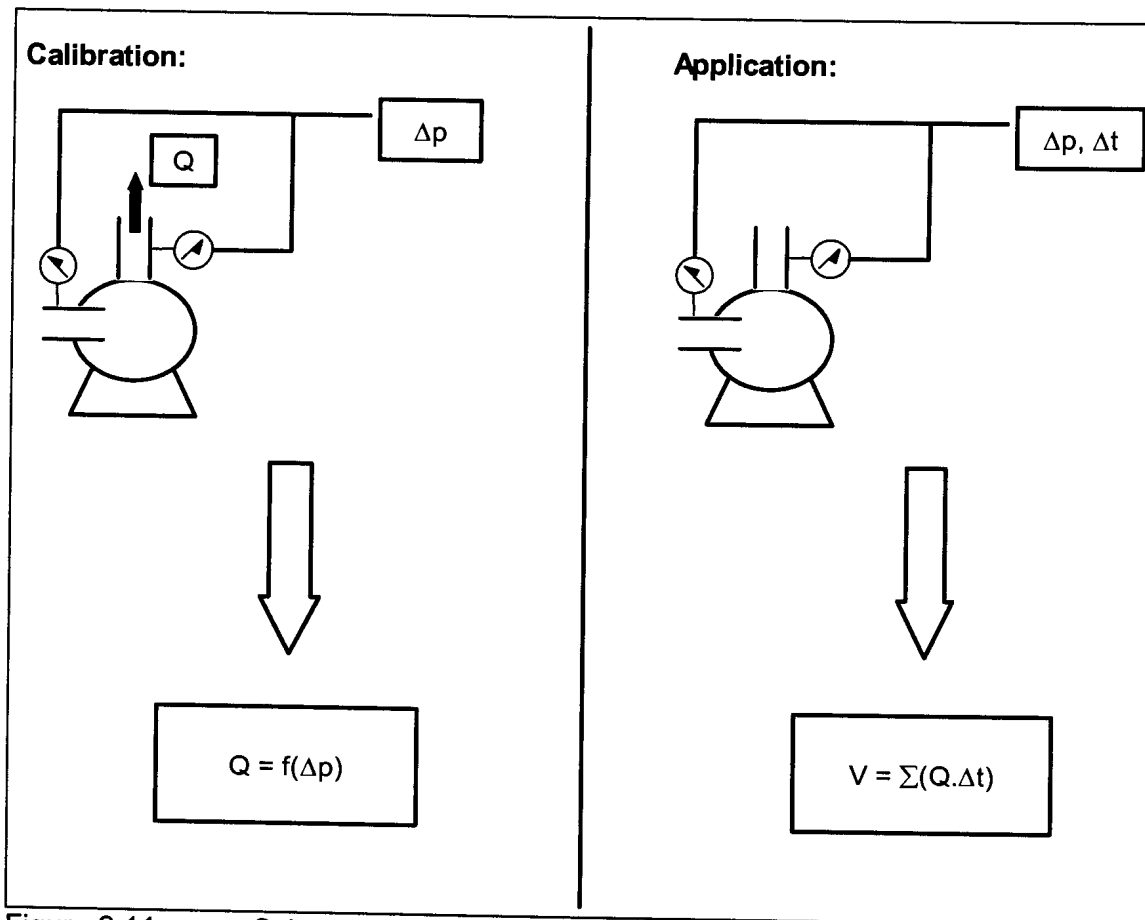


Figure 2.11 Schematic representation of the experimental measuring method

The method will require in field calibration to establish the discharge – differential pressure relationship which will be unique for every pump.

Advantages of the method includes the fact that no major construction work would be required to install the pressure transducers on existing pumping systems (compared to the installation of a flow meter), and that there are no moving parts that can cause an obstruction in the pipeline or wear out over time. Furthermore, although the device is no more tamper-proof than any other meter, if it should stop functioning, the data that had been collected could be used to determine when the breakdown occurred (unless the whole device is completely destroyed or removed). The device will not require more power than the conventional meters fitted with a pulse output requires for operation.

2.4.2 The Head-Discharge relationship in centrifugal pump systems

For a centrifugal pump driven at a constant speed, the pump head, H , as well as the power, efficiency and NPSH, are functions of the pump discharge, Q . These

relationships are represented by characteristic pump curves, resulting from pump tests.

The total pump head is the usable mechanical work or energy that it transferred by the pump to the liquid at a certain discharge (SIHI Group, 1985). It consists of three components, related to the pressure head, dynamic (velocity) head and position of measurement respectively.

Pressure head is the quantity used to express the energy content of a liquid per unit weight of the liquid referred to an arbitrary datum (Karassik et al, 1986). The pump differential pressure head is the increase in pressure head that takes place between the suction and discharge branches of the pump. The velocity head is the increase in energy in the pumped liquid due to the increase in flow velocity between the suction and delivery sides of the pump. The third component refers to the difference in height between the points of measurement on the suction and delivery sides of the pump.

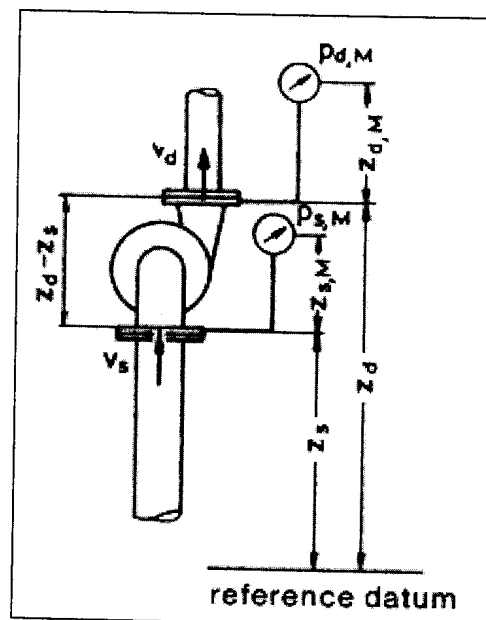


Figure 2.12 Components contributing to the total pump head (SIHI Group, 1985)

For a typical pump installation the components contributing to the total pump head, H (m), is shown in Figure 2.12 (SIHI Group, 1985), and can be applied as shown in equation (3):

$$H = \frac{p_d - p_s}{\rho g} + \frac{v_d^2 - v_s^2}{2g} + (z_d - z_s) \dots \dots \dots (3)$$

- where
- p_d = discharge pressure gauge reading, Pa
 - p_s = suction pressure gauge reading, Pa
 - v_d = velocity in discharge branch, m/s
 - v_s = velocity in suction branch, m/s
 - z_d = elevation of discharge gauge above datum elevation, m
 - z_s = elevation of suction gauge above datum elevation, m

The relation between the pump head and the discharge is represented in the H-Q curve, which generally shows that the head decreases with an increase in pump discharge, like the curve in Figure 2.13.

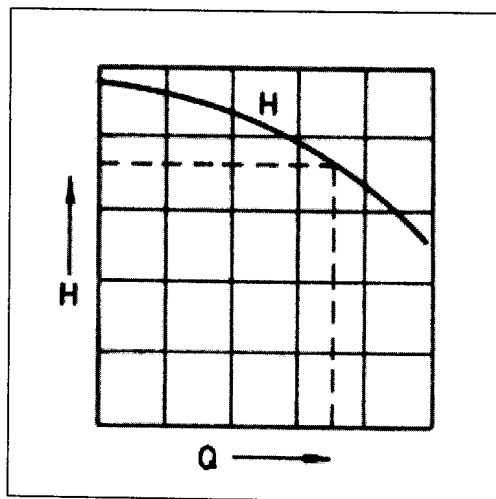


Figure 2.13 Typical H-Q curve (SIHI Group, 1985)

The ratio of the pump head values at $Q = 0$ and at the optimum discharge (point of highest efficiency), can be used to define the steepness of the curve (SIHI Group, 1985):

$$\text{Steepness} = \frac{H_o - H_{opt}}{H_{opt}} \dots \dots \dots (4)$$

where:

- H_o = pump head at $Q = 0$
- H_{opt} = pump head at point of highest efficiency

The steepness and shape of the H-Q curve is a function of the impeller type and efficiency. The characteristic curves for the four types of pump impellers generally encountered are shown in Figure 2.14. The shape of an impeller can also be described as a specific speed, n_q , which is the rotational speed of an impeller that is geometrically similar in all components and which has been dimensioned such that at a total head H_q of 1 m a rate of flow Q_q of 1 m³/s will be delivered (SIHI Group, 1985).

In the figure, P represents power, and η represents efficiency.

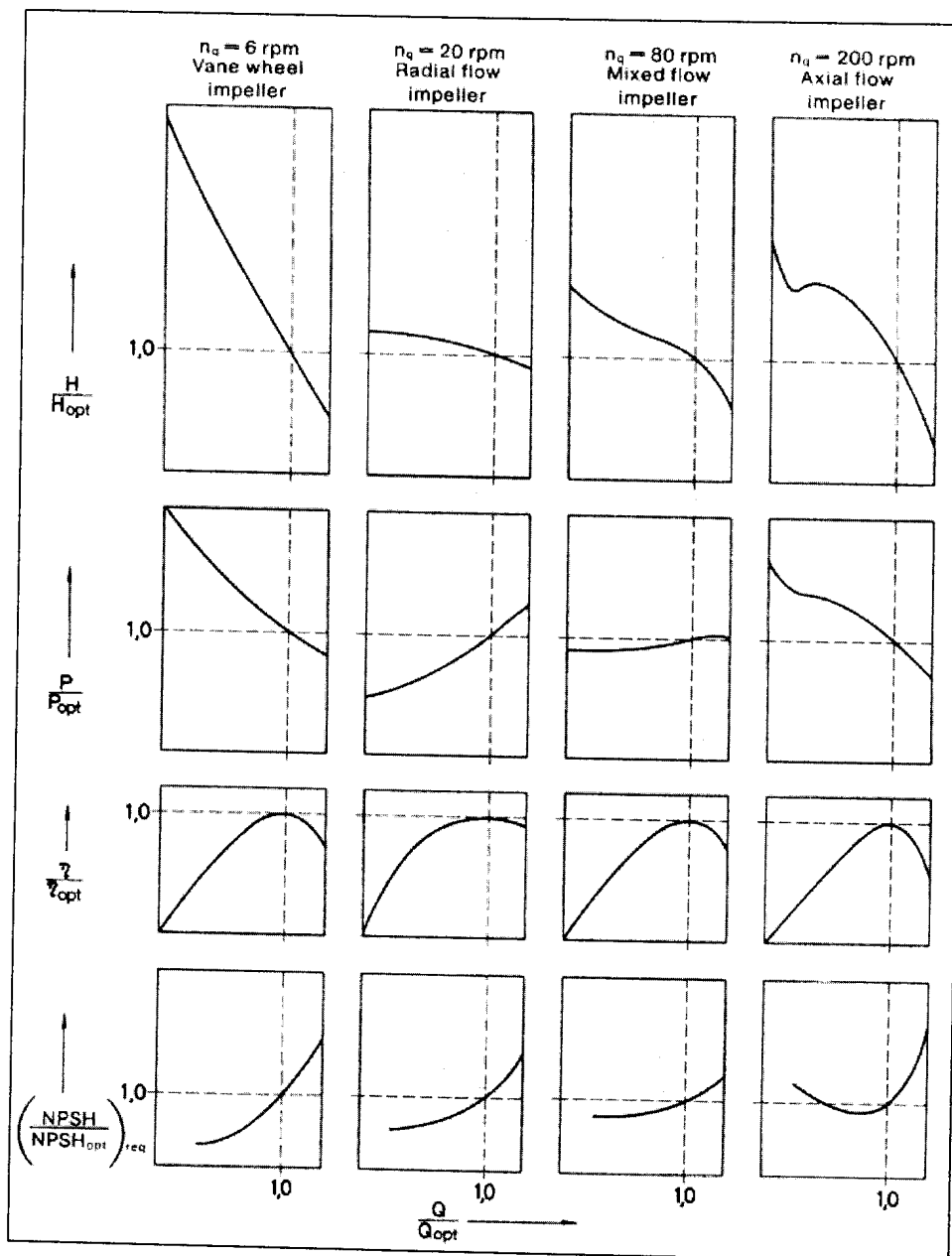


Figure 2.14 Typical pump curves for various impellers (SIHI Group, 1985)

Most irrigation pumps have radial flow impellers ($n_q = 8$ to 45 rpm), and therefore usually have relatively flat H-Q curves, as shown in the second column of graphs. However, the slope becomes steeper as the discharge increases, and the duty point of a pumping system is more likely to be located in the area around the point on the curve where $Q/Q_{opt} = 1.0$, since this is where the pump operates at its highest efficiency.

Another characteristic of pump curves that is sometimes observed is when a curve is said to be “unstable”. Figure 2.13 is example of a “stable” curve, with the highest pump head value being found at $Q = 0$, and the curve sloping down towards the higher discharge values. For every head at which the pump operates, there is only one discharge possible

An unstable curve, however, has a head value at $Q = 0$ that is smaller than the highest head value on the curve. As the discharge increases from zero, initially the pump head also increases, before it peaks and then decrease with an increase in discharge (Figure 2.15). This means that for the higher range of pump head values there are two possible discharge values for each head value. When a pump is operated in this unstable range, it may tend to jump between the two possible duty points.

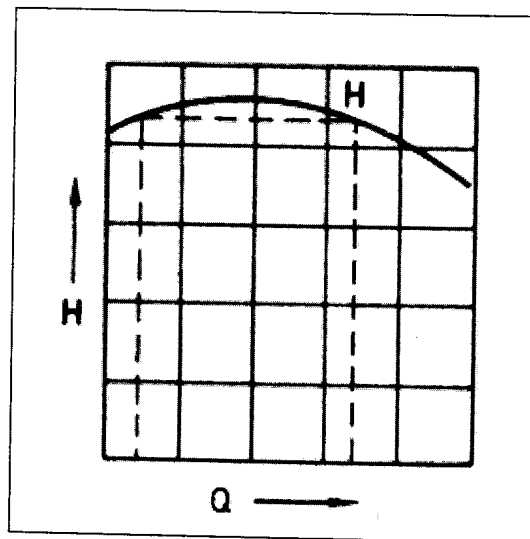


Figure 2.15

Example of an unstable H-Q curve (SIHI Group, 1985)

2.4.3 Using a Q-Δp relationship to determine system discharge

The experimental measuring method requires a discharge-pump differential pressure relationship to be developed. Theoretically, this relationship can be derived from equation (3). If it is assumed that the suction and discharge pressure gauges are positioned at the same height above datum elevation, and making use of the continuity equation, it can be found that:

$$\frac{p_d - p_s}{\rho g} = H + kQ^2 \dots\dots\dots(5)$$

where:

Q = system discharge, m³/h

$$k = \frac{(A_s^2 - A_d^2)}{2.592 \times 10^7 g A_s^2 A_d^2} \dots\dots\dots(6)$$

with A_s = cross-section area of pipe at suction side pressure transducer, m²
A_d = cross-section area of pipe at delivery side pressure transducer, m²

Equation 5 is similar to a relationship that was used by Kolhe, Kolhe & Joshi (2001) to determine the daily volume of pumped water as a function of mechanical energy from a photovoltaic pumping system.

Re-arranging equation 5 so that the system discharge is a function of the pump head, it becomes:

$$Q = \sqrt{\frac{\Delta p - \rho g H}{k \rho g}} \dots\dots\dots(7)$$

where:

$$\Delta p = p_d - p_s, \text{ Pa}$$

Theoretically, equation (7) could be used to calculate the system discharge if the total head and pump differential pressure is known. However the total head is often difficult to determine accurately since it requires measuring the suction and delivery flow velocities, which may be difficult to perform accurately.

The pump differential pressure, however, can be measured more easily, and it is this relationship, $Q^2 \propto \Delta p$, that will be sought in the experimental data. The relationships will be empirical and not derived from first principles. Once this relationship has been determined for a specific system, it can then be used to determine the total volume of water abstracted over a period of time if the pumping time is recorded and the pump is running at a constant speed.

In order to achieve this, it would be required to record the discharge at short, known time intervals. The volume of water pumped during i intervals would then be the sum of all the discharge values per interval multiplied by the interval length, or:

$$V = \sum_{t_0}^{t_i} (Q \times \Delta t) \dots \dots \dots (8)$$

where:

- V = volume of water pumped over the time interval from t_0 to t_i
- Q = average discharge during a specific interval, m³/h
- Δt = time interval, h

2.4.4 Possible limitations

A possibly problematic type of H-Q relationship that may be encountered, is in the case of unstable curves as shown in Figure 2.14. The unstable curve will result in a Q- Δp relationship where there are two possible discharge values (Q_1 and Q_2) for a specific Δp value (p_1) over the lower range of discharge values, as shown in Figure 2.16.

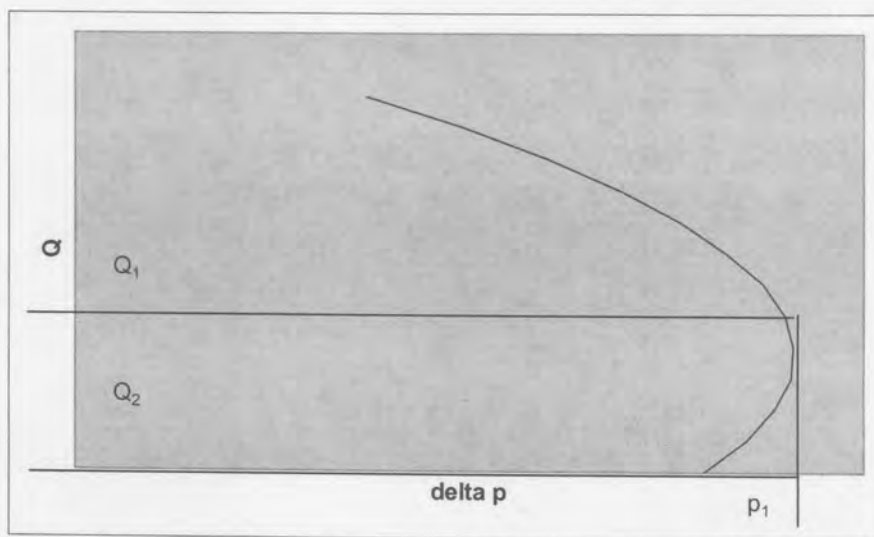


Figure 2.16 Two possible discharge values with unstable curves

3. Materials and methods

3.1 Introduction

This introduction aims to present a clear overview of the activities undertaken during the project, as shown in Table 3.1 and discussed below.

Table 3.1 Chronological order of project activities

Phase nr	Experimental work	Dates of activities	Included in main report or as appendix
1	Field evaluation of previously installed meters	April – June 2002	Appendix A
2	Field investigation of Q- Δp relationships at pumps	July – October 2002	Appendix B
3	Laboratory investigation of Q- Δp relationship	December 2002	Main report
4	Laboratory evaluation of reference meters for field investigations	November 2002 and June 2003	Appendix C
5	Field investigation of experimental measuring method: install and calibrate	July 2003	Main report
6	Field investigation of experimental measuring method: monitoring	August 2003	Main report

During 2002, field tests were initially conducted to investigate water users' claims that meters were inaccurate and unreliable through random field evaluations of meters that had previously been installed by water users (Phase 1 in Table 3.1). These tests helped in the identification and definition of the problem statement, and an overview of the tests as submitted previously, is attached in Appendix A for reference purposes.

Phase 1 contributed to the formation of a preliminary hypothesis of the experimental measuring method as described in section 2.4, i.e. that the discharge of a pump could possibly be measured through the relationship between discharge and pump differential pressure. The practical aspects of the method were investigated through the field tests of Phase 2, and the results presented in a progress report. It is attached in Appendix B.

Although the field tests conducted during Phase 2 pointed out a number of potential weaknesses, the results were favourable and provided valuable experience that could be put to good use in setting up of the laboratory experiment, where the experimental measuring method was evaluated further under controlled conditions during Phase 3.

In support of the experimental work, the equipment used for verification and referencing the measurements were evaluated through independent laboratory tests (Phase 4). The results are presented in Appendix C (transit time meter tests).

The final two phases concerns the empirical testing of the application of the experimental measuring method through field tests. The necessary equipment was installed and calibrated at an irrigation system pump station (Phase 5), and data collected over two week period (Phase 6). The data is attached in Appendices D, E and F.

This chapter provides background to the methods and equipment used during Phases 3, 5, and 6. Reference is made to the contents of Appendices B and C.

3.2 Hydraulic testing standards and procedures

The test required discharge and pressure measurements under a wide range of conditions to be performed. Relevant procedures and standards for conducting, computing and reporting on tests of pumping systems for obtaining information on the head, capacity, power, efficiency and suction requirements, are mainly those used by pump manufacturers to perform pump acceptance tests. Examples of the standards that are commonly referred to in literature are the ISO Code for acceptance tests (ISO 2548), the German standard Acceptance Tests for centrifugal

pumps (DIN 1944), and the ASME Power Test Code for Centrifugal Pumps (PTC 8.2) (Karassik et al, 1986, SIHI Group, 1985).

All these standards provide guidelines for pressure and discharge measurement equipment to be used during tests to obtain results of a desired accuracy.

3.2.1 Pressure measurement

The following three devices are recognized as acceptable for pressure measurement in pump testing (Karassik et al, 1986):

- Liquid column manometers
- Bourdon (spring) gauges
- Electronic pressure transducers

Pressure transducers with 4-20 mA output were used in both the laboratory and field tests.

For pump acceptance tests as performed by pump manufacturers, accurate measurement of the true pump head is of great importance since it directly reflects on the performance of the pump. Great care is taken when positioning the tapplings for the pressure gauges to ensure steady flow conditions, and the following five conditions should be satisfied (SIHI Group, 1985):

- The tapping in the pipe wall should be flush with and normal to the wall of the water passage, with no projecting edges or burrs.
- In order to ensure a fully developed flow profile, the pressure tapping should be positioned at least four times the pipe diameter from the pump outlet.
- The connecting tube between the pressure gauge and the tapping should be kept free from air.
- The connecting tube between the vacuum gauge and the tapping should be kept free from water.
- Bourdon gauges should be calibrated before or after the tests.

These conditions are considered important for the purpose of the experimental measuring method too, but not because the true head needs to be measured, but rather to ensure good repeatability of the data. The pressure readings will be used to establish a Q- Δp relationship (rather than a H-Q relationship), which will in turn be

used to calculate the discharge through the system based on independent pressure readings.

Since it is often the case with existing pumping plants that there are no long sections of straight pipe available, the second condition mentioned above may not always be satisfied.. Data collected from the tests were also analysed to investigate whether satisfying this condition would be a prerequisite for the experimental method to function properly.

3.2.2 Discharge measurement

The following discharge measurement methods are recognized as acceptable for performing pump tests:

- Volumetric tank (discussed in section 2.1.4)
- Weighing tank (discussed in section 2.1.4)
- Positive displacement meter (e.g. rotary piston)
- Differential pressure meters (venture, orifice plate, pitot tube)
- Head- area meters (weirs and flumes)
- Current meters

The field tests presented a number of difficulties that prevented using any one of these methods. Measurements needed to be made on closed pipeline systems, feeding into an irrigation system, eliminating the possibilities of using either tanks, weirs or flumes. Positive displacement meters would be susceptible to clogging and malfunction due to the dirtiness of the water, and differential head meters would cause additional head loss in the system, which could results in the irrigation system operating at a too low pressure, which could affect distribution, and eventually also crop yield. Further more, the pipeline systems are the property of individual farmers and could not be altered or changed without permission.

For the purpose of this study, the discharge measurements were made with an ultrasonic transit-time meter (Panametrics AT868), which is a portable clamp-on unit with measuring at accuracies at shown in Table 3.2:

Table 3.2 Accuracy specifications of the transit time meter

Pipe size	Velocity > 0.3 m/s	Velocity ≤0.3 m/s
Pipe diameter > 150 mm	± 2 % of reading	± 0.01 m/s
Pipe diameter ≤150 mm	± 2-5 % of reading	± 0.05 m/s

The meter has the advantages of being fully portable, non-intrusive to the flow path, and being able to measure velocities of between -12.2 and 12.2 m/s (rangeability of 400:1).

The only disadvantage found in the field was the installation requirements of 10 to 20 straight pipe diameter lengths in front of the meter, and 5 to 10 diameters beyond. These conditions can often not be met in the field, and to investigate the effect of non-conformance, the influence of flow disturbing components (such as a 90 degree bend or gate valve) was investigated in a laboratory. The meter's performance under ideal conditions was also evaluated in the laboratory against a 90 degree v-notch weir. The experimental lay-out and results are attached in Appendix C.

3.3 Laboratory evaluation of the experimental measuring method

3.3.1 Introduction

The results of the initial field tests (described as Phase 2 in Table 3.1) indicated that unique Q-Δp relationships do exist for the three irrigation pumping systems that were evaluated, but the method of determining the relationship had to be refined and analysed under controlled conditions. The methodology and results of the field tests are not discussed any further here, but is attached in Appendix B.

The aims of the laboratory tests were firstly to evaluate the repeatability of the Q-Δp relationship that is obtained from the test data, and secondly to evaluate the validity of the relationship that has been developed using clean water and near ideal conditions.

The laboratory tests were performed in the hydraulic laboratory of the Cape Technicon as part of a series of tests for the WRC project (Van der Stoep et al, 2002). The test bench consisted of a 5000 l tank, a 65-200 centrifugal pump (pump curve shown in Figure 3.1) with full size impeller, driven by an electrical motor at

2900 rpm, a turbine type flow meter, and gate valves on the suction and delivery sides of the pump, as shown in Figure 3.2.

The discharge was measured with the turbine flow meter ($\pm 2\%$ accuracy) with digital display, and suction and delivery side pressure with pressure transducers with a $\pm 0.25\%$ accuracy at full scale and 4-20 mA output.

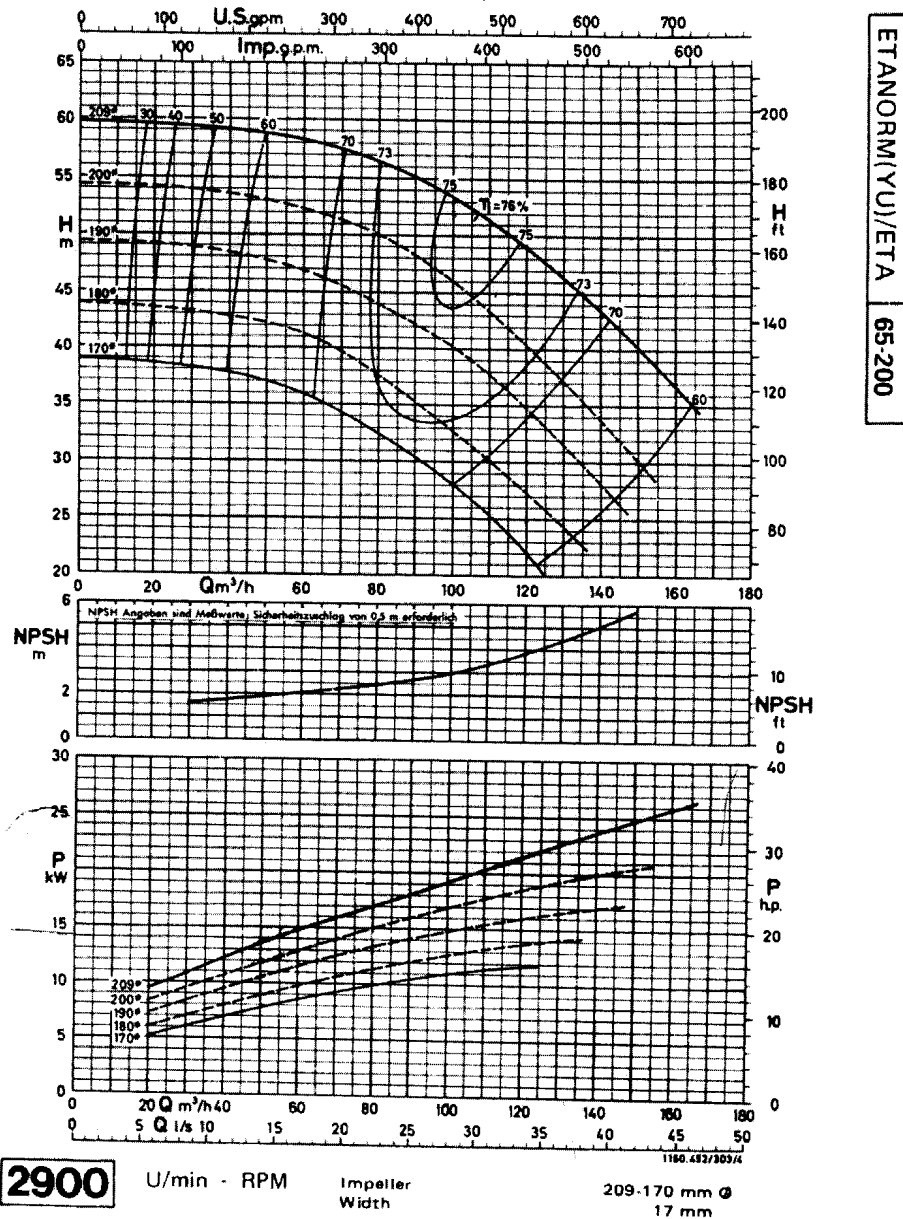


Figure 3.1 Manufacturer's curve for laboratory pump (KSB Pumps, 1994)

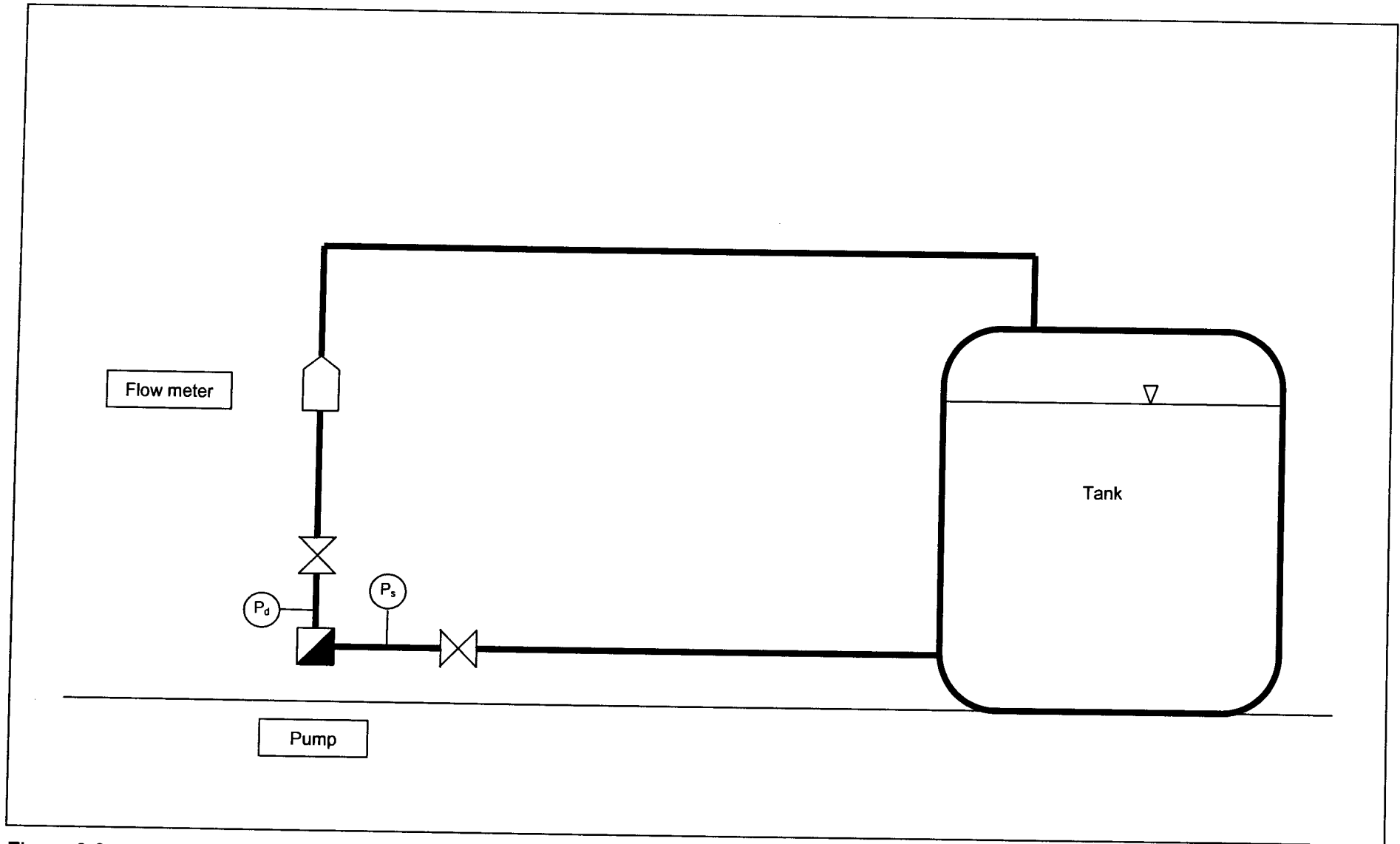


Figure 3.2 Schematic lay-out of the laboratory test bench at the Cape Technikon (elevation, not to scale)

3.3.2 Determining the Q- Δp relationship

Three independent tests were done to obtain data for the Q- Δp relationship.

The methodology that was followed for each test was as follows. Discharge and pressure readings were taken every time after a valve had been adjusted and the readings stabilised:

- The pump was started with the suction side valve fully open and the delivery side valve fully closed (zero flow)
- The delivery side valve was opened partially, and then progressively more in increments, until fully open.
- The delivery side valve was then closed in increments until the flow stopped.
- The delivery side valve was then fully opened, and the suction side valve was closed in increments, until the risk of serious cavitation became likely.
- A further few readings were then taken with the suction and delivery valves adjusted randomly.

This methodology made it possible to obtain data over the whole flow range of the pump, as well as different combinations of suction and delivery side pressures. These situations may occur in the field when one pump is used to supply water at a number of different duty points (for example, when pumping to different size irrigation blocks, or supplying different numbers of sprinklers from time to time).

The data from the three tests were analysed individually to determine the Q- Δp relationship for the pump, and the results compared to evaluate the repeatability. The results were first plotted as Δp -Q relationships, which produced curves similar in shape as a typical pump curve. If the curve was found to be unstable, only the data points on the part of the curve with a negative slope (in other words, with Δp values higher than the Δp value occurring at the peak discharge value) were used for developing the Q- Δp relationship.

A Q- Δp relationship was developed for each of the three pump tests by plotting the data points and fitting a regression curve through the points using an MS Excel spreadsheet.

3.3.3 Evaluation of the validity of the Q- Δp relationship

Once the Q- Δp relationships had been developed, a new test was performed in the same manner as the first and the Q- Δp relationship used to calculate the discharge. The calculated

discharge values were then compared with the measured discharge values as recorded during the test.

An error analysis was performed and the results of the three relationships compared.

3.4 Field evaluation of the experimental measuring method

3.4.1 Introduction

Once satisfactory results had been obtained in the laboratory, the validity and usefulness of the experimental measuring method had to be investigated in a real situation as it would be applied in practice, through empirical testing.

It was envisaged that the field evaluation would entail the following activities:

- Identification of a suitable site with a cooperative farmer
- Installation of two pressure transducers, a flow meter for referencing (to compare the experimental measuring method's results against) and a datalogger
- Verification of the flow meter readings
- Determining the $Q-\Delta p$ relationship for the pump (calibration)
- Recording pressure transducer and flow meter reading over an extended period of time (ideally a complete irrigation season)
- Applying the $Q-\Delta p$ relationship to the pressure transducer data to determine the volumetric discharge over the period of time, and comparing the results with the flow meter data
- Analysing the results and making adjustments to the experimental measuring method if necessary

Some problems were encountered during the site selection and commissioning of the equipment. The equipment was initially installed at a pump station on the Vaal River upstream of the Douglas weir in February 2003, but during the first follow-up visit in March 2003 it was observed that the datalogger had malfunctioned and it was removed for repairs. On return to the site to re-install the datalogger, it was found that the farmer had removed the reference flow meter from the system because he felt it caused too much additional head loss in the supply pipe to the irrigation system. Although there was in fact adequate pressure available at the irrigation system even if the flow meter was installed, the farmer would not agree to re-installing the flow meter, and it was decided to move the equipment to another site.

In May 2003 it was decided to install the pressure transducers at a pump station on the Umlaas River near Pietermaritzburg, where a flow meter had already been installed earlier as part of WRC Project K5/1265. The pump station was easily accessible by tar road and could be visited regularly by researchers from the local CSIR office who would be using the site for other monitoring purposes. However, when the calibration of the pressure transducers were attempted, it was found that there was a problem with the electrical supply to the pump's motor that the farmer had not been aware of. He also then only indicated that the pump had not been operated for a period of time and that he would only be using it from August 2003 onwards, when the new irrigation season would start. No data was obtained from this site.

The equipment was finally installed in July 2003 at the site at the Orange-Riet WUA where a previously installed meter was evaluated in 2002, but the installation wasn't without incident either. Although a month's data was obtained here, only two weeks' readings could be used since one of the pressure transducers were damaged by extreme cold conditions two weeks after commissioning the equipment and malfunctioned from then onwards. Furthermore, although a reference flow meter was already in place, previous evaluations of the meter as shown in Appendix A indicated that the meter could produce measurement errors of between -5 % and +50 % of the real value. However, an additional reference meter was also installed and other methods of verification also used.

3.4.2 Site description

The pump station at the Orange-Riet WUA is situated on the farm Ramdam, where water is abstracted from the Orange-Riet Canal and pumped directly to the irrigation system. The pump serves two center pivot irrigation systems, one 10 ha and the other 30 ha in size, requiring design flow rates of 35 m³/h and 150 m³/h respectively, according to the system design (Andrag-Agrico, 2002). The two systems can be operated separately or together, which means that the pump can be required to supply water at three possible flow rates (35, 150 or 185 m³/h).

Water is abstracted at a submerged off-take protected by a screen against floating debris, from the canal through a 250 mm diameter steel pipe to the pump. The water goes through another strainer positioned directly before the pump inlet branch. On the delivery side of the pump, the 200 mm steel pipeline is fitted with a butterfly valve and an impeller type flow meter before the pipe splits into separate supply lines for the two center pivot systems. The lay-out is presented schematically in Figure 3.3.

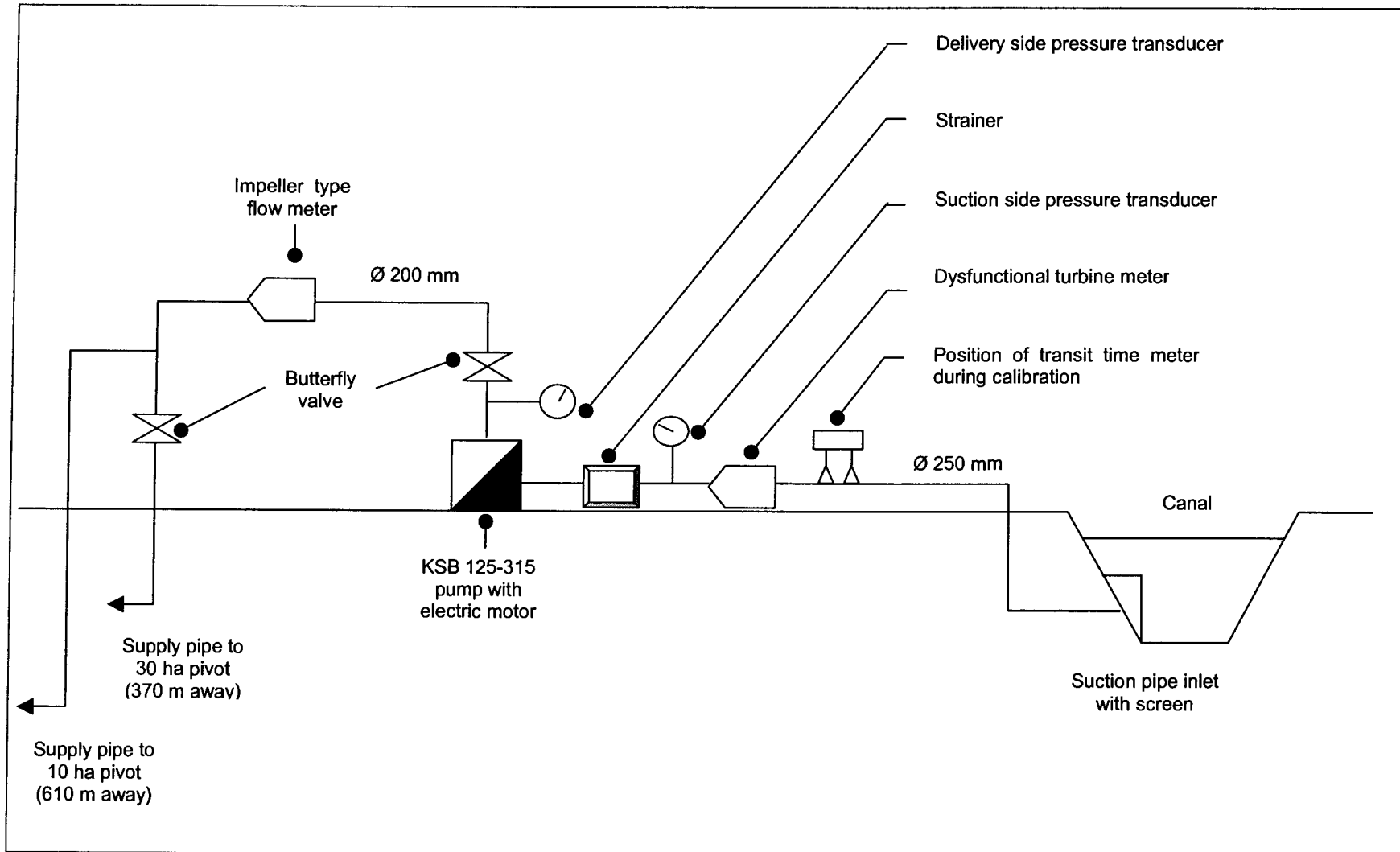


Figure 3.3 Schematic lay-out of pump and equipment at field evaluation site (elevation, not to scale)

The pump in the system is a KSB 125-315 model with a full size impeller driven at 1465 rpm with a directly coupled 30 kW electric motor (Figure 3.4). The pump was installed in 2001.

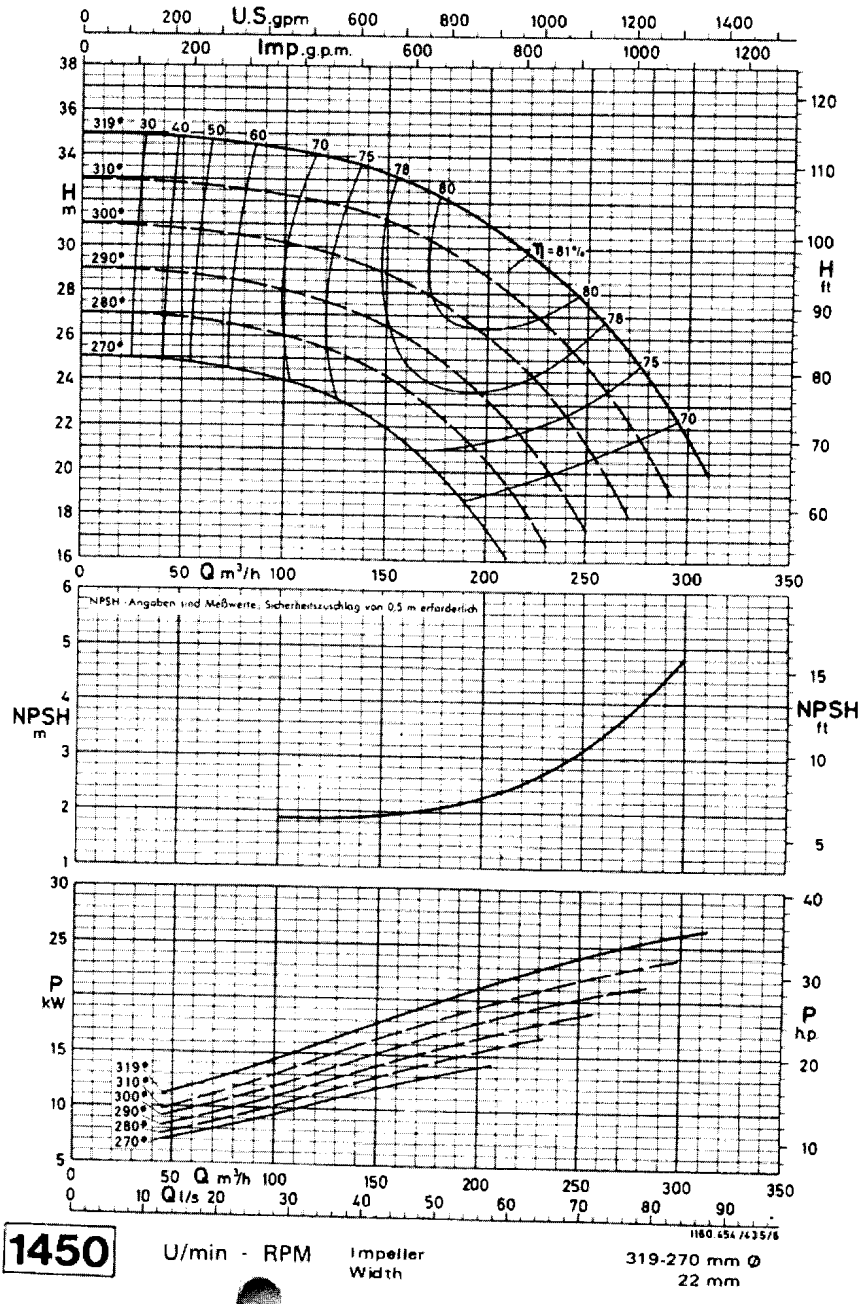


Figure 3.4 Manufacturer's curve for the field test pump (KSB Pumps, 1994)

This site was also used in WRC Project K5/1190 (MBB Consulting Engineers, 2003) to test a prototype electronic flow meter that works on the principle of the relationship between the pump discharge and the power consumption of the pump's motor. These tests were very successful with the prototype meter performing consistently within $\pm 3\%$ of actual flow.

3.4.3 Discharge measurements

The system discharge was measured with three different types of flow meters.

Two of the meters were permanently installed in the system and could be used as reference for the results of the experimental measuring method. These were the impeller type mechanical meter and the prototype electronic meter. The third meter used was the portable transit time meter which was only used during field visits.

The impeller type meter was a 200 mm WP-T-M flanged irrigation water meter supplied by ABB Metering (Pty)Ltd. The impeller is mounted in the top section of the meter body, and allows unrestricted flow through with little head loss. The volumetric discharge through the meter can be read on the dry dial register in cubic meter, up to two decimals. The meter can also be fitted with a magnetic reed switch that produces a pulse output of one pulse per 100 liters or one pulse per 1 m³. No specific installation requirements with regard to the pipework are necessary according to the manufacturers.

Previous evaluations of the impeller type meter showed measurement errors of between -5 % and + 50 % may occur at this specific site (Appendix A). The reference measurements were made with the portable transit time meter. Considering the installation conditions, it was possible that the combination of the pump, butterfly valve and 90 degree bend a short distance before the meter was contributing to the errors. Despite this, it was thought best to evaluate the meter in a laboratory to ensure that it was operating correctly under ideal conditions, with no flow disturbances directly upstream. Unfortunately these test produced similar results as the field tests and it was decided not to use this meter as reference due to its inaccuracy.

The prototype electronic flow meter had been developed for WRC Project K5/1190 (MBB Consulting Engineers, 2003), and was installed at this site in September 2003. Since its installation, it had been monitored and its output verified regularly, and it was found to be very consistent in its performance.

The device is basically an energy meter that measures the power consumption of the motor driving the pump, and uses an internal mathematical equation and calibrated look-up tables to convert the power reading into a discharge and then into a volume of water for a specific time interval. Both cumulative power consumption (kWh) and the volume of water discharged (m³) is displayed on an LCD screen. While the pump is being operated, the meter also displays the

momentary discharge (m^3/h) and power consumption (kW). It is possible to program the meter to record daily values that can be collected via an RS232 connection.

The portable transit time meter was used to take discharge measurements to determine the Q- Δp relationship for the experimental measuring method. The meter had already been described in section 3.2.2 above. The transducers were mounted on the suction side of the pump on a straight section of 250 mm steel pipe with magnetic clamps, as shown in Figure 3.3.

3.4.4 Pressure measurement

The suction and delivery pressures were measured with electronic pressure transducers mounted as shown in Figure 3.3. The suction side transducer had to be mounted in front of the strainer since the strainer was fitted against the pump inlet flange and there was no place for the mounting to be welded on. The delivery side transducer had to be mounted closer than the prescribed four pipe diameter lengths (see section 3.2.1) since it had to be in front of the butterfly valve controlling the flow.

The pressure transducers used were from the GEMS 2200 series with a 4-20 mA output and $\pm 0.25\%$ of full scale accuracy, and was attached directly to the pipe by the 10 mm coupling thread. The suction side pressure transducer had a range of -1 bar to 1 bar gauge pressure (or 0 to 2 bar absolute pressure), and the delivery side a range of 0 to 6 bar gauge pressure. A smaller ranged pressure transducer could have used on the delivery side, but the one used was originally purchased for installation at the Vaal River site, where a KSB 80-400 pump was used.

The transducers were connected to a Vanguard VGD-400 datalogger for power supply and data collection. For the calibration process, the real-time data from the datalogger was displayed on a laptop computer. For the monitoring process, pressure readings from both transducers were recorded at one minute intervals when the pump was switched on. The datalogger was powered by a 12 volt deep cycle battery, which was charged by a 20 W solar panel.

3.4.5 Determining the Q- Δp relationship

The Q- Δp relationship was determined by simultaneously measuring the suction and delivery pressures with the pressure transducers and datalogger, and the system discharge with the

portable transit time meter, which also has a datalogging function. Readings were taken at 10 second intervals for both parameters.

Although initially data was collected in the same way as in the laboratory, in other words, by trying to obtain readings over the whole flow range of the pump, it was realized that in practice the pump is dedicated to operating at one of three possible duty points at any given time, depending on which of the center pivot systems are switch on. It was therefore decided to obtain data mainly for the three duty points. Once these three duty points were known, future readings could be sorted by applying basic logical (if-type) statements to analyse the data. Since data were being collected continuously, any operation of the system at other duty points would be recorded and could then be analysed.

Data at the three duty points were collected at 10 second intervals over a period of 20 minutes per duty point. Only 10 minutes' data at each duty point were used to allow for any delayed reaction in system discharge or pressure due to adjustments to the valves and switching on or off of the systems.

3.4.6 Long-term field tests

Data was collected for the period 31 July 2003 to 27 August 2003. Pressure readings were recorded by the datalogger at 1 minute intervals only while the pump was running. Continuous discharge readings could not be collected by the reference flow meter, the cumulative volume of water pumped during the test period could be determined by taking the readings on the meter at the beginning and end of the period and calculating the difference.

4. Results

4.1 Introduction

The results of the laboratory and field test that were performed as described in Chapter 3 are presented here.

4.2 Laboratory evaluation of the experimental measuring method

4.2.1 Determining the Q- Δp relationship

The results of the three tests that were done to obtain data for the Q- Δp relationship are shown in Figures 4.1 a, b and c. The results are presented as pressure-discharge graphs, and the similarity with conventional pump curves can be seen. Each graph shows the suction and delivery side pressures over the flow range of the pump, as well as the pump differential head ($\Delta p = p_d - p_s$) values. A regression curve was fitted through the Δp values and the equation of the curve displayed on the graph.

All three graphs show the typical unstable curve shape discussed in section 2.4. Since it is unlikely that the pump would be operated for prolonged periods at the low discharge values where the curve has a positive slope, it was decided to base further analysis of the data on those points falling within the 35 to 170 m³/h range, which would then be assumed to represent a stable curve. The sets of data compared well with each other, and the three regression curves can be described by the following equations, one for the data of each test respectively:

$$\Delta p = -0.0018Q^2 + 0.1262Q + 58 \quad (9)$$

$$(R^2 = 0.995)$$

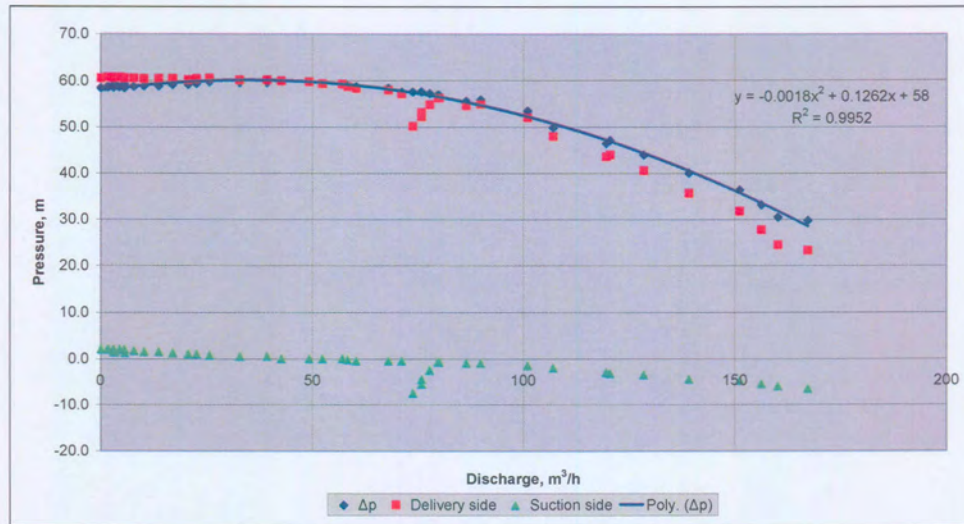
$$\Delta p = -0.002Q^2 + 0.1535Q + 58 \quad (10)$$

$$(R^2 = 0.996)$$

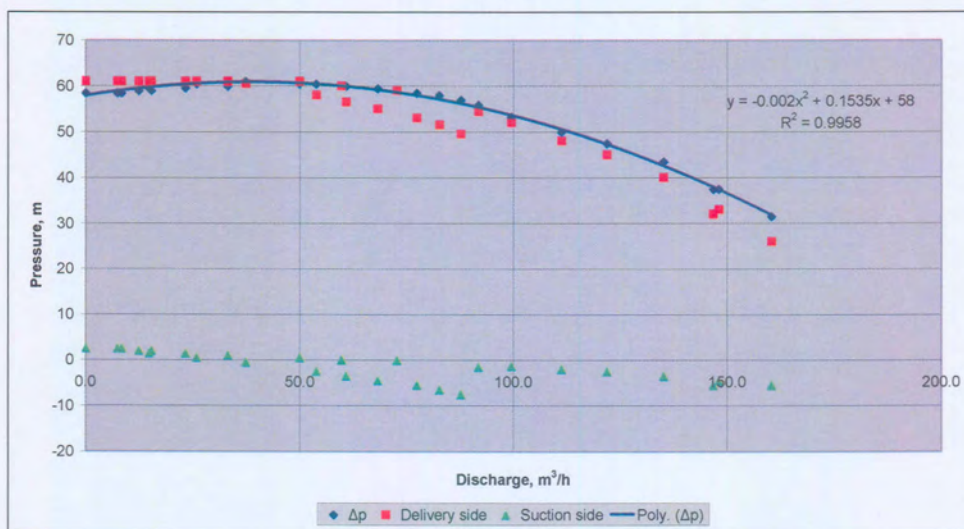
$$\Delta p = -0.0019Q^2 + 0.1496Q + 58 \quad (11)$$

$$(R^2 = 0.989)$$

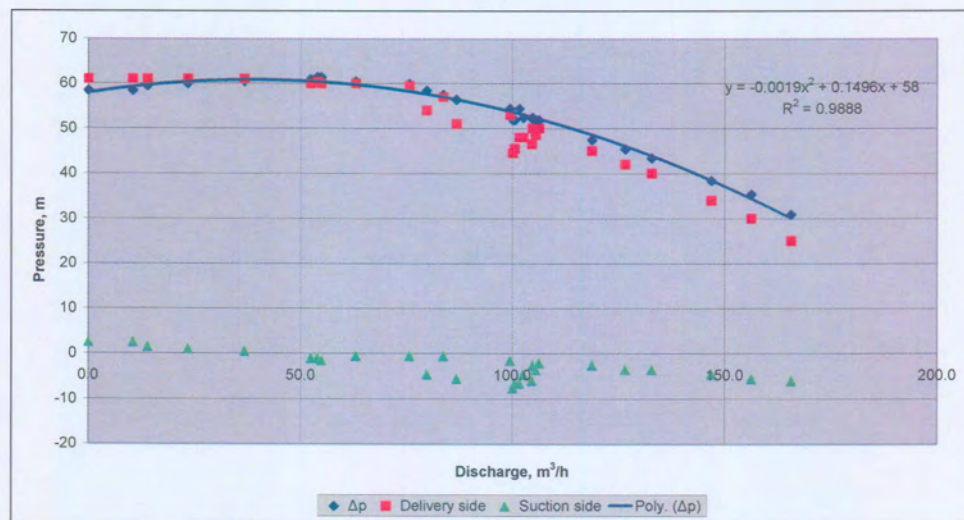
The data from the tests is shown in Appendix D.



(a)



(b)



(c)

Figure 4.1 Pressure-discharge graphs of the laboratory pump

The data points from all three the tests within the 35 to 170 m³/h flow range was then plotted as curves of discharge against pump differential pressure (Δp). Three regression lines, a linear, and a second and third order polynomial, were fitted through the points as shown on the graph of the second test's data in Figure 4.2.

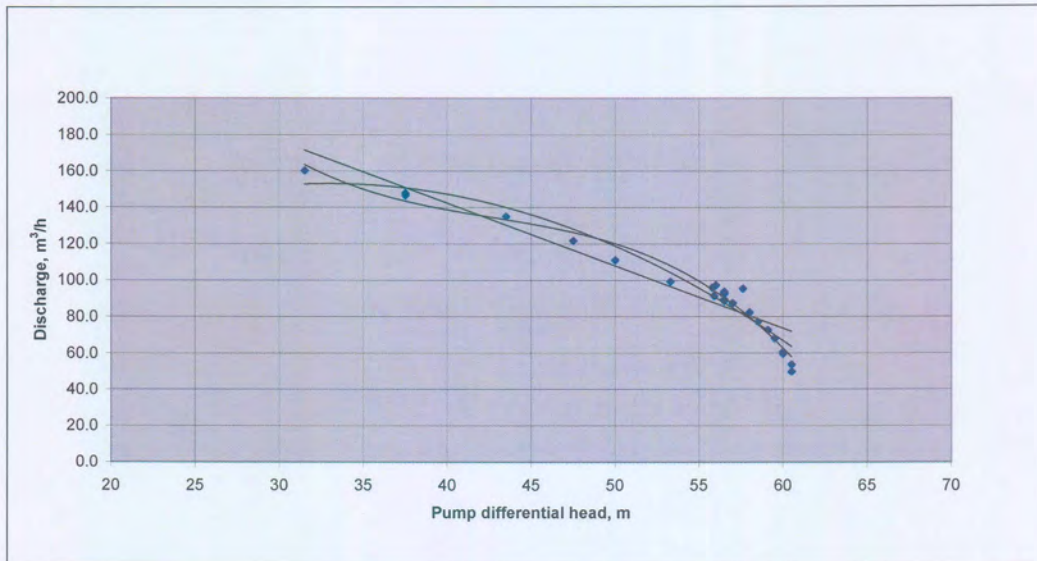
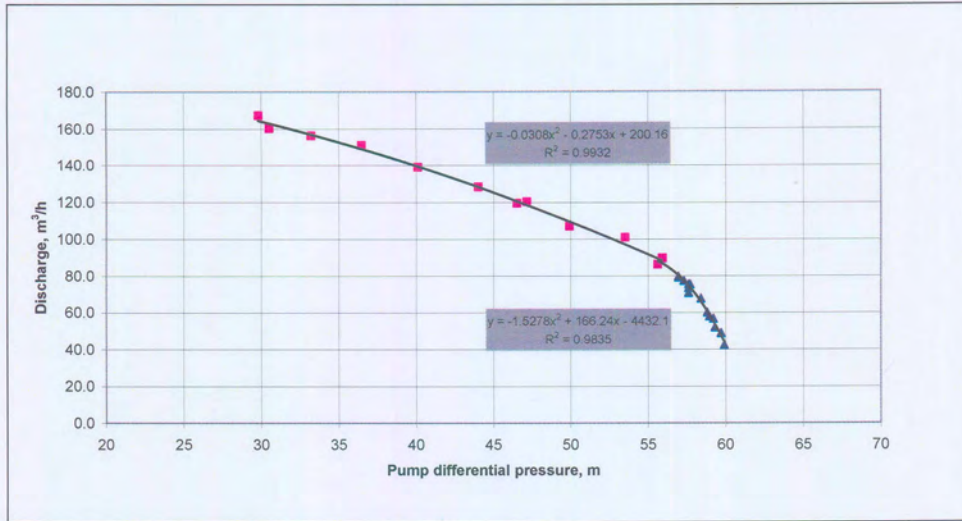


Figure 4.2 Q- Δp relationship based on results of the second laboratory test

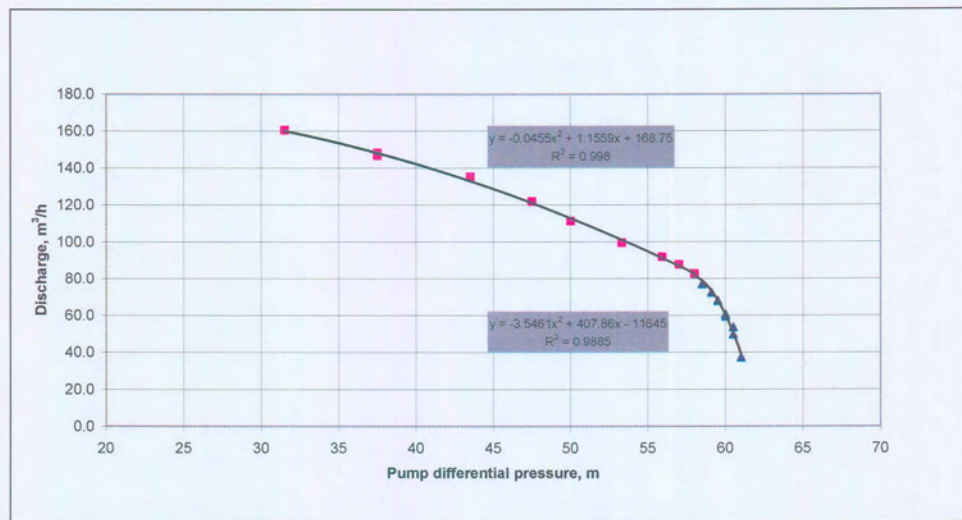
These regression curves were not found to fit the data points very well, especially in the higher flow range (above 90 m³/h). The R^2 values were typically between 0.88 and 0.97, and when the equations describing the regression curves were used to calculate the discharge, errors greater than 10 % were found over the whole flow range.

Another approach was then taken, by developing separate regression curves for data points in the 30 to 80 m³/h and 80 to 170 m³/h flow ranges. This approach therefore produced two equations for each set of test data, both with R^2 values greater than 0.98. The regression curves are graphically presented in Figures 4.3 a, b and c, and a summary of the equations describing the curves is shown in Table 4.1.

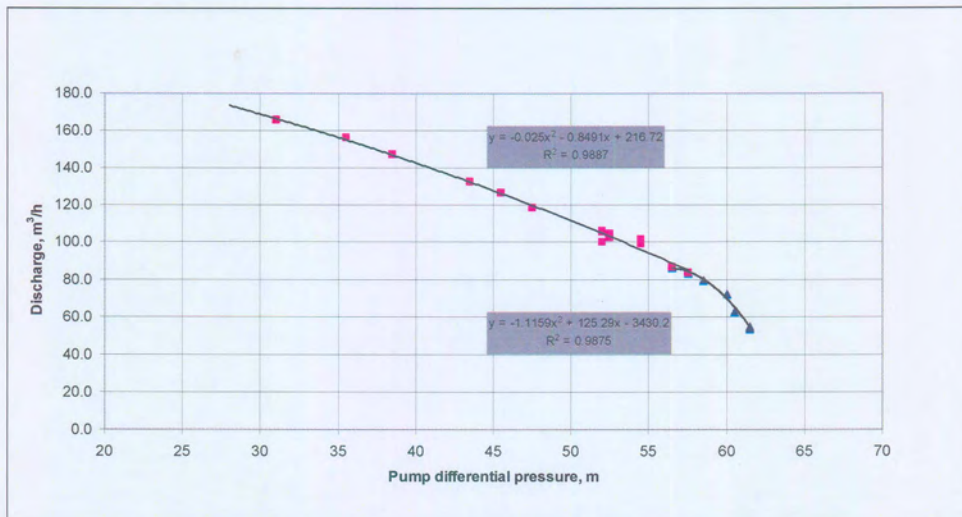
On the graphs it can be clearly seen that in the 80 to 170 m³/h flow range there is a near linear relationship between the discharge and the pump differential pressure. In the lower discharge range (or higher differential pressure range), the discharge values decrease exponentially with an increase in differential pressure.



(a) Test 1



(b) Test 2



(c) Test 3

Figure 4.3 Q-Δp relationships for the three laboratory tests

The slopes of the different graphs varied slightly from one test to the next, and the differences were more pronounced in the low flow range curves, with the third test's results showing a slightly flatter slope in the low flow range (differential pressure values higher than 58 m) than the first and second tests.

Table 4.1 Q- Δp relationships for the three laboratory tests

Test nr	Flow range	Equations	R ²	Eq. Nr
1	30 - 80 m ³ /h	$Q = -1.5278 \Delta p^2 + 166.24 \Delta p - 4432.1$	0.98	(12)
1	80-170 m ³ /h	$Q = -0.0308 \Delta p^2 - 0.2753 \Delta p + 200.16$	0.99	(13)
2	30 - 80 m ³ /h	$Q = -3.5461 \Delta p^2 + 407.86 \Delta p - 11645$	0.99	(14)
2	80-170 m ³ /h	$Q = -0.0455 \Delta p^2 + 1.1559 \Delta p + 168.75$	0.99	(15)
3	30 - 80 m ³ /h	$Q = -1.1159 \Delta p^2 + 125.29 \Delta p - 3430.2$	0.99	(16)
3	80-170 m ³ /h	$Q = -0.025 \Delta p^2 - 0.8491 \Delta p + 216.72$	0.99	(17)

Although all the curves fitted the data well, the coefficients varied greatly between the three tests' results.

4.2.2 Evaluation of the Q- Δp relationships

Equations 12 to 17 were used to calculate the discharge using differential pressure measurements taken during a second test, and the calculated values compared with the actual measured values by calculating the measurement error of the indirect method. The results based on the first three tests' equations are shown in Figure 4.4 and 4.5.

In Figure 4.4, the results over the whole flow range (30 to 170 m³/h) are shown. In the flow range 30 to 70 m³/h, all three sets of equations produced results with errors higher than 10 %. The second set produced the best results, with errors becoming smaller than 10 % at discharge values higher than 44 m³/h.

At discharge readings higher than 80 m³/h, however, all three equations (13, 15 and 17) predicted the discharge within ± 5.4 % of the actual value. These results are shown with a larger scale on the y-axis in Figure 4.5. The errors of the three equations converge slightly with an increase in discharge, up to the 160 m³/h.

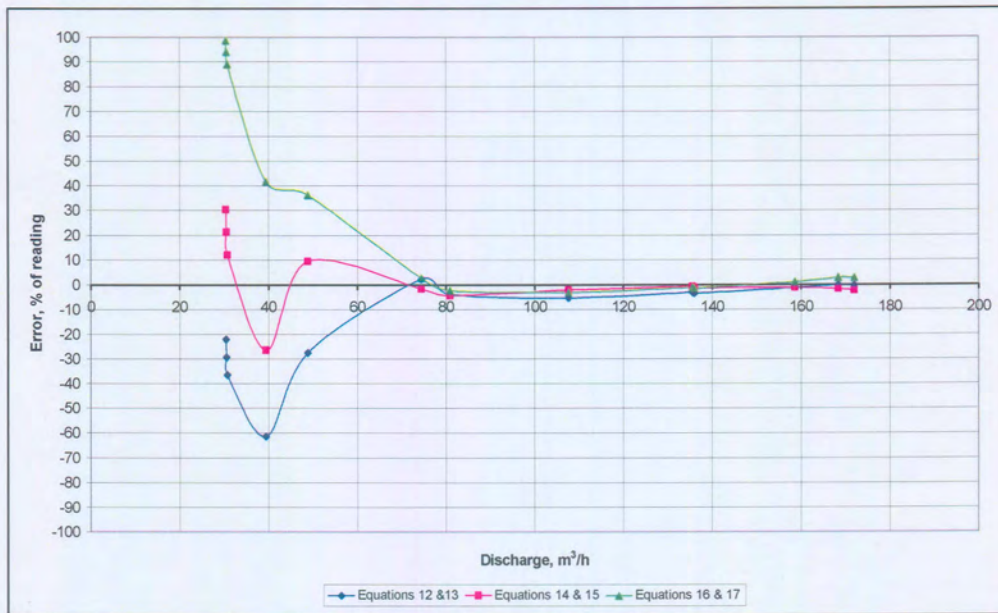


Figure 4.4 Measurement errors for the whole flow range

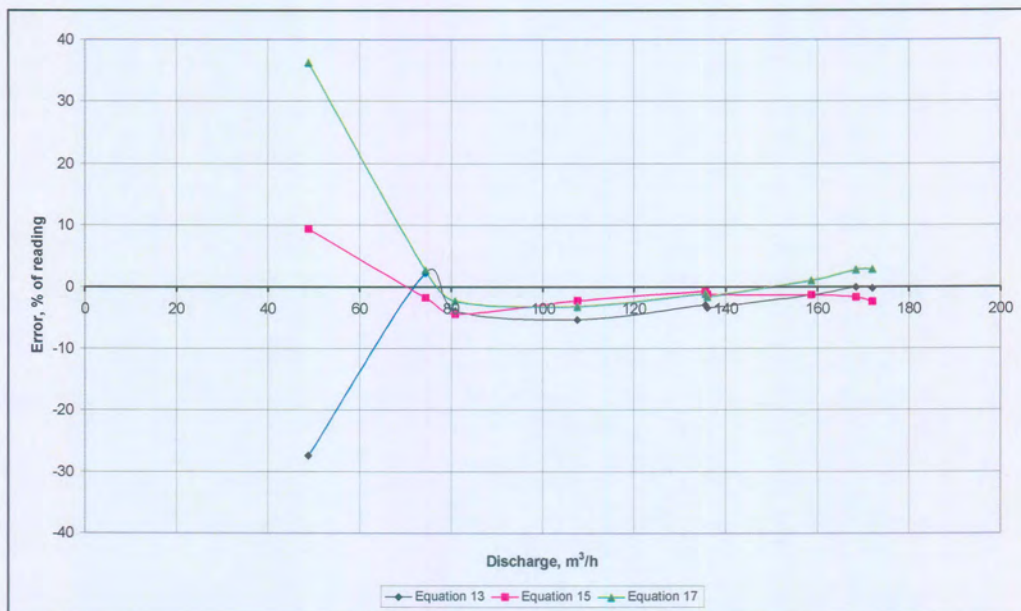


Figure 4.5 Measurement errors for discharge values higher than 40 m³/h

The standard deviations of the error measurements for discharge readings higher than 80 m³/h, were calculated as 2.5 %, 1.14 % and 2.51 % for the three tests respectively, which confirms that the second test produced the best results.

4.2.3 Comparison of results with pump curve

The differential pressure readings were also evaluated against the total head values at the measured discharge readings according to the manufacturer's pump curve. This was only done for Pump test 3, which had the fewest data points in the low flow rate range where it was difficult to read the total head values on the pump curve.

In Figure 4.6 the differential pressure as measured and total head obtained from the pump curve is compared over the discharge range. The difference between the two graphs is due to the position and installation fittings on the differential pressure readings as well as the fact that the total head on the pump curve includes a velocity head component which was not measured by the pressure transducers.

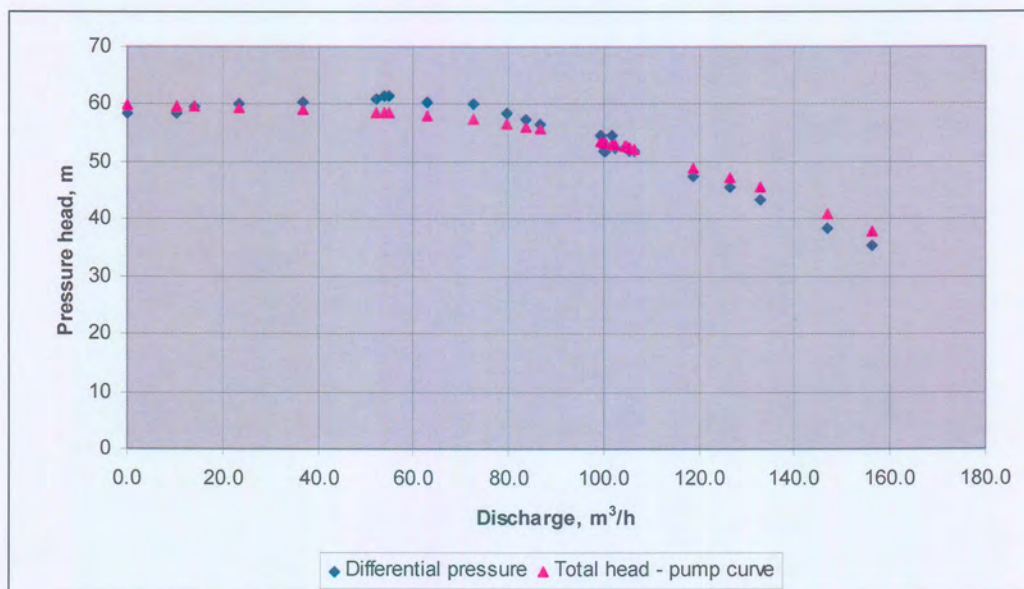


Figure 4.6 Comparison of differential pressure readings and total pump head

Another way of comparing the measured readings with the pump characteristics was to read the discharge according to the pump curve at each of the measured differential pressure readings and to compare it with the measured discharge. The results are shown in the graph in Figure 4.7, where the effect of the unstable curve shaped results of the differential pressure readings can be seen.

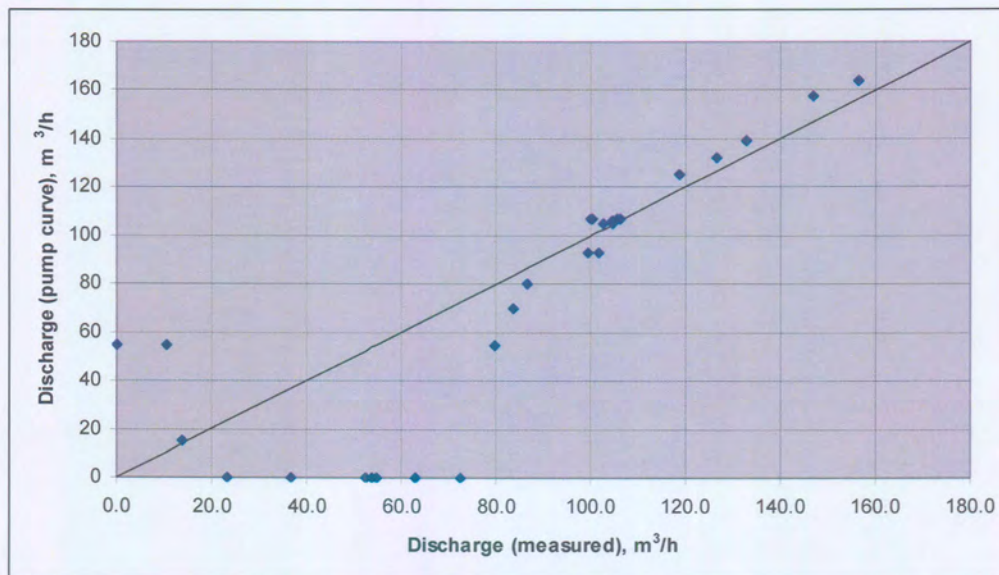


Figure 4.7 Comparison of measured and pump curve discharge values

4.3 Field evaluation of the experimental measuring method

4.3.1 Introduction

The results of the field evaluations are discussed according to the two phases it consisted of, i.e. a phase during which tests were performed to determine the $Q-\Delta p$ relationship, and a phase of continuous measurements to evaluate the usefulness of using the relationship to determine volumetric discharge over a period of time.

4.3.2 The $Q - \Delta p$ relationship

Initially it was envisaged that a mathematical relationship that describes the relationship between the discharge and pump differential pressure would be used to calculate the discharge from differential pressure measurements, and the same procedure that was used in the laboratory to determine the $Q-\Delta p$ relationship was applied in the field. The graph that resulted from the tests is shown in Figure 4.8.

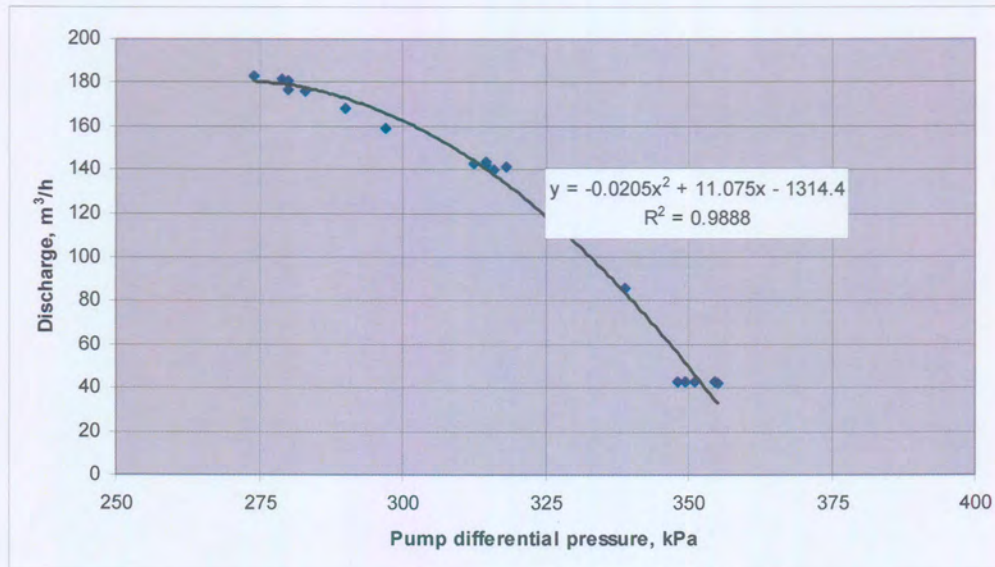


Figure 4.8 The Q- Δp relationship for the field test pump

A regression curve described by the following equation was fitted through the data points:

$$Q = -0.0205\Delta p^2 + 11.075\Delta p - 1314.4 \quad (18)$$

$(R^2 = 0.9888)$

Although the curve fitted the data well ($R^2 = 0.9888$), when it was attempted to apply this equation to measured differential pressure data, it was found that due to continuous small fluctuations in the pressure readings, it was near impossible to obtain the correct relative discharge at any given moment, regardless of the accuracy of the pressure transducers. At any duty point, both the discharge and the pressure readings varied continuously between certain observed upper and lower limits.

Based on these observations and the fact that the pump was dedicated to operating at one of three possible duty points at any time, the following was decided:

- The Q- Δp relationship would only be determined at the three possible duty points, and
- In practice the Q- Δp relationship will not be a continuous mathematical function but rather a series of defined differential pressure intervals, each with a related average discharge.

This would mean that if a differential pressure reading during a specific time interval falls between a defined upper and lower limit, there is a related average discharge value that will be used to determine the volumetric discharge for the time interval.

The upper and lower limits of the differential pressure intervals and the average discharge for each interval for the three duty points were determined by analysing the simultaneous differential pressure and discharge readings taken over a period of 10 minutes at each duty point, which are presented graphically in Figure 4.9.

The two tests for the duty points where the two pivots are being operated individually provided well – grouped data points. During the test performed with both pivots being operated together, however, a lot of fluctuation of both the suction and delivery pressure and discharge readings were observed.

The suction pressure values varied between -63 and -67 kPa gauge pressure, which is very low. Other observations included audible slight cavitation in the pump and a constant release of air at the air valve situated after the impeller type flow meter. The canal was flowing at a depth of about 80 % of its maximum capacity, and a slight vortex could be seen in the sump at the suction pipe inlet. It was a very windy day with small waves visible in the canal.

The low suction pressure was probably caused by a dirty trash screen at the suction pipe inlet from the canal, and in turn affected the pump's performance.

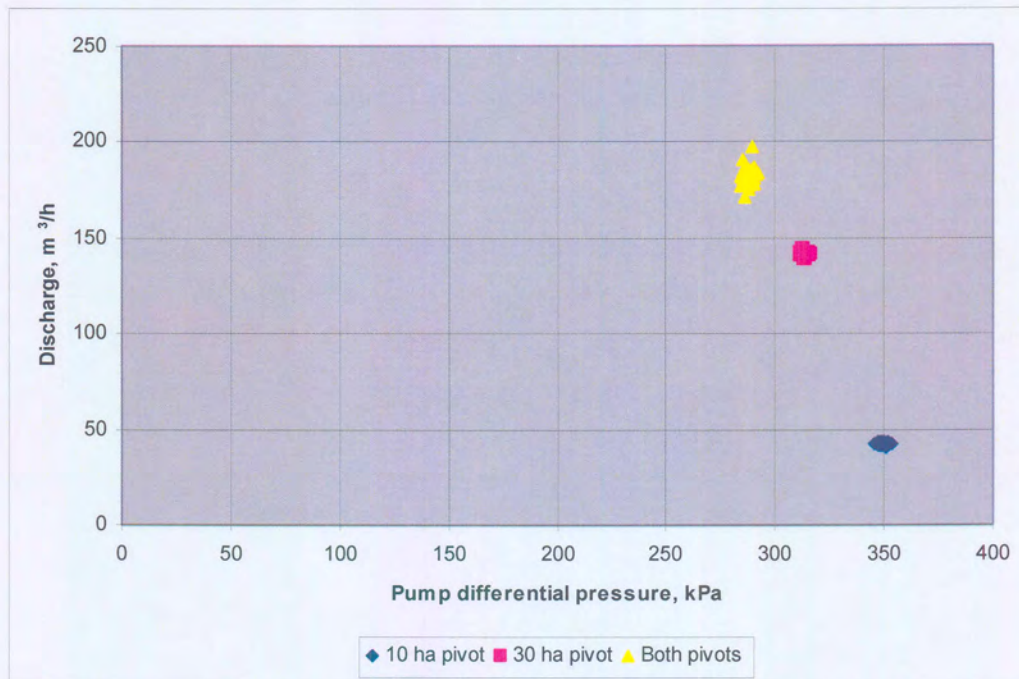
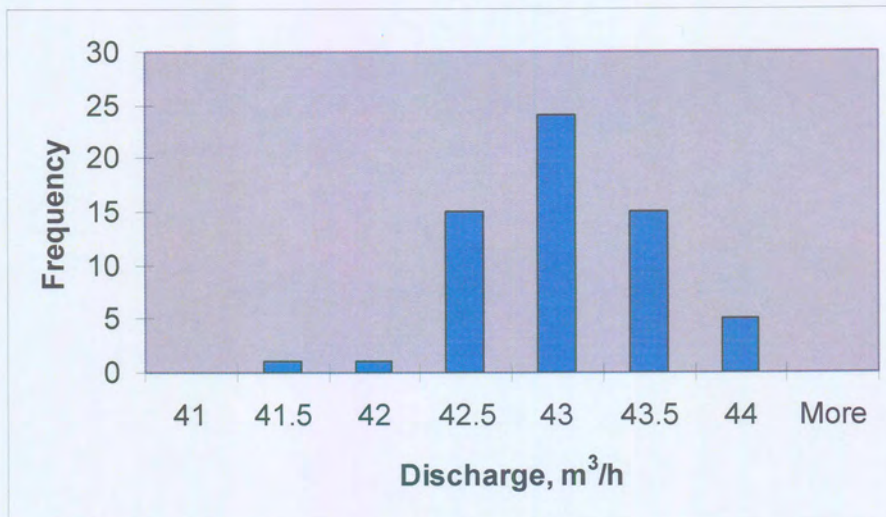


Figure 4.9 Discharge and differential pressure at three duty points

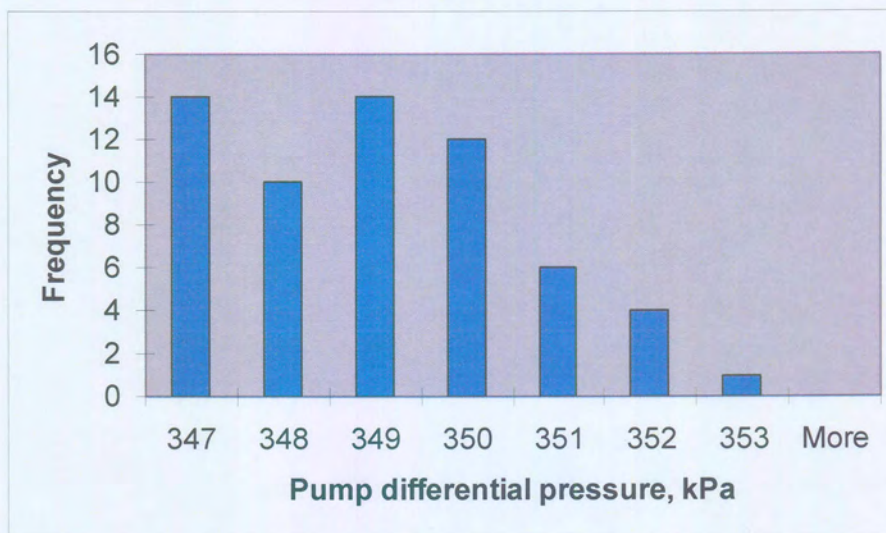
After the data was collected, the upper and lower limits of the differential pressure and discharge readings determined through inspection. A frequency analysis of the data was performed and the results sorted according to values within the limits of each interval and plotted as a histogram. This process produced 6 graphs, one for differential pressure and one for discharge, for each duty point.

The data and analysis is attached in Appendix E, and the histograms are shown below in Figures 4.10, 4.11 and 4.12.

The frequency values on the y-axes of the graphs show how often a specific discharge or differential pressure value occurred in the course of the test period. Mostly the histograms showed a normal distribution of values around an average value.



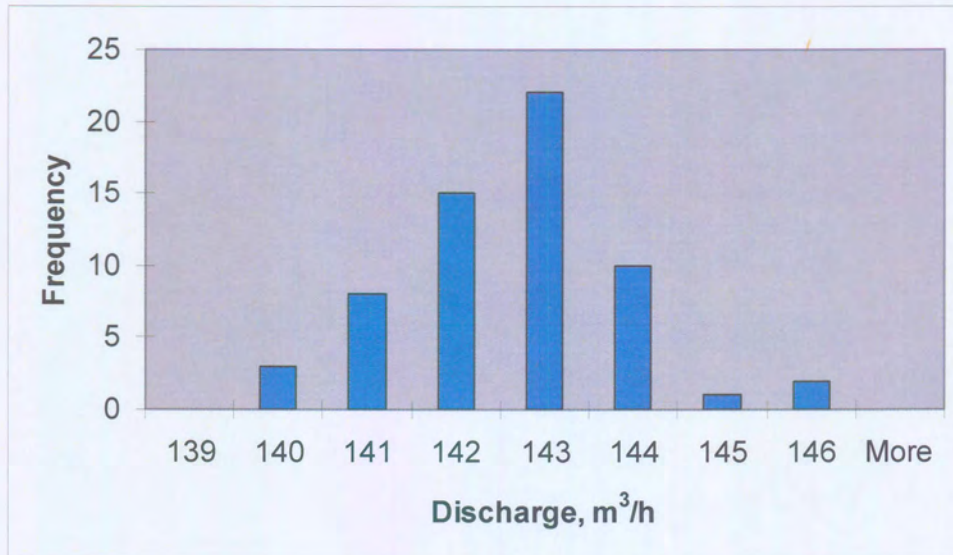
(b) Discharge



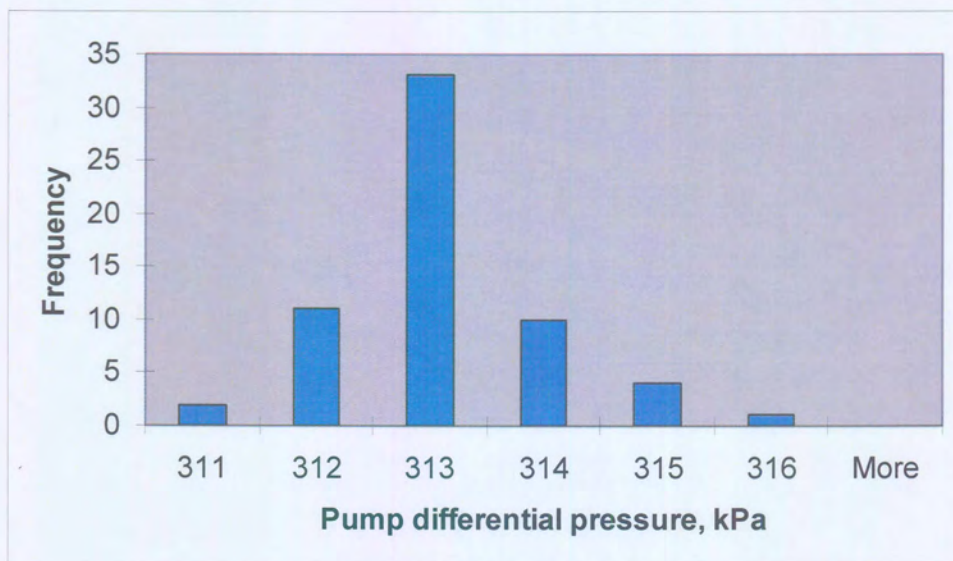
(a) Differential pressure

Figure 4.10 Frequency analysis at duty point for 10 ha pivot

The test conducted with only the 10 ha pivot in operation, showed that the differential pressure varied between 347 and 353 kPa during the test period. The discharge varied between 41 and 44 m³/h, with average discharge during the test period calculated as 42.81 m³/h.



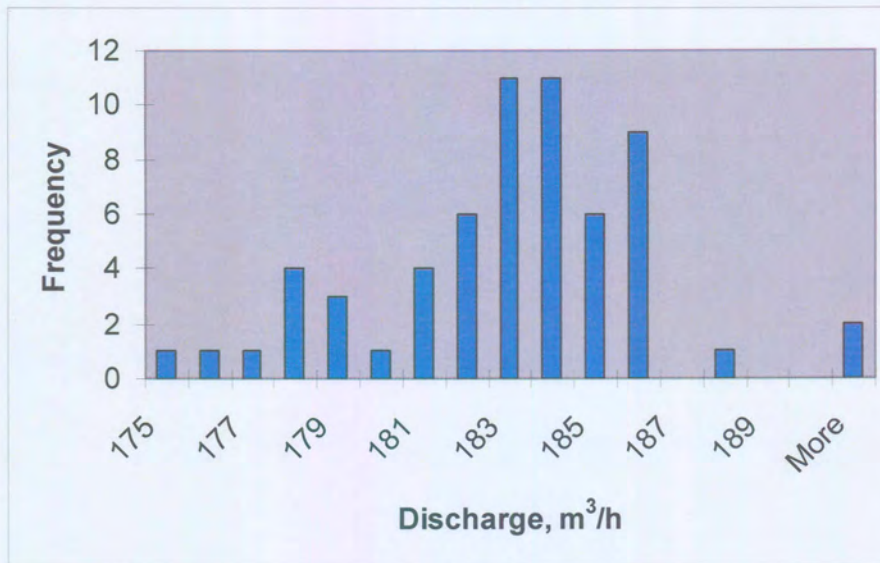
(b) Discharge



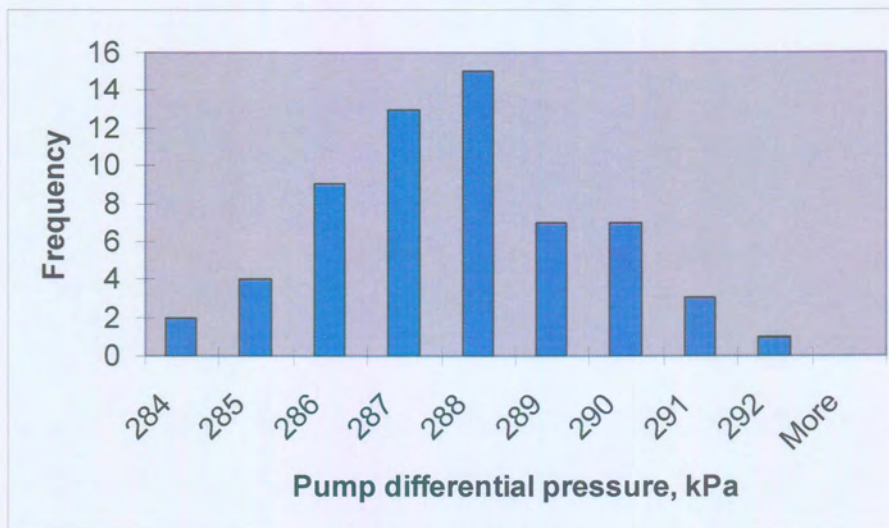
(a) Differential pressure

Figure 4.11 Frequency analysis at duty point for 30 ha pivot

The test conducted with only the 30 ha pivot in operation, showed that the differential pressure varied between 311 and 316 kPa during the test period. The discharge varied between 140 and 146 m³/h, with average discharge during the test period calculated as 142.05 m³/h.



(b) Discharge



(a) Differential pressure

Figure 4.12 Frequency analysis at duty point for both pivots

The test conducted with both the pivots in operation, showed that the differential pressure varied between 284 and 292 kPa during the test period. The discharge varied between mostly 175 and 189 m³/h, excluding to outlier values, with the average discharge during the test period calculated as 182.64 m³/h.

The differential pressure intervals and related average discharge values are summarised in Table 4.2.

Table 4.2 Summary of differential pressure intervals and average discharge values

Irrigation system	Differential pressure interval, kPa		Average discharge, m ³ /h
	Lower limit	Upper limit	
10 ha pivot	347	353	42.81
30 ha pivot	311	316	142.05
Both pivots	284	292	182.64

The results of the frequency analyses were used to structure a set of logical statements that could be used to evaluate continuous data in stead of the continuous equation describing the Q- Δp relationship, as shown below:

```

IF 347 ≤ Δp ≤ 353
THEN Q = 42.81
ELSE
IF 311 ≤ Δp ≤ 316
THEN Q = 142.05
ELSE
IF 284 ≤ Δp ≤ 292
THEN Q = 182.64
ELSE Q = 0

```

The application of this set of statements is further discussed under section 4.3.3 below.

4.3.3 Comparison of the Q- Δp relationship with the pump curve

As in the case of the laboratory tests, the measured differential pressure values were compared with the pump curve values at the measured discharge readings, by reading the theoretical discharge from the pump curve at the measured differential pressure values. The results are presented graphically in Figure 4.13.

As in the case of the laboratory pump there were large deviations at the low discharge values, but the further on the discharge according to the pump curve is consistently higher than the measured values, due to the increase in the velocity head component of the total head with the increase in discharge. It would seem

therefore that the pressure transducers in the field were better positioned than those in the laboratory, and consequently better quality measurements were made in the field.

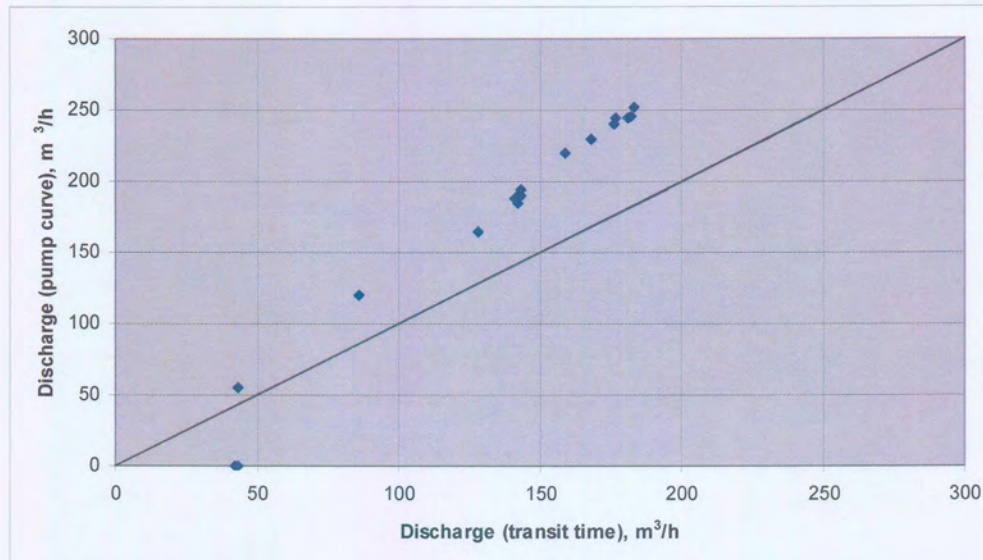


Figure 4.13 Comparison of measured and pump curve discharge values

4.3.4 Calculation of volumetric discharge over 2 weeks

Data was recorded for a period of one month, but after it had been downloaded from the datalogger it was found that one of the pressure transducers failed two weeks after the start of the test. The failure was probably caused by the extremely cold conditions in the week of 18 to 22 August 2003, because the last correct measurement was recorded on 16 August 2003 according to the datalogger record.

The pressure readings from the two pressure transducers as well as the resultant pump differential pressure are presented graphically in Figure 4.14. Please note that the x-axis is not linear, since only the irrigation times were plotted and not a complete time scale for the test period.

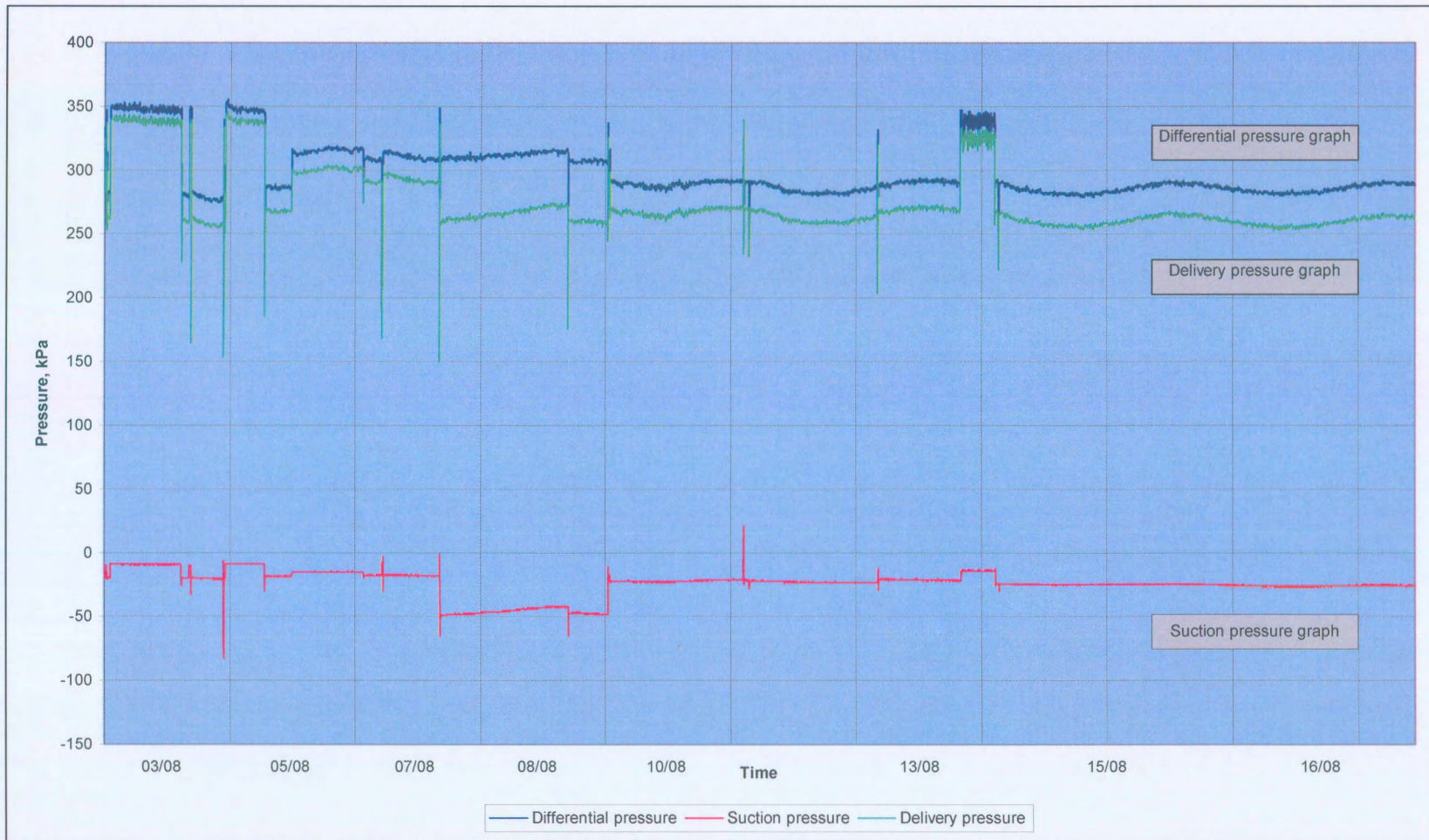


Figure 4.14 Suction, Delivery and Differential Pressure from the ield test

The suction pressure graph in Figure 4.14 shows little fluctuations and few outlier values over the two week period. On 8 August 2003 very low suction pressures were recorded, similar to the data from the calibration tests. It could possibly have been due to a dirty trash screen or low canal levels.

From the delivery side and differential pressure graphs, three main observations can be made:

- There are considerably more fluctuations (“noise”) between consecutive measurements.
- Outlier pressure values are recorded every time the pump is started, or changes are made on the demand side by a change in irrigation system.
- The graphs have a sinusoidal wave shape, which is the result of topographical changes encountered by the center pivot irrigation systems as they revolve. When the irrigation system is in a position downhill from the inlet, the static pressure head component of the system head requirement decreases, and vice versa.

The useful data was analysed using the logical statements described in section 4.3.2, but it returned many zero discharge values because of the fluctuation in measurements as observed on the graph. It was decided to widen the limits for each differential pressure interval to determine whether better results could be achieved, and after some adjustments the final intervals that were used are shown in Table 4.3.

Table 4.3 Summary of final differential pressure intervals and average discharge values

Irrigation system	Differential pressure interval, kPa		Average discharge, m ³ /h
	Lower limit	Upper limit	
10 ha pivot	320	360	42.81
30 ha pivot	295	320	142.05
Both pivots	270	295	182.64

The calculated discharge values together with the differential pressures are presented graphically in Figure 4.15. A sample of the data is attached in Appendix F (the total amount of data is more than 6000 rows long).

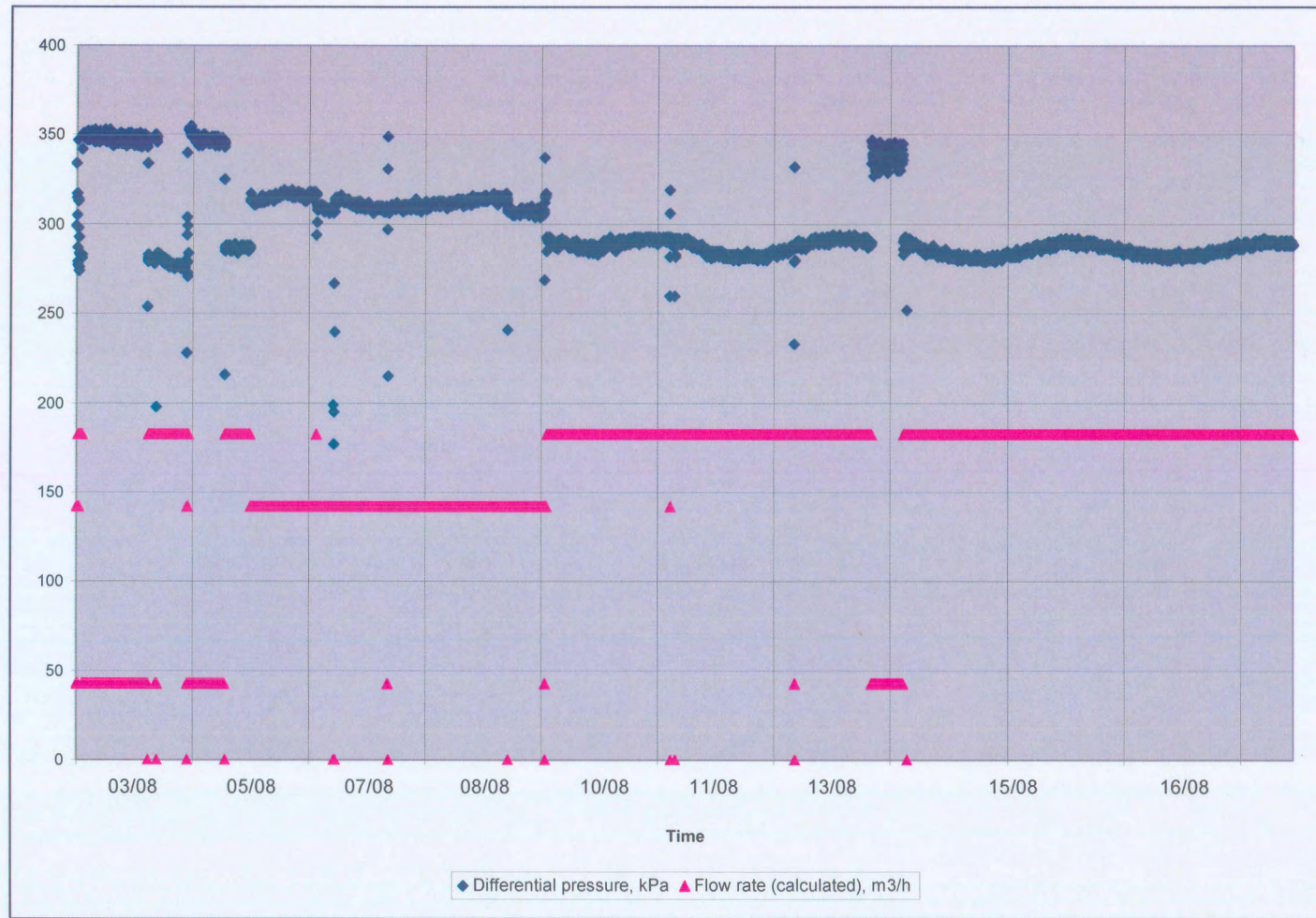


Figure 4.15 Calculated discharge values for the field test

Despite the increased differential pressure intervals, a small number of outlier values were still present in the discharge data and can be seen on the graph in Figure 4.15. The sinusoidal wave-like differential pressure graphs are now represented by linear sections of the discharge graphs. The effect of this simplification can only be investigated by recording the actual discharge continuously over a period of time at least equal to the length of one complete cycle of the irrigation systems, to see whether there are significantly fluctuations in the discharge values, as observed with the differential pressure values.

The volume of water abstracted during the two week period was calculated by adding the discharge per minute over the whole period, which gave a total of 16359.29 m³. A graph of the cumulative volume over water abstracted over time is shown in Figure 4.16.

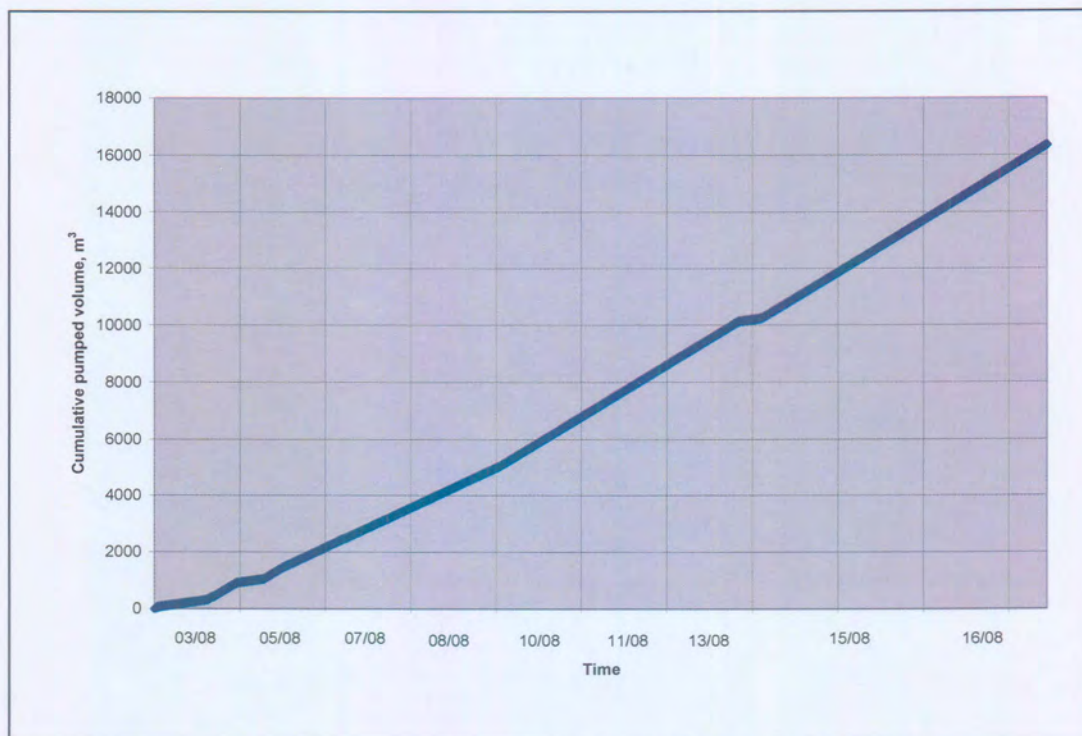


Figure 4.16 Cumulative volume of water pumped during the field test

4.3.5 Verification of measurements

In order to evaluate the validity of the results, the calculated volume was compared with the measurement output of the prototype electronic flow meter, as well as with typical crop water requirements as estimated for the climatic area by the computer

program SAPWAT. SAPWAT is the official irrigation planning tool of the Department of Water Affairs and Forestry, and has been tested extensively in the area where the experimental work was done. It was therefore considered to provide an accurate benchmark at least for irrigation requirements in the area.

The impeller type mechanical meter reading could not be used since numerous in-field verifications with the portable transit time meter showed that the mechanical meter produced errors that varied between -4.7% and $+56.4\%$ when compared to the transit time meter readings, and was therefore not considered to be reliable. The mechanical meter was returned to the manufacturers for checking after completion of the study and it was found to be faulty. The transit time meter could not be used for record keeping since it was not permanently installed, and security was a concern.

According to the electronic meter a volume of 16015 m^3 was pumped during the test period. This agrees well with the theoretical nett irrigation requirement of 16796 m^3 as calculated with SAPWAT.

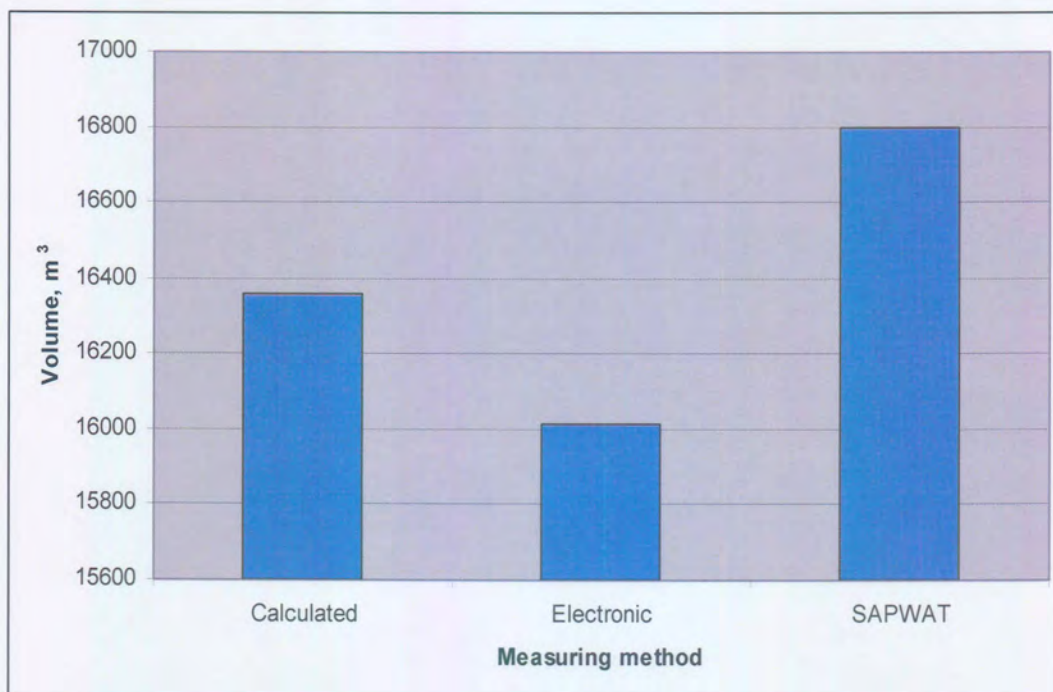


Figure 4.17 Comparison of pumped volumes according to three methods

Making use of these two reference values, the measurement error of the experimental measuring method can be calculated as $+2.15\%$ of the electronic meter reading.

Although these results are promising, ideally one would want to conduct a long term test where the discharge can be measured and recorded continuously with a flow meter of known accuracy together with the pressure readings.

5. Conclusion and recommendations

5.1 Conclusion based on technical results

A possible alternative method for the measuring of irrigation water abstracted from surface water sources by centrifugal pumps have been developed and tested in the course of this study. An overview of the conclusions based on the technical results is presented here.

5.1.1 System requirements

The application of the experimental measuring method is limited to water pumped with a centrifugal pump to an irrigation system under pressure. Ideally the pump and switchgear have to be enclosed in a pump house to protect the measuring equipment against the elements and vandalism. The farmer should be informed about the equipment and preferably be supportive to the implementation of volumetric water measurements.

5.1.2 The equipment

Appropriate equipment was identified and used in the laboratory and field evaluations. The application of the experimental measuring method requires the installation of two pressure transducers (one upstream and one downstream of the pump) and datalogger (which requires electricity) as well as suitable pipe work to install a portable ultrasonic flow meter for calibration.

The measuring range of the pressure transducers has to be chosen according to the pump head. They may be connected to existing threaded connections, if they are suitably placed, or alternatively connections may have to be fitted to the pipe work in the field. In the case of large diameter pipes, this may require specialist equipment and skills.

Care has be taken if there is a possibility that temperatures may drop to freezing point or below, since this may cause damage to the pressure transducers. Provision should be made for it to be drained if cold weather is expected.

The datalogger has to be installed in a protective enclosure and preferably off the ground to prevent damage from water due to rain and leaks in the pump house. It

needs a reliable power supply to ensure data is not lost. Most irrigation farmers use electrical motors to drive centrifugal pumps nowadays, and this source could be used if the farmer agrees. Although one could argue that the farmer can't irrigate if the power supply is switched off and therefore no data would be lost if the logger is switched off, the datalogger may require a back-up battery as standby power source since some models reset some function if disconnected from the power supply.

In order for calibration of the pressure transducers to take place, the system discharge will need to be measured. Since this is usually only a temporary installation, the use of portable clamp-on type meters (usually ultrasonic) is recommended. Insertion type electromagnetic meters may also be used but it will require a threaded coupling on the pipe work to be installed. Unfortunately the ultrasonic meters' performance is negatively influenced by disturbances in the flow profile, which means that their installation requirements often demands up to 20 pipe diameter lengths of straight pipe, and this is often not available. The manufacturers' installation guidelines should always be followed as closely as possible.

The cost of the equipment varies greatly according to what specifications one requires, but even a simple unit for one pump will cost at least the same or probably more than a mechanical flow meter. However, it will provide the user with a lot more information than the mechanical meter, such as pumping time and rates. Some options for equipment are shown below in Table 5.1.

By spending more on the equipment, for instance investing in a telemetric communications system or buying a datalogger with more storage capacity, the cost of data collection can be reduced considerably since it could eliminate visits to the installation sites, which are often remote and may be inaccessible in bad weather conditions.

A comparison of the experimental method with other conventional methods according to initial costs (supply and install) and accuracy is shown in Figure 5.1. It can be seen that the benefit of improved accuracy can be gained without incurring the high cost of conventional accurate measuring methods.

The cost of installation is also shown, although it can be seen that it is considerably less than the cost of supplying any meter.

Table 5.1 Cost of equipment

Item	Options	Price
Pressure transducers	Two separate electronic transducers, 0.25 % FS accuracy, 4-20 mA output	R2200 each
	Differential pressure transducer with similar specifications as above (will produce half the number of data points compared to two separate PTs)	R3500 each (only 1 required)
Datalogger	Low cost logger with 2 input channels and 8000 data point storage capacity (may require weekly data collection if two PTs are used)	R2000 (excluding software and communications cable)
	Mid-range datalogger with 5 input channels and 60 000 data point storage capacity and programming capability	R4000 (excluding software and communications cable)
	Same as above with internal radio frequency communication hardware for remote data collection	R6000 (excluding software and communications cable or antenna and radio unit at base station)
Power supply	Back-up battery and trickle charger for pressure transducers and datalogger	R600 – R1000
	Solar panel and regulator in stead of trickle charger	R2000
Ultrasonic flow meter		R30000 – R120000

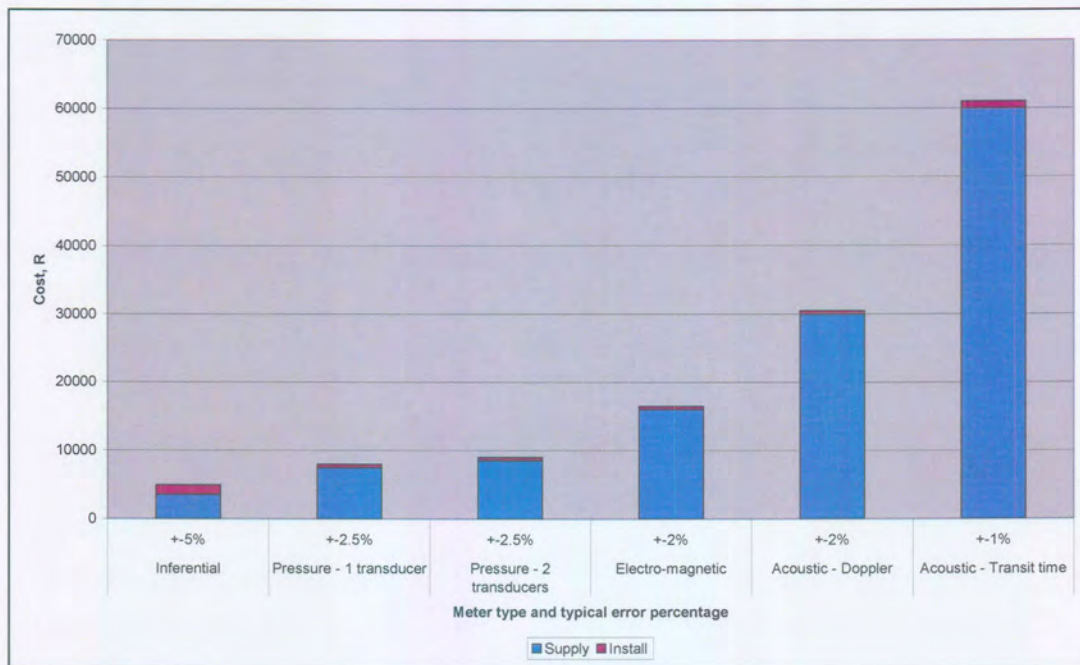


Figure 5.1 Comparison of meters according to cost and accuracy

5.1.3 Calibration (determining the Q- Δp relationship)

The results showed that although it was possible to find a mathematical function that describes the relationship between the discharge and differential pressure of a centrifugal pump, it was not feasible to use the relationship to calculate the discharge accurately from differential pressure readings. Continuous fluctuation in the pressure, particularly on the delivery side, cause incorrect discharge values to be determined.

Since most pumps used for irrigation water supply is dedicated to operating at one or more fixed duty points depending on the size of the irrigation system, a better approach is to identify these duty points and determine the intervals within which the pressure fluctuates as well as the average discharge when the pump is being operated at each of the duty points.

The number of data points collected for the calibration will depend on the irrigation system. If it is a static system, like micro irrigation, the pressure fluctuations will be less. If it is mobile system however, care has to be taken that all possible operating conditions are covered by the calibration data.

In the case of the field test in this study, only one average discharge value was assigned per duty point, but to improve accuracy it may be necessary to distinguish between different differential pressure intervals at one duty point. The discharge should be measured as accurately as possible since it will directly affect the experimental measuring method's accuracy.

It may be necessary to repeat the calibration at regular intervals, for instance annually, to make provision for any changes in the pump performance or irrigation system. Due to wear on the pump and motor elements, the pump's characteristics may change over time which will render the previous calibration inaccurate. Furthermore, it may also be possible that the irrigation system demand may change over time, for instance due to the enlarging of sprinkler nozzles due to abrasive water, or the blockage of micro irrigation emitters.

For cases other than those where the water is pumped directly to the irrigation system, such as where the water is discharged into a dam, the use of the continuous Q- Δp relationship will have to be investigated further, especially if the water level on the suction side varies often.

The cost of calibration at one site is difficult to quantify since it needs to consider factors such as whether a portable ultrasonic meter is available, how far the calibration team must travel, how many sites can they calibrate during one trip, and do they need to be paid specifically for the calibration (or are they full-time employees of a WUA).

5.1.4 Monitoring

The results of long-term monitoring of volumetric discharge were favourable and compared well with the reference value that was available (measurement error of +2.15% of the electronic flow meter reading), although the study would have benefited from better in-field verification of results. Both meters' readings also compared well with the crop water requirement benchmark as calculated with SAPWAT, although this cannot be used to verify the actual pumped volume.

For effective monitoring to take place there has to be decided on a suitable datalogging interval. This will depend on a number of factors some of which can be

evaluated during the calibration process, such as the size and regularity of fluctuations.

The capacity and sophistication of the datalogger is often the deciding factor. If the storage capacity of the datalogger is small, an interval will have to be chosen that ensure that the memory will not become full or overwrite itself before the data is collected. Some dataloggers have a function that enables it to only collect data when triggered by an external signal, for instance, if the pressure on a specific channel increases above a specified level it only starts recording. Unfortunately this function is usually reserved for more complex loggers.

In general shorter intervals are better because any unnecessary data can be discarded, but outstanding data cannot be created. Regular data collection is also important to ensure that malfunctioning equipment is repaired or replaced without too much data loss.

It was found that the data can be useful for more than just measurement purposes. It provides a record of when irrigation took place and this could be useful for effective irrigation scheduling and energy management. For WUAs, historical data could be used to predict peak demands on the distribution system or to monitor abstraction rates, where it is used as a control measure.

5.2 Implications for theory and practice

In order to evaluate the useful contribution the experimental measuring method could make to practical irrigation water measurement, some of the advantages and disadvantages compared to commercially available flow meters are listed below.

5.2.1 Advantages

- The equipment used is easier and less expensive to install into an existing pumping system than mechanical meters, since long straight pipe sections and expensive pipe fittings are not required.
- The cost of the meter does not increase for bigger pumps. Only the measuring range of the pressure transducers change, but the cost stays the same.

- A calibration laboratory is not required for meter calibration or maintenance.
- There are no moving parts that can wear out or be damaged through contact with the water.
- There is no obstruction to the flow in pipes or pump, and no additional headloss in the system.
- The data is recorded in a format that can be collected via telemetric communication without any changes.
- The recorded data include pumping times and rates which is useful for water management at scheme and farm level.

5.2.2 Disadvantages.

- The equipment that is used is not any less expensive than a mechanical meter.
- Sensitive electronic equipment could be easily damaged by harsh outdoor conditions or vandalism.
- The equipment requires electric power for operation.
- Re-calibration is required if any changes are made to the irrigation system.

5.3 Recommendations for further work

The results from this study have shown that measurement is possible with the experimental method, but it also raised further questions, especially with regard to the robustness of the equipment. It is envisaged that further work on the following aspects would contribute to evaluating the feasibility of practical implementation.

5.4.1 Equipment

- The use of a differential pressure transducer (rather than two separate suction and delivery side transducers) needs to be investigated. This may reduce costs and the number of recorded data points.
- The installation of the pressure transducers directly on the pipework needs to be reconsidered. If the pressure transducer(s) could be housed in the same enclosure as the datalogger, it would be better protected against the elements and vandalism.

5.4.2 Calibration

- The validity of the $Q-\Delta p$ relationship and calibration over a long period of time needs to be investigated, since it may change due to wear on the pump or motor.

5.4.3 Monitoring

- Further long-term tests need to be performed where the experimental method is used to measure the volume of water discharged by a specific pump, for instance over one irrigation season, in a system where the results can be compared continuously with the output from another measurement device of known accuracy.

References

- Andrag-Agrico. 2002. PERSONAL COMMUNICATION: MR G OBERHOLSER. Kimberley.
- Bosman, H. 2001. PERSONAL COMMUNICATION. Pretoria: Department of Water Affairs and Forestry.
- Cipindu, P. & Wantenaar, C.J. 2000. DOMESTIC WATER METERS: INFLUENCE OF VARIOUS FITTINGS AND INSTALLATION CONFIGURATIONS ON ACCURACY OF 15 mm WATER METERS. WRC Report nr 948/1/00. Pretoria: Water Research Commission of South Africa.
- Crabtree, M. 2000. MICK CRABTREE'S FLOW HANDBOOK (second edition). Bedfordview: Crown Publications.
- Department of Water Affairs and Forestry (DWAF). 2000. IMPLEMENTATION GUIDELINES FOR THE WATER CONSERVATION AND WATER DEMAND MANAGEMENT STRATEGY IN THE AGRICULTURAL SECTOR. Pretoria: Department of Water Affairs and Forestry.
- Department of Water Affairs and Forestry (DWAF). 2002. NATIONAL WATER RESOURCES STRATEGY. Pretoria: Department of Water Affairs and Forestry.
- Dunnicliff, J. 1988. GEOTECHNICAL INSTRUMENTATION FOR MONITORING FIELD PERFORMANCE. New York: Chapman & Hall.
- Hanson, B.R. & Schwankl, L.J. 1998. ERROR ANALYSIS OF FLOW METER MEASUREMENTS. Journal of Irrigation and Drainage Engineering, vol. 124 nr 5, pp 248-256.
- Hoffmann, J. 1991. MANAGEMENT OF FARM IRRIGATION SYSTEMS. ASAE Monograph. St Joseph: American Society of Agricultural Engineers, pp 315 – 370.
- Karassik, I.J., Krutzch, W.C., Fraser, W.H., Messina, J.P. (eds). 1986. PUMP HANDBOOK. New York: McGraw-Hill Book Company.

Kolhe, M. Kolhe, S. & Joshi, J.C. 2001. DETERMINATION OF DAILY VOLUME OF PUMPED WATER AS A FUNCTION OF MECHANICAL ENERGY FROM A PHOTOVOLTAIC WATER-PUMPING SYSTEM. Proceedings of the Institution of Mechanical Engineers, vol 215, part A, pp 399-402

Kriek, C.J. 1986. 'n VERSLAG INSAKE DIE GEBRUIK VAN WATERMETERS VIR BESPROEINGSDOELEINDES. Pretoria: Department van Waterwese.

KSB Pumps. 1994. LOW PRESSURE CENTRIFUGAL PUMPS ETA + ETA-X. Technical brochure. Johannesburg: KSB Pumps (Pty)Ltd.

MBB Consulting Engineers. 1997. POSSIBLE MONITORING METHODS FOR ABSTRACTIONS FROM THE THEEWATERSKLOOF DAM. Report nr S1741/1 to the Department of Water Affairs and Forestry. Stellenbosch.

MBB Consulting Engineers. 2001. THE DETERMINATION OF THE ACCURACY WHEREBY THE FLOW RATE OF ELECTRIC DRIVEN PUMPS CAN BE CALCULATED THROUGH MEASUREMENT OF THE ELECTRIC POWER SUPPLIED TO THE MOTOR: PROGRESS REPORT. WRC Project Nr K5/1190. Stellenbosch.

MBB Consulting Engineers. 2003. DRAFT FINAL REPORT: PROJECT S1844. WRC Report nr K5/1190. Stellenbosch.

Meinecke Meters. 2001. PRODUCTS, SYSTEMS, APPLICATIONS. Laatzen: H Meinecke AG

Miller, R.W. 1989. FLOW MEASUREMENT ENGINEERING HANDBOOK (second edition). New York: McGraw-Hill Publishing Company.

National Water Act. 1998. ACT NO 36 OF 1998. Department of Water Affairs and Forestry: Republic of South Africa.

Replogle, J. 1999. MEASURING IRRIGATION WELL DISCHARGES. Journal of Irrigation and Drainage Engineering, vol. 125 nr 4, pp 223-229.

SIHI Group (ed.). 1985. BASIC PRINCIPLES FOR THE DESIGN OF CENTRIFUGAL PUMP INSTALLATIONS. Ludwigshafen: SIHI-Halberg.

United States Bureau of Reclamation (USBR). 1997. WATER MEASUREMENT MANUAL. Denver: US Government Printing Office.

Van der Stoep, I., Benadé, N. & Smal, H.S. 2002. PROGRESS REPORT: WRC PROJECT NR K5/1265 IRRIGATION WATER MEASUREMENT. Pretoria: University of Pretoria, Department of Civil and Biosystems Engineering.

Zimmermann, H. 1999. EXAMINATION OF DISTURBED PIPE FLOW AND ITS EFFECT ON FLOW MEASUREMENT USING ORIFICE PLATES. Flow measurement and Instrumentation, vol. 10, pp 233-240.

Appendix A: Evaluation of meters previously installed by WUAs

A1. Evaluation methodology

A1.1 Introduction

Three different types of flow meters were evaluated at WUAs in the Western and Northern Cape:

Readings from the meters were compared with the discharge measurements done with the transit time meter. During the identification of suitable sites, some difficulties were encountered with finding sites where the required straight pipe diameter lengths before the meter as required by the manufacturer could be met. This raised the question of what effect any deviation from the guidelines would have on the accuracy of readings. In order to determine the possible effect, a series of tests were performed under laboratory conditions.

A1.2 Field tests of existing meters

A summary of the three sites at which meter were evaluated is shown in Table A1.

Table A1 Sites where existing meters were evaluated

Site nr	Site description	Meter brand	Meter type	Nominal diameter	Normal discharge
1	Orange-Riet WUA: Canal abstraction	ABB Kent	Inferential (impeller)	200 mm	185 m ³ /h
2	Stellenbosch WUA: Simonsig Pump Station	Emflux	Electro- magnetic	350 mm	490 m ³ /h
3	Worcester East WUA shallow well abstraction	Meinecke (now Invensys)	Inferential (turbine)	50 mm	25 m ³ /h

A1.2.1 Orange-Riet WUA

The meter that was evaluated, was a newly installed impeller type meter. The pumping system is used to abstract water from a canal and deliver it to two center pivot irrigation systems. The system was previously fitted with a turbine type meter

which was still in place but not registering any flow on the counter, probably due to stripped gears or the turbine being jammed.

The farmer experiences a lot of problems in summer with algae and other organic material in the water, and this was probably also the cause of the old meter's failure. Despite the trash screen in the canal at the pipe inlet, strings of algae and water grass still finds its way into the system and gets caught in the mechanism of the flow meter. Eventually the turbine stops turning and no flow is recorded.

The impeller type meter is said to be more resistant to failure due to the effect of dirty water since the impeller is fitted at the top of the meter casing and only partially obstructs the flow path of the water. Furthermore, the system is fitted with a strainer, and the new meter was installed downstream of the strainer (the old meter was in front of the strainer). See Figure A1.

The impeller meter is fitted with a pulse output, which makes it possible to read the meter discharge on a digital display unit.

A number of positions for installation of the transit time meter were tested, and the best found to be between the turbine meter and the strainer, where a good signal strength and repeatability of readings were observed. At positions downstream of the pump, problems were encountered with maintaining a strong signal due to vibration of the pipe (steel) and excessive turbulence due to the butterfly valves, especially when one of the valves were partially closed.

Readings with both the mechanical and the transit time meters were taken over a flow range of 20 to 250 m³/h by adjusting the butterfly valve downstream of the impeller type meter.

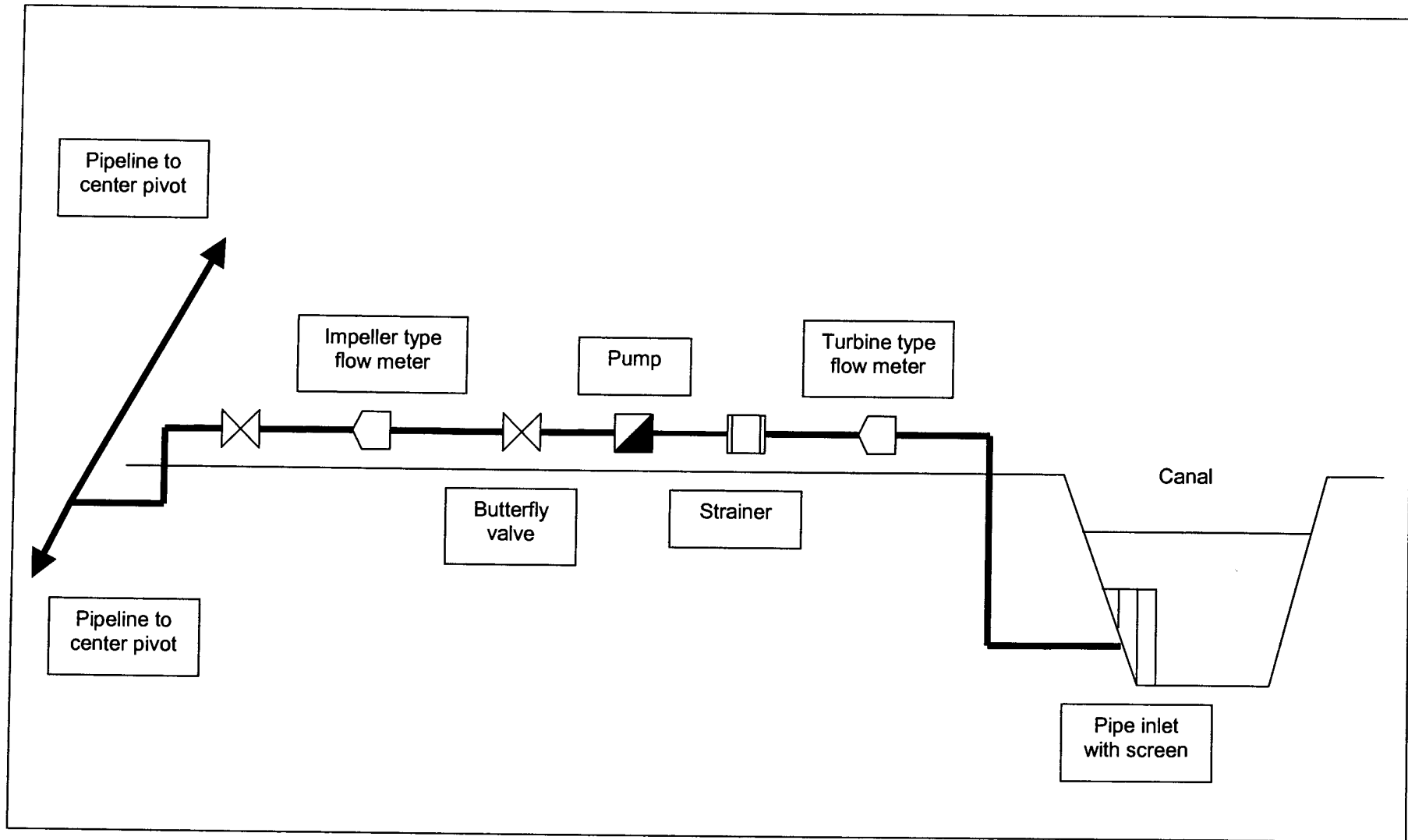


Figure A1 Pumping system lay-out: Orange-Riet WUA (elevation, not to scale)

A1.2.2 Stellenbosch WUA

The Stellenbosch WUA has the longest pipe distribution system of all WUAs in the country, as well as the highest water tariffs. Water is provided to farmers cultivating a total listed irrigated area of approximately 6000 ha at 4000 m³/ha/year, and to a number of small municipalities. The whole system is piped, and water delivered at a guaranteed discharge and pressure.

The test site is not a individual abstraction point, but a booster pump station operated by the Stellenbosch WUA. It consists of three Allis-Chalmer 9000 (10x6x22) pumps in parallel and discharge is measured with an electromagnetic flow meter which was installed about 7 years ago. The demand on the system at this stage is low enough so that only one pump is operated at a time. The pump station was designed with future development downstream in mind.

All the pipes at the pump station are steel; the suction side nominal diameter is 400 mm, and the delivery side is 350 mm. Readings were taken over a flow range of 20 to 500 m³/h.

The transit time meter was tried at two positions, one on the suction sided, before the inlet manifold, and at another on the delivery side, after the electromagnetic meter. The second position was found to give the most credible readings. On the suction side, fluctuations in the flow were often detected after adjustments to the valves; it could also be observed on the suction side pressure gauge.

This site was also used for the field tests to evaluate the measurement method.

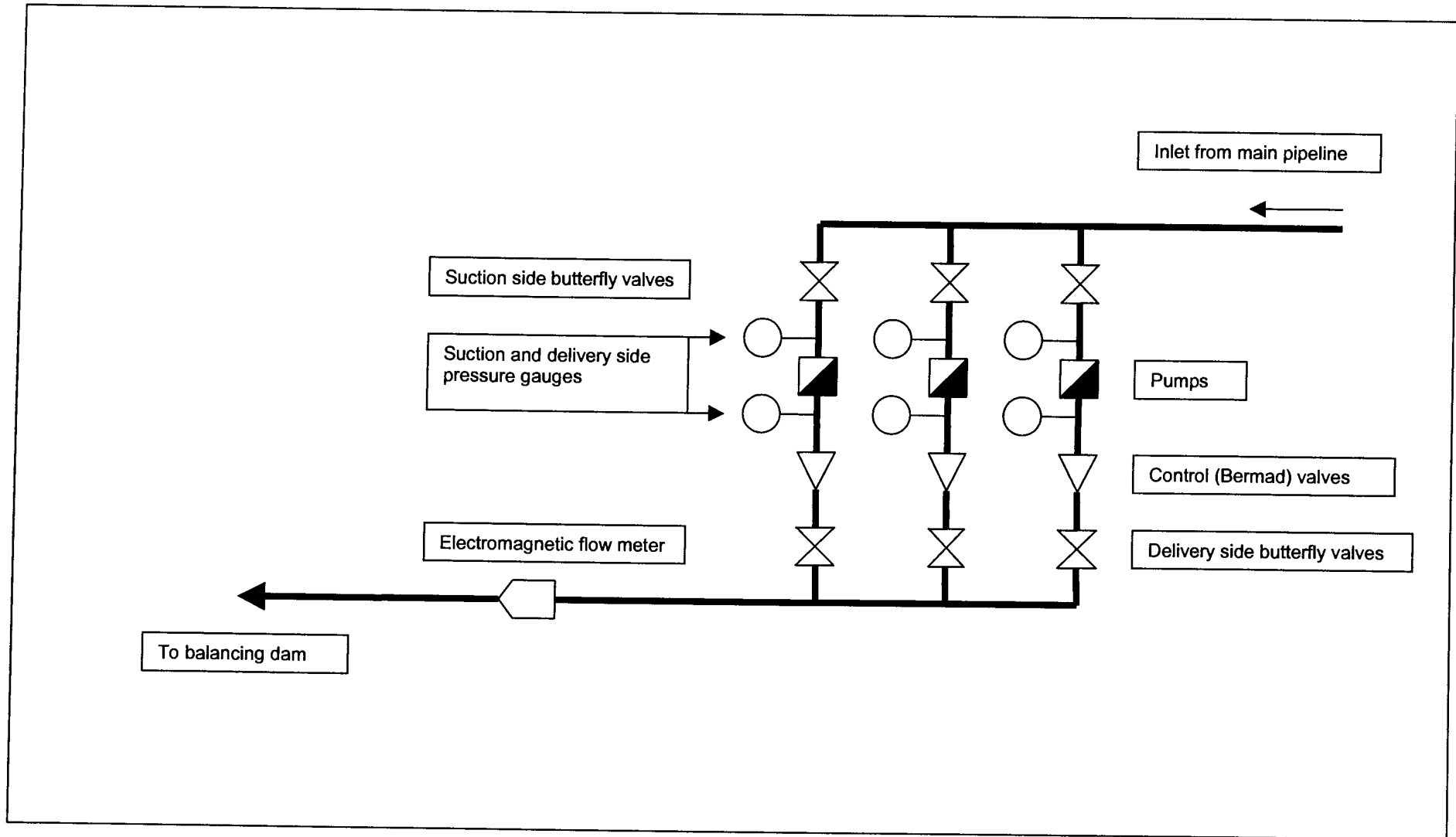


Figure A2 Schematic lay-out of the Simonsig pump station at the Stellenbosch WUA (plan, not to scale)

A1.2.3 Worcester-East WUA

The site at the Worcester East WUA is situated close to the Hex River. The farmer does not abstract directly from the river, but the practice is to dig a shallow well, slightly deeper than the riverbed, near the river. Because the well is deeper than the level of the water table, ground water filters through the porous soil from the river and fills the well.

The WUA actually releases water down the river ordered by farmers that have “legal” abstraction points directly from the river. Abstraction through the wells, however, is not metered, but it influences the river flow, often resulting in water shortages at the bottom end of the WUA’s area, and disputes between the staff and farmers.

The pump at this site (DAB K28/500T) is mounted on a float that floats on the water in the well, and the turbine type meter was installed in the 50 mm delivery side pipe (poly ethylene) from the pump to the side of the well.

The transit time meter was installed on the PE pipe between the pump and the gate valve. The turbine meter was fitted with a pulse counter and digital display to monitor the discharge and readings with both flow meters were taken over a flow range of 4 to 25 m³/h.

This site was also used to perform field tests of the experimental measuring method.

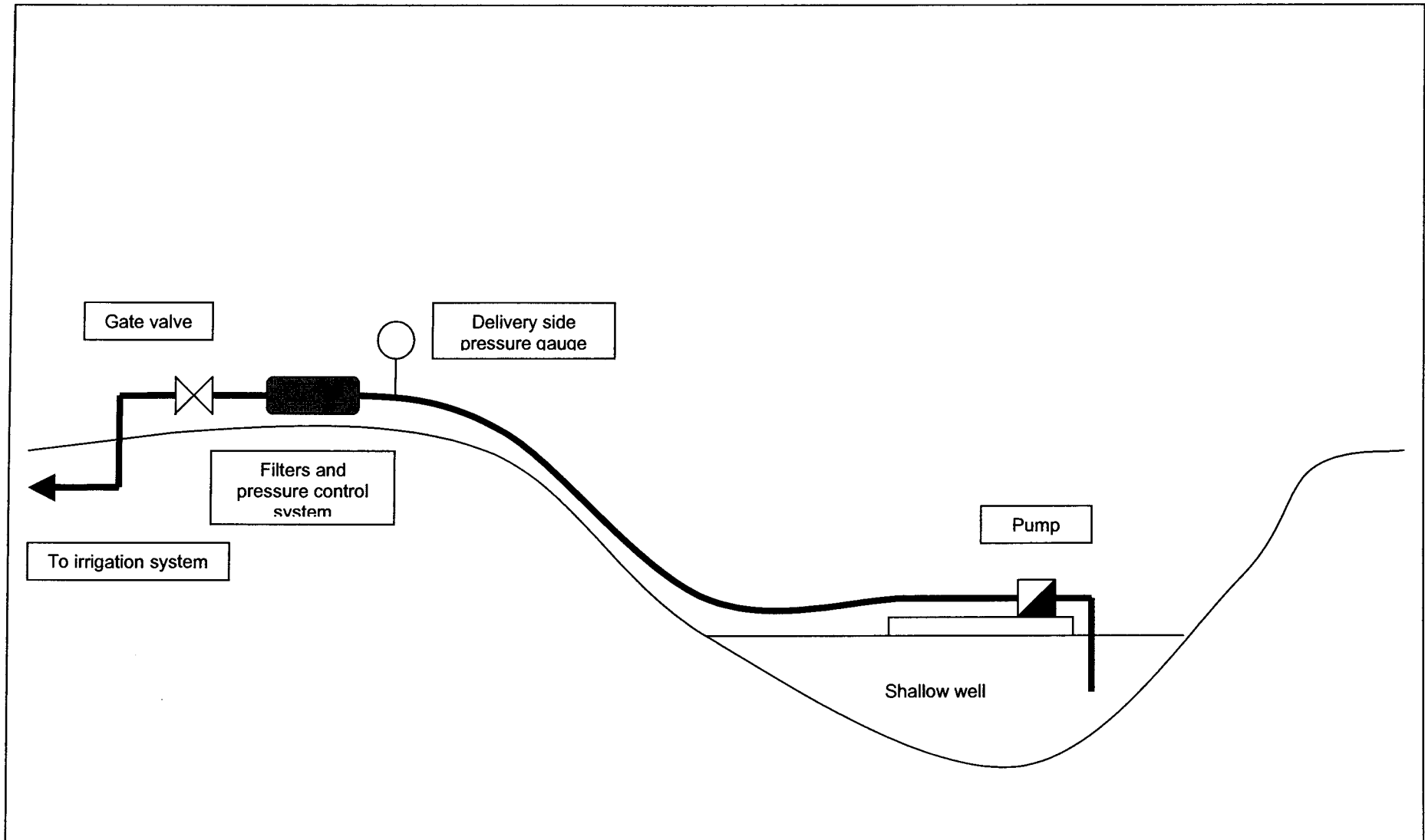


Figure A3 Schematic lay-out of the test site at the Worcester East WUA (elevation, not to scale)

A2. Test results

A2.1 Orange-Riet WUA

Although the data points show a slight tendency of decreasing error with increase in discharge, the points are erratically scattered, mostly indicating errors between –5% and +50 %.

The meter seems to give too high readings, but it had not been in use for very long at the time of the test, so the readings may decrease overall after some time of use.

Although it had been installed according to the manufacturer's installation instructions, it is down-stream from the pump, a butterfly valve and a 90 degree bend which may be causing excessive turbulence in the pipe. During the test it was observed that the counter on the dial does not turn smoothly, almost as if it is getting stuck or becomes unbalanced, but whether the results is superficial cannot be said for certain. Another factor is the high concentration of algae and other physical impurities in the water.

This meter performed the worst of the three that were evaluated.

A2.2 Stellenbosch WUA

Although this electromagnetic meter's readings were consistently higher than those of the transit time meter, the points are better grouped and less scattered.

The maximum error recorded was 39.4 % at 119 m³/h, but it is an outlier value and all the other points fall within the ± 30 % error range.

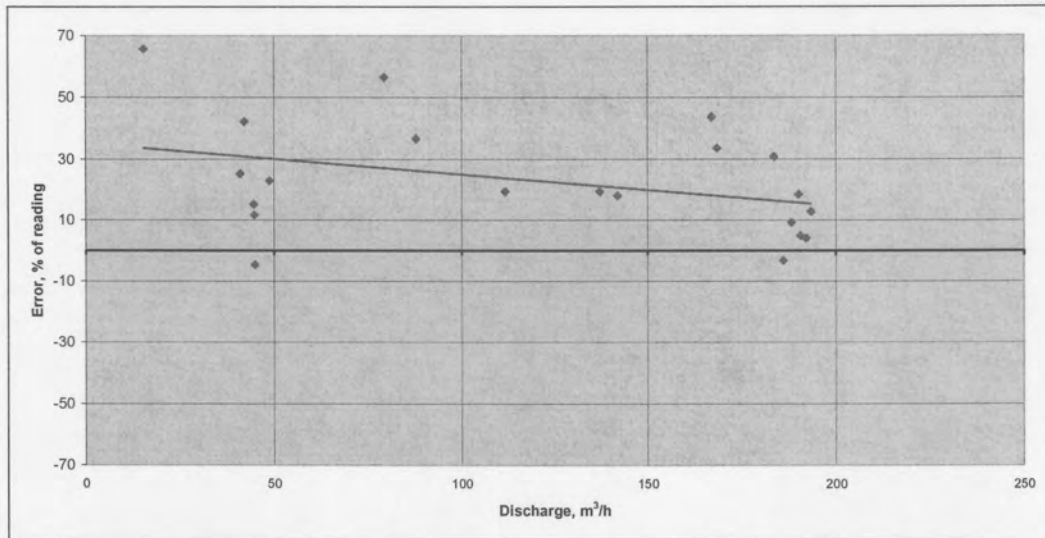
It would seem therefore that this meter could probably benefit from re-calibration (it was seven years old at the time of the tests). The place of installation of the transit time meter, however, was less than ideal and turbulence caused by the manifolds in the delivery pipe.

A2.3 Worcester East WUA

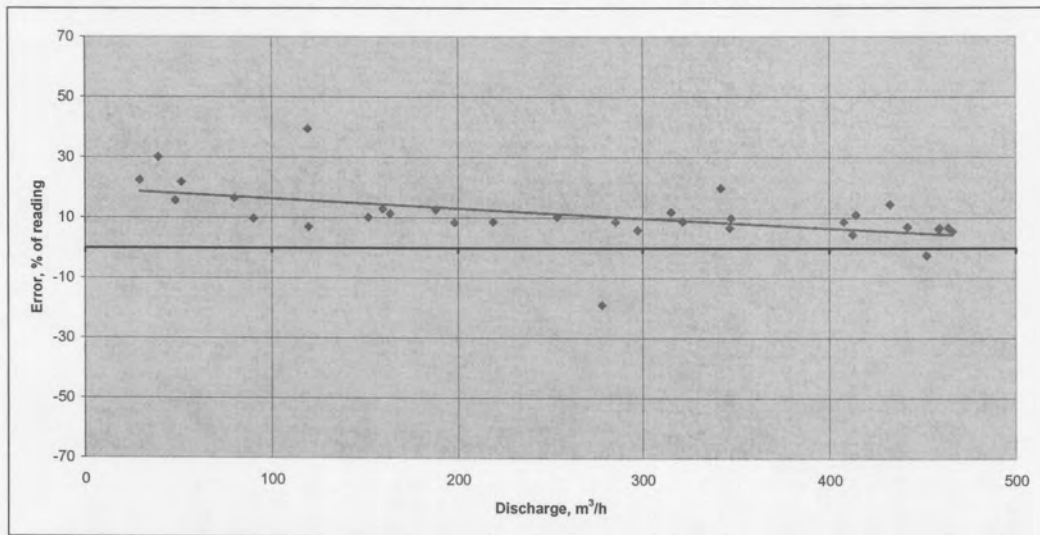
This meter performed the best of the three meters, and was also installed under the best conditions of the three, in a long straight slightly uphill sloping pipe without any disturbances.

The maximum error recorded was -13.3 % of reading at 4.5 m³/h, with the average of the readings being -11.1 %. The meter reads consistently low, and the data points show a linear relationship between error and discharge with a nearly flat slope (0.1698).

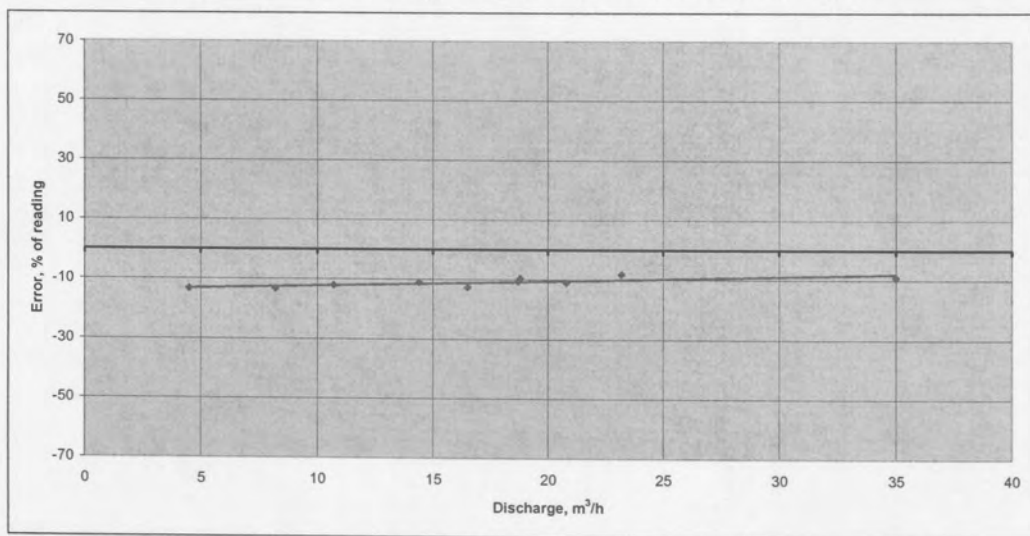
The data for all three tests is attached at the end of this Appendix.



(a) Impeller type meter at Orange-Riet WUA



(b) Electromagnetic meter at Stellenbosch WUA



(c) Turbine type meter at Worcester East WUA

Figure A4 Measurement errors of three typical irrigation water meters

A3. Conclusion

The evaluation of meters that are typically used for irrigation water measurement confirmed allegations by farmers and water management officials that the meters are inaccurate. All of the meters that were tested produced measurement errors larger than $\pm 10\%$ of the actual discharge.

The impeller type meter that was tested had only recently become available in South Africa and is looked upon favourably by WUAs because of the low head loss and little flow obstruction it causes in a pipeline, as well as affordability. However, it seems as if in their search for a measurement device with these characteristics, WUAs tend to give up measurement accuracy in return for these characteristics in a meter.

There is a definite need for training and capacity building amongst water users and WUA officials on different types of meters, choice of the right size meter and installation requirements.

During the field work, the portable transit time meter generated a lot of interest amongst the water users and officials, confirming the need for more technical information at grassroots level.



Orange-Riet WUA				
Transit time - impeller type meter comparison				
Transit time meter	Impeller type meter	Error		
Discharge	Discharge			
m ³ /h	m ³ /h	% of TT reading	(Xave-Xi) ²	
0	0.0			
15.53	25.7	65.6	1819.0	
41.09	51.4	25.2	5.0	
42.21	60.0	42.1	369.3	
44.66	51.4	15.2	60.4	
44.82	50.0	11.6	129.3	
44.96	42.9	-4.7	762.1	
48.83	60.0	22.9	0.0	
79.34	124.1	56.5	1124.6	
87.83	120.0	36.6	187.7	
111.77	133.3	19.3	13.2	
137.17	163.6	19.3	13.2	
141.93	167.4	18.0	24.5	
167.08	240.0	43.6	429.1	
168.52	225.0	33.5	112.1	
183.6	240.0	30.7	60.7	
186.06	180.0	-3.3	685.7	
188.27	205.7	9.3	186.7	
190.16	225.0	18.3	21.2	
190.6	200.0	4.9	323.9	
192.09	200.0	4.1	353.8	
193.45	218.2	12.8	102.9	
	Ave =	22.9	6784.4	
		S =	18.4	%



Stellenbosch WUA: Simonsig Pump Station					
Transit time - electromagnetic meter comparison					
Q	Q		Error		St dev.
magmeter	transit time				
m ³ /h	m ³ /h		% of reading		($\sum(Xave - Xi)^2$)
0	0				
36	29.4		22.4		133.9
51	39.2		30.1		369.7
56	48.4		15.7		23.3
63	51.7		21.9		120.6
93	79.9		16.4		30.5
99	90.2		9.8		1.3
128	119.6		7.0		14.8
166	119.1		39.4		812.4
167	151.6		10.2		0.5
180	159.4		12.9		4.2
182	163.4		11.4		0.3
212	188		12.8		3.6
215	198.2		8.5		5.8
225	278.1		-19.1		898.2
238	219.1		8.6		5.1
280	253.8		10.3		0.3
310	285.4		8.6		5.1
315	297.4		5.9		24.6
350	321.8		8.8		4.5
353	315.4		11.9		1.1
370	346.8		6.7		17.5
382	347.5		9.9		0.9
410	342.1		19.8		80.5
431	412.4		4.5		40.5
441	451.9		-2.4		176.6
443	407.7		8.7		4.9
460	414.1		11.1		0.0
473	441.7		7.1		14.4
488	458.6		6.4		19.9
490	458.9		6.8		16.8
492	465.9		5.6		27.8
495	463.7		6.8		17.0
495	432.3		14.5		13.2
		Average =	10.9	Sum =	2889.6
				S =	9.5 %



Worcester East WUA				
Transit time – turbine meter comparison				
Turbine m ³ /h	Transit time m ³ /h	Error % of reading	St dev. Calc (Xave-Xi) ²	
3.9	4.5	-13.3	4.8	
7.1	8.2	-13.4	5.2	
9.4	10.7	-12.1	1.0	
12.8	14.4	-11.1	0.0	
14.4	16.5	-12.7	2.5	
16.7	18.7	-10.7	0.2	
17.0	18.8	-9.6	2.4	
18.5	20.8	-11.1	0.0	
21.3	23.2	-8.2	8.7	
31.8	35	-9.1	4.0	
	Average =	-11.1	28.9	
		S =	1.8	%

Appendix B: Q- Δ p relationship field tests

B1. Test methodology

B1.1 Introduction

Further evaluation of the experimental method was done through a series of field tests at three locations. Two of the locations were the same as those used for the evaluation of existing meters (Stellenbosch WUA and Worcester East WUA); the third site was a river abstraction point on the farm Le Mouillage near Franschhoek.

The tests were performed in the same way as the laboratory tests, except that only two sets of tests were done at each site: one set to obtain data for the Q- Δp relationship, and a second set to evaluate the relationship.

B1.2 Stellenbosch WUA

A description of this site was given in section A1.2.2.

Although the pump station is not an individual abstraction point that needs to be measured, the WUA expressed interest in the experimental method for economical reasons. Their supply network consists of large diameter pipes (> 250 mm) for which flow meters are very expensive to install, and they are interested in more cost effective solutions.

Only one of the pumps at the pump station was used. The conditions under which it is being operated is ideally suited to the experimental measuring method since water is pumped to a storage dam and the pump is therefore always operated at the same duty point. There may be some variation in the duty point because of a variation in the suction side pressure, which is determined by the level of a reservoir in the supply line before the pump station.

Discharge was measured with the transit time meter installed as far as possible downstream of the pump as described previously. Pressure was measured with transducers on the suction as well as delivery sides of the pump.

B1.3 Worcester East WUA

This site has also previously been discussed in section A1.2.3.

Discharge measurement was done with the transit time meter.

Only the delivery side pressure was measured at this site. The reason is that the pump is mounted on a float which means that at a specific discharge, the suction head will always be the same, no matter what the level of the water is in the well. The suction side pressure will decrease exponentially with an increase in discharge due to an increase in friction in the suction pipe, but because the water level stays constant in relation to the reference datum (the eye of the impeller), the suction side pressure does not need to be measured.

B1.4 Franschhoek River

This river pump abstracts water from the Franschhoek River for a micro-irrigation system. The pump operates at various duty points throughout the year as the level of the river changes, and also since it supplies two different sizes irrigation blocks.

The pump discharges a maximum of about 18 m³/h into a 50 mm PE pipe. This caused some difficulties when using the transit time meter to measure the discharge. The meter becomes less accurate when used on small pipe diameter, since the signal path is very short and therefore the transit time that is measured, too. The readings were compared with those of the system's turbine type meter, and although the readings of the two meters differed, there was a linear relationship between the readings over the whole flow range. The transit time meter's readings were used in the results and analysis below.

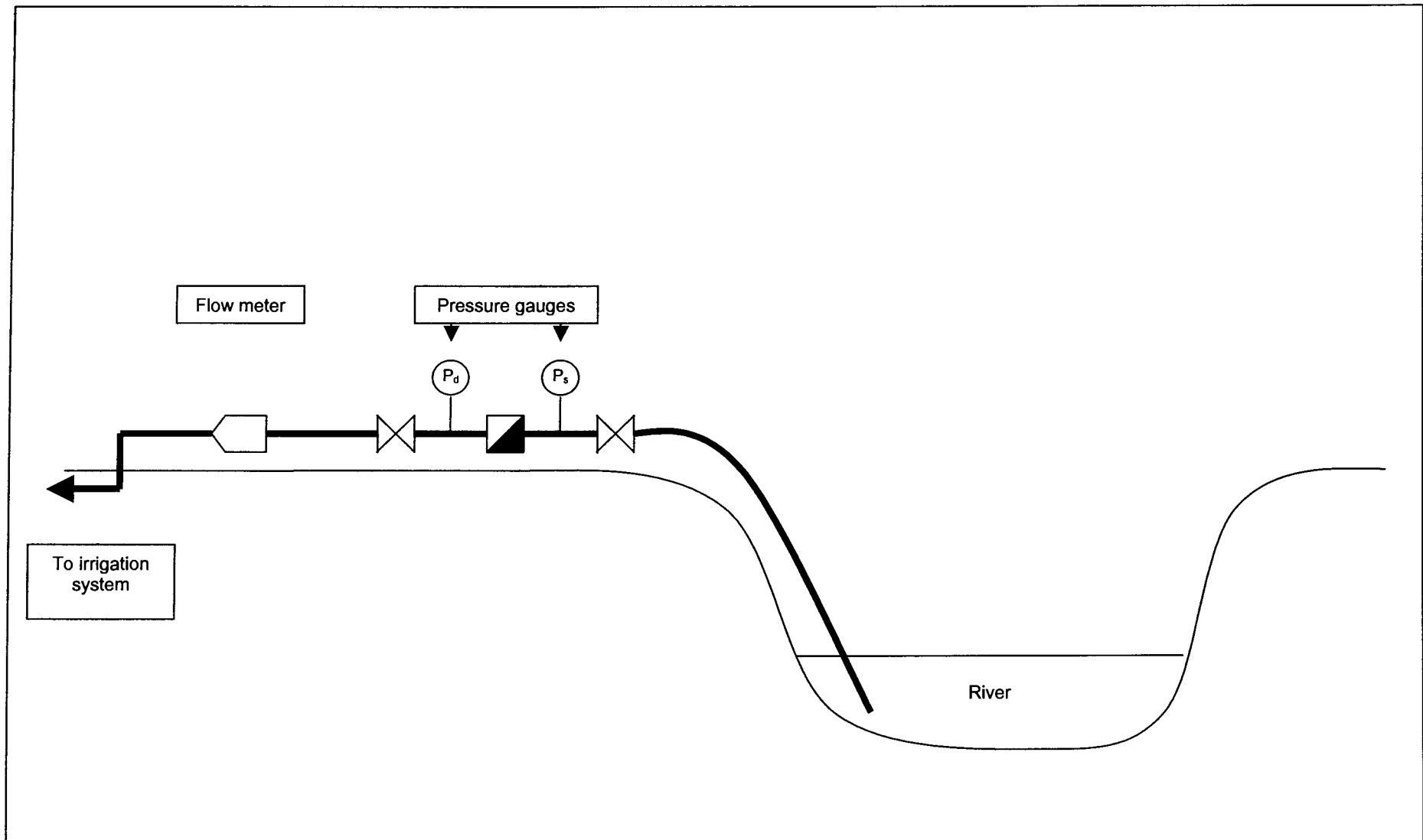


Figure B1 Schematic lay-out of Franschoek River site (elevation, not to scale)

B2. Test results

B2.1 Stellenbosch WUA

The pump test at this site produced a stable but very flat $\Delta p - Q$ curve, as shown in Figure B2. The regression curve through the differential pressure data points only has a positive slope at the very small discharge values, peaking at 14.5 m³/h, from where onwards it has a negative slope. However, the slope is very flat up to about 200 m³/h, and some difficulty was therefore expected in using the $Q - \Delta p$ relationship to calculate the discharge in the low flow range.

Because it is used as a booster pump, the pump is always subject to a positive suction head.

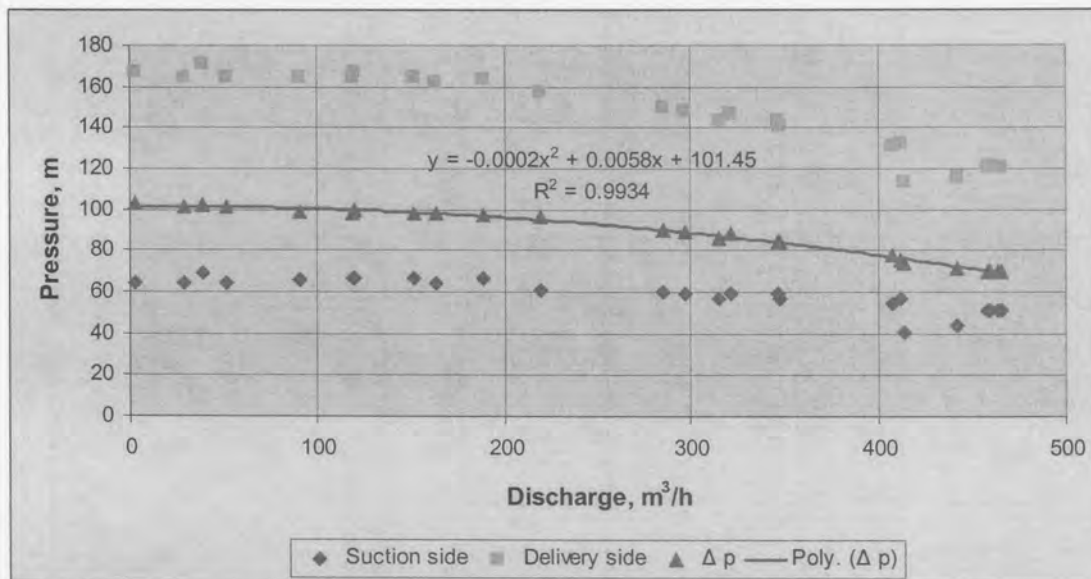


Figure B2 $\Delta p - Q$ curve for the Stellenbosch WUA pump test

Data points from the whole flow range were used to determine the $Q - \Delta p$ relationship. At first, two separate regression curves were developed, one for the low flow range data points and another for the high flow range data points. The curve for the high flow range fitted the data well ($R^2 = 0.9889$), in the low flow range no curve could be found with an R^2 value higher than 0.92.

It was then decided to use the original approach of developing one curve for the whole range of points, and a second order polynomial was fitted to the data, as shown in Figure B3. The curve is described by the following equation:

$$Q = -0.3566 \Delta p^2 + 48.737 \Delta p - 1215.2 \quad (\text{B1})$$
$$(R^2 = 0.9819)$$

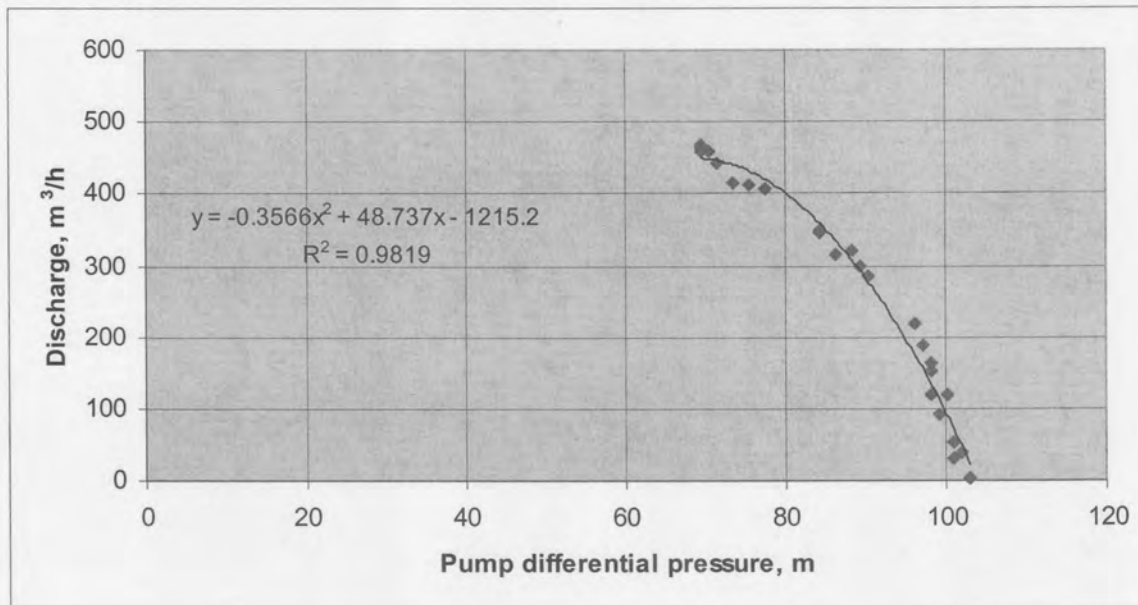


Figure B3 Q- Δp regression curves for Stellenbosch WUA pump test

Equation B1 was then evaluated using data from a separate pump test. The measurement errors as a percentage of reading were calculated and are graphically presented in Figure B4.

In the low flow range (0 to 250 m³/h), the equation produced errors larger than $\pm 10\%$ of reading, which is probably due to the very steep slope of the Q- Δp regression curve.

In the high flow range the second order polynomial produced errors less than $\pm 15\%$ of reading. From the distribution of the data points on the graph it seems as if there could have been some interference by the pipe elements.

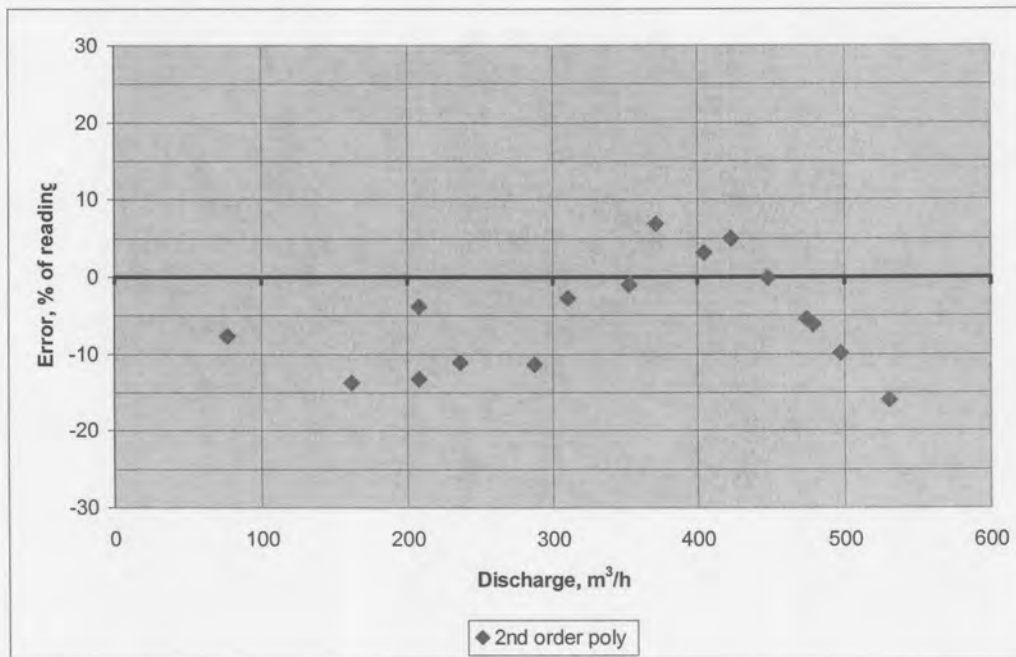


Figure B4 Measurement error graph for the Stellenbosch WUA test

The standard deviation of the error values was calculated as 6.75 % for the second order polynomial.

The data from the Stellenbosch WUA tests is attached at the end of this Appendix.

B2.2 Worcester East WUA

As explained in section B1, only the delivery side pressure was used at this pump. The Δp -Q curve that resulted from the test data as shown in Figure B5 is stable with a good slope in both the high and low flow ranges. Since the pump at this site has a maximum discharge of about 30 m³/h, it operates over a fairly limited flow and pressure range, with the maximum pressure that can be produced being 35 m.

The pump test produced relatively few data points because of the short operating range and the insensitivity of the gate valve used for adjusting the system discharge, but the regression curve fitted the points well ($R^2 = 0.9983$).

Two separate curves were fitted to the data on the Q- Δp graph (Figure B6) to determine the relationship between discharge and differential pressure, over the low flow range and the high flow range respectively.

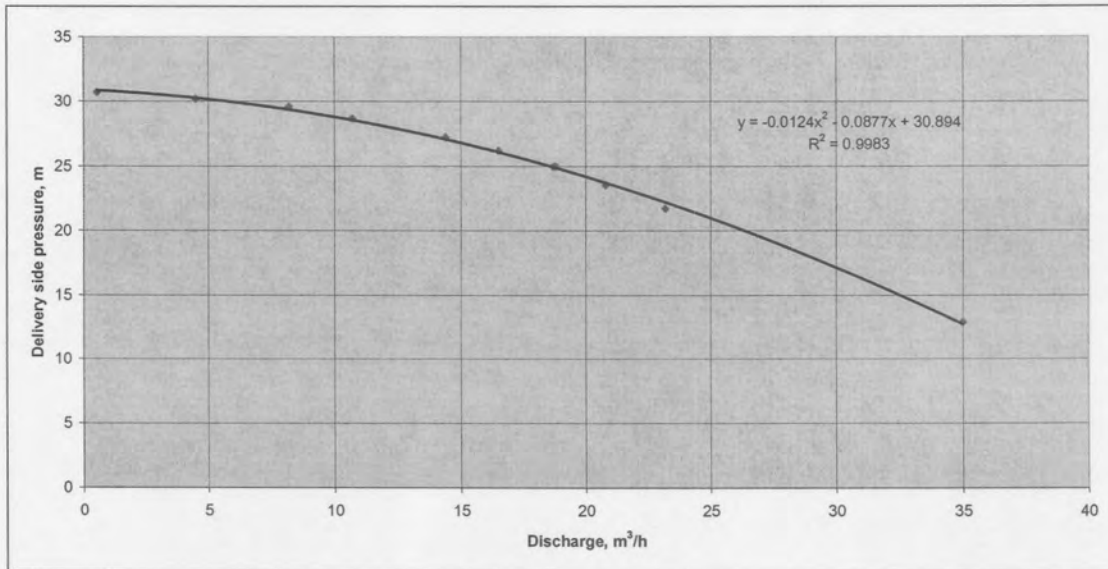


Figure B5 Δp -Q regression curve for Worcester East pump test

The Q- Δp curves are described by the following two equations:

For the low flow range (0 to 10 m³/h):

$$Q = -1.9477 \Delta p^2 + 110.55 \Delta p - 1557.9 \quad (B2)$$

$$(R^2 = 0.9998)$$

For the high flow range (10 to 35 m³/h)

$$Q = -0.0364 \Delta p^2 + 0.0147 \Delta p + 40.716 \quad (B3)$$

$$(R^2 = 0.9902)$$

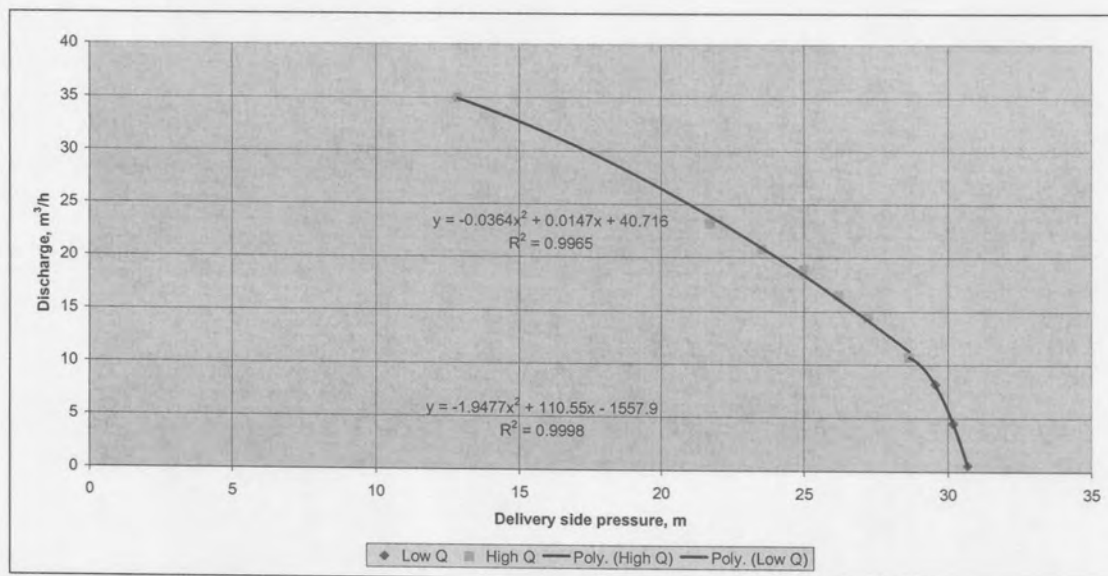


Figure B6 Q- Δp regression curves for Worcester East WUA pump test

The results of the separate test to evaluate the two curves are shown in Figure B7. In the high flow range, all the calculated discharge values were within $\pm 5\%$ of the actual measured discharge. The standard deviation of these points was calculated as 2.37 %.

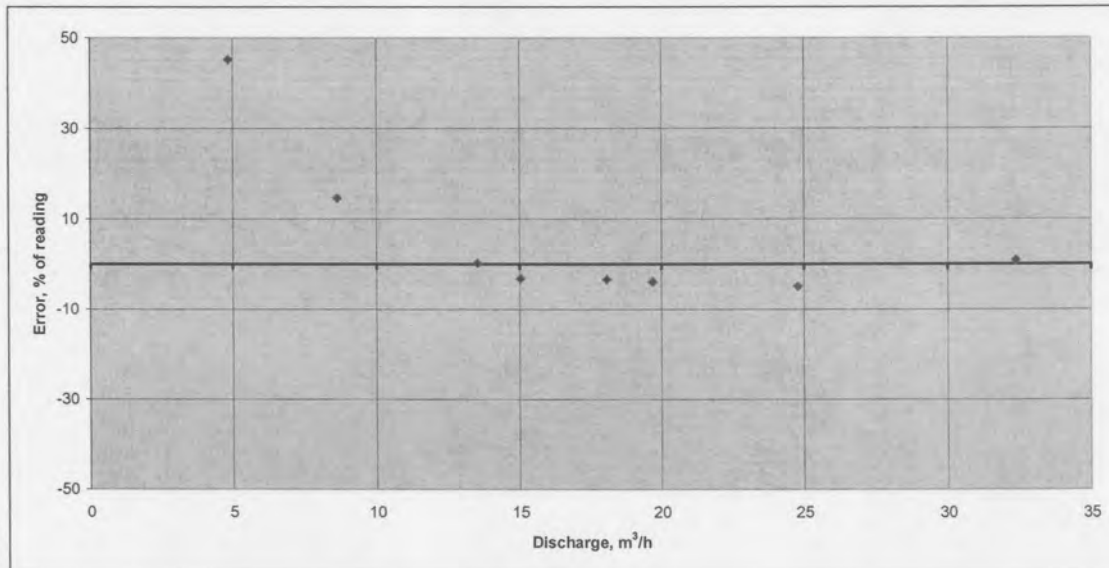


Figure B7 Measurement error graph for the Worcester East WUA test

The data from the tests are attached at the end of this Appendix.

B2.3 Franschoek River

The pump at this site produced a very unstable and flat curve, the result of age and low net positive suction head (NPSH). The lowest 60 % of the discharge values fitted on the positive sloping part of the regression curve, and only at discharges higher than 14.4 m³/h did the slope become negative (Figure B8).

Since such large percentage of the pump's operating range fitted on the unstable curve, it was decided to develop two separate Q- Δp relationships for the low and high discharges ranges. Although it was achieved, no satisfactory relationship could be found to describe the relationship around the turning point of the regression curve. This was also reflected in the error analysis' results.

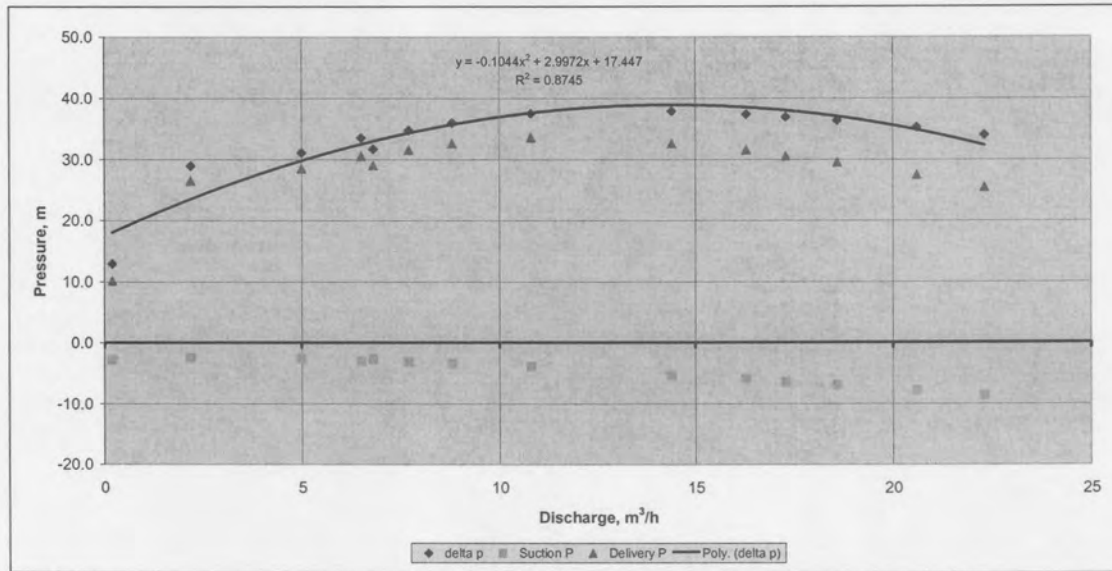


Figure B8 Δp -Q regression curve for Franschhoek River pump test

The low flow range data points (0 to 14.4 m³/h) fitted a third order polynomial best:

$$Q = 0.0304 \Delta p^3 - 3.0458 \Delta p^2 + 102.26 \Delta p - 1142.6 \quad (B4)$$

$$(R^2 = 0.9742)$$

A second order polynomial was fitted to the high flow range data points (14.4 to 23 m³/h):

$$Q = -0.2813 \Delta p^2 + 18.262 \Delta p - 273.48 \quad (B5)$$

$$(R^2 = 0.9974)$$

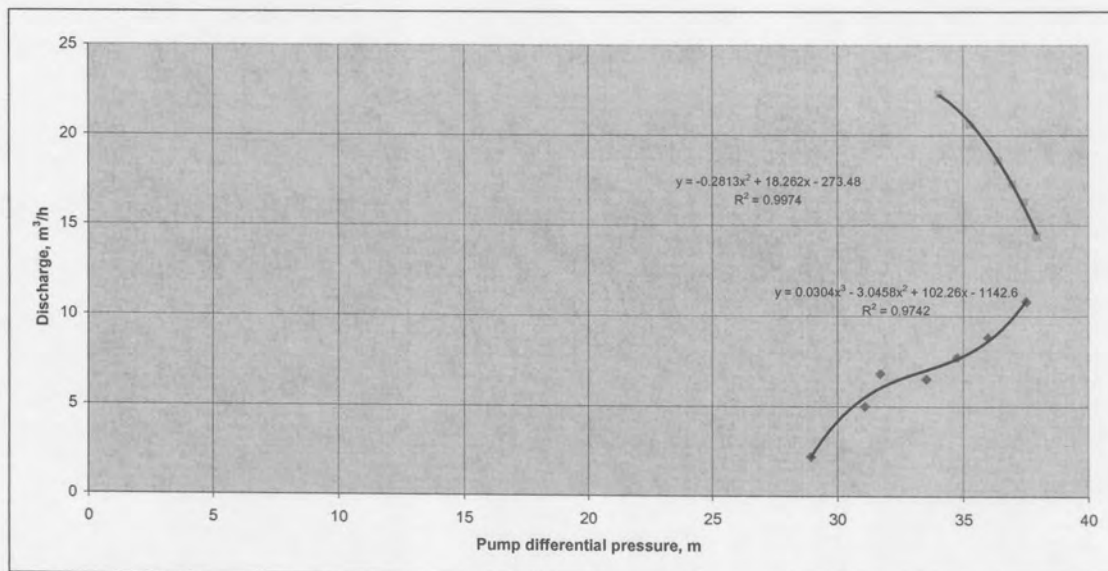


Figure B9 Q- Δp regression curves for Franschhoek River pump test

The two curves were used to calculate the discharge values based on differential pressure measurements in a separate test, and the errors are presented graphically in Figure B10.

At this pump, the errors in the low flow range were smaller than those at the first two sites (± 4 to 33 % of reading). However, unlike the other two sites, the accuracy didn't improve as much in the high flow range, except at the very high flow rates where it approached zero. It can also be seen that the equations does not predict the discharge very well around 15 m³/h.

Although this was to be expected from the Q- Δp relationships, as discussed earlier, another contributing factor could be the problems that were encountered during the discharge measurements with the clamp-on transit time meter on the small diameter pipes. The transducers do not fit the smaller diameter pipes very well, and it is therefore possible that the discharge measurements were not accurate.

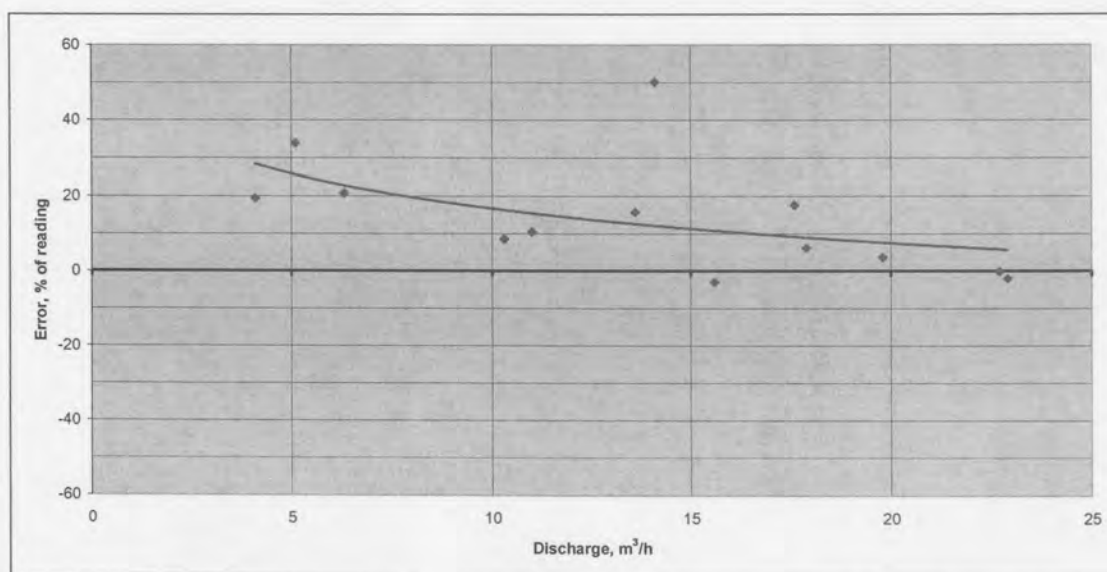


Figure B10 Measurement error graph for the Franschhoek River test

The data and calculations for the Franschhoek River tests are attached at the end of this Appendix.

B3. Validity of the experimental method under field conditions

The field tests also produced generally favourable results, providing opportunities to evaluate the method at different types of pumps.

The Q- Δp relationships were very different for the three sites, and it was found that in the case of very flat, stable curves, the relationship can be described by a single regression curve for the whole flow range, and still produce measurement errors smaller than $\pm 5\%$ of reading.

It was also possible to use the experimental method successfully on a pump with a very unstable curve by developing two separate equations, but producing errors of $\pm 18\%$ of reading.



Stellenbosch WUA: Simonsig Pump Station						
Pump tests for Q-Δp relationship data						
Q	p suction	p delivery	Δ p			
transit time						
m ³ /h	m	m	m			
2.3	63.8	166.8	103.0			
29.4	63.8	164.8	101.0			
39.2	68.7	170.7	102.0			
51.7	63.8	164.8	101.0			
90.2	65.7	164.8	99.1			
119.6	66.7	166.8	100.1			
119.1	66.7	164.8	98.1			
151.6	66.7	164.8	98.1			
163.4	63.8	161.9	98.1			
188	66.7	163.8	97.1			
219.1	60.8	157.0	96.1			
285.4	59.8	150.1	90.3			
297.4	58.9	148.1	89.3			
321.8	58.9	147.2	88.3			
315.4	56.9	143.2	86.3			
346.8	58.9	143.2	84.4			
347.5	56.9	141.3	84.4			
412.4	56.9	132.4	75.5			
407.7	54.0	131.5	77.5			
414.1	40.2	113.8	73.6			
441.7	44.1	115.8	71.6			
458.6	51.0	120.7	69.7			
458.9	51.0	121.6	70.6			
465.9	51.0	120.7	69.7			
463.7	51.0	120.7	69.7			



SBR Simonsig pump station									
Evaluation of Q-Δp relationship									
				TT	TT	TT	TT		
Q TT	Hs	Hd	Hd-Hs	Q(predict)	Q(predict)	Error %	Error %	(Xave-Xind)^2	(Xave-Xind)^2
m ³ /h	kPa	kPa	m	2nd poly	3rd poly	2ndpoly	3rd poly		
				m ³ /h	m ³ /h				
0	700	1685	100.4	83.2	107.0				
77	680	1670	100.9	71.5	91.4	-8	18	5	171
161	640	1600	97.9	139.2	176.0	-14	9	69	16
208	610	1550	95.8	180.7	221.5	-13	6	60	2
208	630	1560	94.8	200.3	241.3	-4	16	3	120
236	630	1555	94.3	209.8	250.5	-11	6	33	1
288	595	1495	91.7	254.7	290.6	-11	1	36	15
311	580	1450	88.7	302.4	327.1	-3	5	7	0
353	545	1380	85.1	349.6	358.2	-1	1	20	12
372	540	1330	80.5	397.0	387.7	7	4	151	0
404	515	1280	78.0	416.9	402.9	3	0	73	28
423	505	1215	72.4	444.2	444.3	5	5	110	0
448	495	1190	70.8	447.8	459.6	0	3	29	6
474	490	1180	70.3	448.6	465.2	-5	-2	0	48
479	485	1170	69.8	449.2	471.1	-6	-2	1	44
498	475	1125	66.3	448.5	521.9	-10	5	20	0
530	475	1110	64.7	445.4	549.5	-16	4	112	2
					Ave =	-5	5	728	467
							S (%) =	6.75	5.40
0				y = -0.3566x ² + 48.737x - 1215.2					
700				R ² = 0.9819					
				y = -0.0193x ³ + 4.6326x ² - 376.54x + 10747					
				R ² = 0.9902					



Worcester East WUA							
Pump test for Q-Δp relationship							
Transit time	P delivery	P delivery					
m ³ /h	(kPa / 10)	m					
0.56	30.1	30.7					
4.5	29.6	30.2					
8.2	29	29.6					
10.7	28.1	28.6					
14.4	26.7	27.2					
16.5	25.7	26.2					
18.7	24.5	25.0					
18.8	24.5	25.0					
20.8	23.1	23.5					
23.2	21.3	21.7					
35	12.6	12.8					
Evaluation of Q-Δp relationship							
Q (TT)	P	P	Q Predict	Error		St dev. Calc.	
m ³ /h	kPa / 10	m	m ³ /h	%			
0.5	30	30.6	1.34	161.7			
4.8	29.2	29.8	7.04	45.3			
8.6	28.5	29.1	9.90	14.6			
13.5	27	27.5	13.55	0.2		6.875143	
15.0	26.5	27.0	14.55	-3.2		0.657646	
18.1	25	25.5	17.45	-3.4		1.034703	
19.7	24.2	24.7	18.93	-3.9		2.220093	
24.8	21.5	21.9	23.55	-5.0		6.615752	
32.4	14.8	15.1	32.65	0.9		10.68124	
			Ave =	-2.4	S =	2.37	%
Low Q:							
y = -1.9477x ² + 110.55x - 1557.9							
R ² = 0.9998							
High Q:							
y = -0.0364x ² + 0.0147x + 40.716							
R ² = 0.9965							

Appendix C: Transit time meter laboratory tests

C1 Testing methodology

C1.1 Introduction

The tests were performed in the hydraulic laboratory of the ARC Institute for Agricultural Engineering in Pretoria. The pipeline system that was used for the tests is fitted of two pumps that can be connected in either series or parallel, a turbine type flow meter and a flow control valve, before it discharges into a stilling basin with a 90 degree v-notch weir as overflow on the opposite end from the inlet. The overflow discharges into the pump sump. A schematic representation of the lay-out is shown in Figure C1 below.

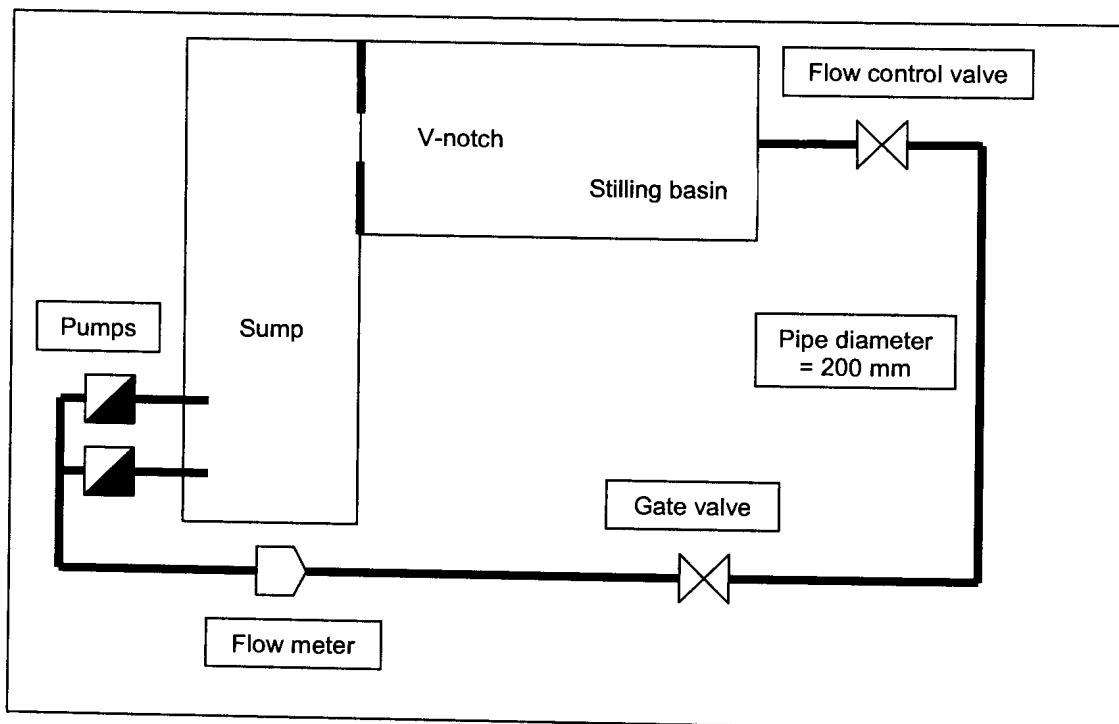


Figure C1 Schematic lay-out of the laboratory at ARC-ILI (plan, not to scale)

Some of the system parameters are shown in Table C1 below.

Table C1 Detail of the laboratory system

Centrifugal pumps:	ETA 65 – 250 with full size impeller (259 mm)
Electrical motors:	55 kW at 2900 rpm
Maximum discharge:	175 m ³ /h
Discharge at highest efficiency:	120 m ³ /h ($\eta = 71\%$)
Pipe diameter:	200 mm (nominal)

Three sets of tests were done in the laboratory:

- A comparison of flow rates recorded with the transit time meter and the v-notch weir, with the transit time meter installed according to the manufacturer's specifications of 20 straight pipe diameter lengths upstream, and 10 straight pipe diameter lengths downstream of the meter;
- A comparison of flow rates recorded with the transit time meter and the v-notch weir, with the transit time meter installed only 2 straight pipe diameter lengths upstream and downstream of a gate valve in the open position (2 tests); and
- A comparison of flow rates recorded with the transit time meter and the v-notch weir, with the transit time meter installed only 2 straight pipe diameter lengths upstream and downstream of a 90 degree elbow (2 tests).

C2 Results

C2.1 Meter installed according to specifications

The following results were obtained from tests that were done with the meter installed according to the manufacturer's requirements of 10 to 20 straight pipe diameter lengths in front, and 5 to 10 straight pipe diameter lengths after the transducers.

The measurement error as a percentage of the actual flow according to the v-notch weir, is shown in Figure C2. Except for the first two readings, taken at discharges less than 50 m³/h, the meter performed according to the manufacturer's specifications of $\pm 2\%$ of reading.

Although the first data point indicates an error of 3.1 %, it is actually also within the specifications since the flow velocity is less than 0.3 m/s, meaning that an error of ± 0.01 m/s is allowed. The velocity according to the v-notch measurement is 0.25 m/s and according to the transit time meter, it is 0.26 m/s (see data at the end of the Appendix).

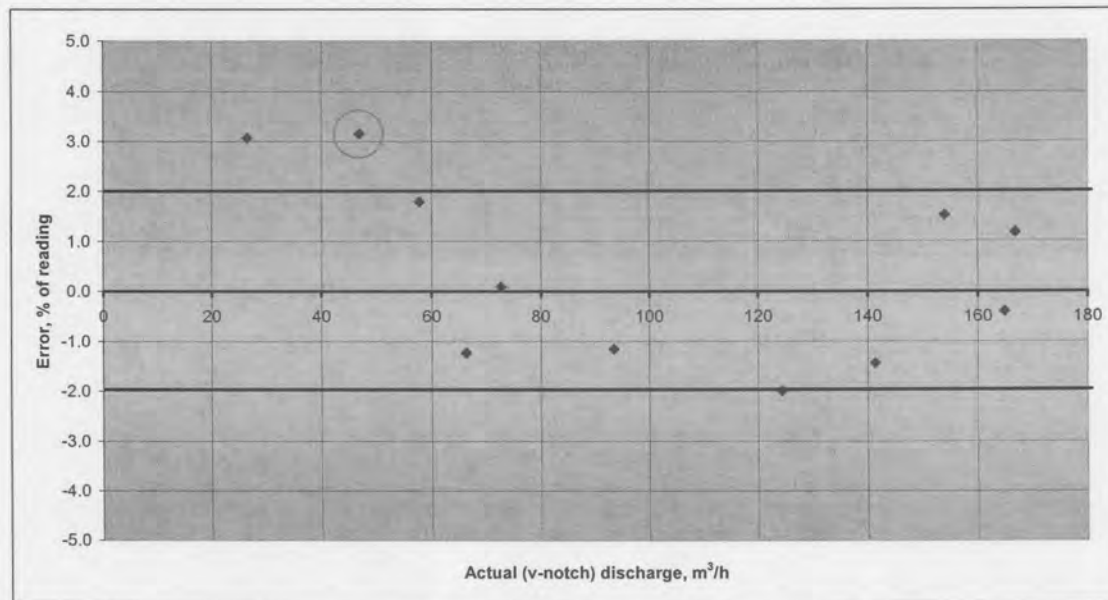


Figure C2 Measurement error (% of reading) of the transit time meter

The standard deviation of the errors as a percentage of reading was calculated as 1.83 %.

C2.2 Effect of flow disturbances on accuracy

The next four sets of test were done to evaluate performance of the transit time meter when the meter's transducers are positioned only 2 straight pipe diameter lengths upstream or downstream from of a gate valve and a 90 degree bend.

The results of the tests are shown at the end of this Appendix, and a summary is presented through graphs in Figures C3 and C4. The following observations can be made:

- Measurement errors as a percentage of reading caused by the gate valve were less than ± 8 %, while the 90 degree bend caused errors of up to ± 26 % of reading
- In both cases, the meter's performance was more affected when the transducers were positioned downstream of the cause of disturbance
- Except for the case where the transit time meter was positioned downstream of the gate valve, the transit time meter registered a smaller than actual discharge
- In all tests, the bigger percentage of reading errors were recorded at lower flow rates
- In all tests, the bigger percentage of full scale errors were recorded at higher flow rates

The third observation could probably be explained by the fact that the gate valve causes a slight reduction in the pipe diameter and consequently the velocity of the water at that point increases (a venturi effect). Since the transit time meter measures the velocity and then convert the value to discharge, a higher discharge is registered.

The last two observations indicate that the error as a discharge value in m^3/h increases as the system discharge increases, although when one only looks at the errors as a percentage of reading (Figures C3a, C3b, C4a and C4b), it seems as if the measurement error decreases with an increase in discharge. The flow disturbances do therefore not cause a constant error over the whole flow range. The tests showed that the manufacturer's recommendations should be followed as far as possible where the installation of the transit time meter is concerned.

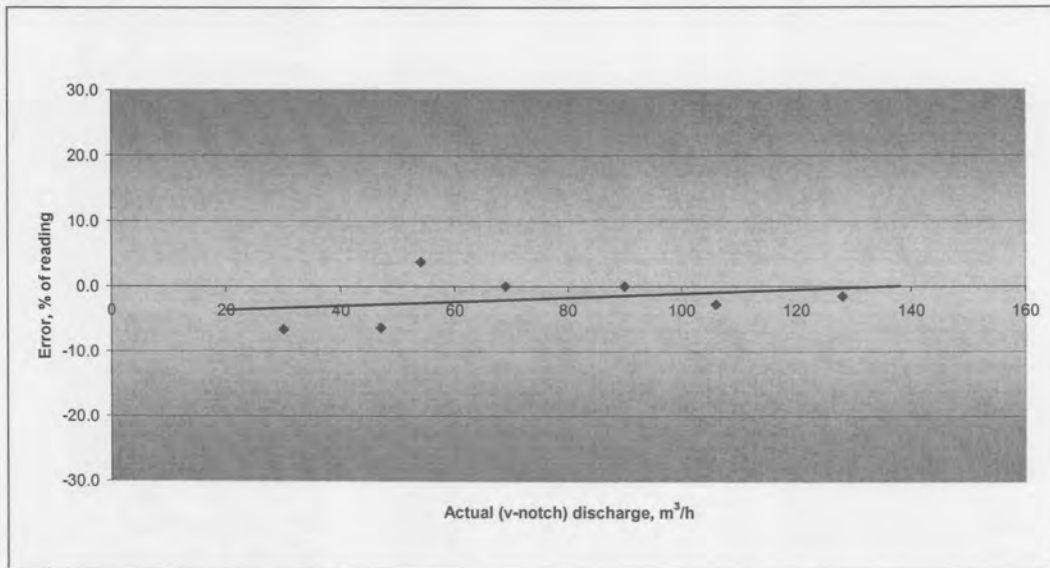


Figure C3a Measurement error (% of reading) due to a gate valve positioned 200 mm downstream of the transit time meter

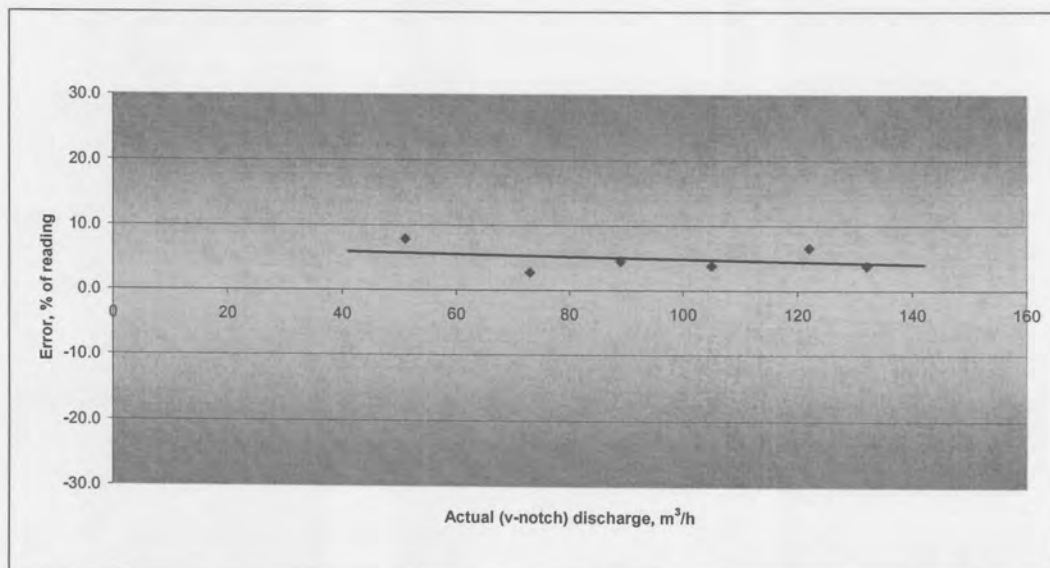


Figure C3b Measurement error (% of reading) due to a gate valve positioned 200 mm upstream of the transit time meter

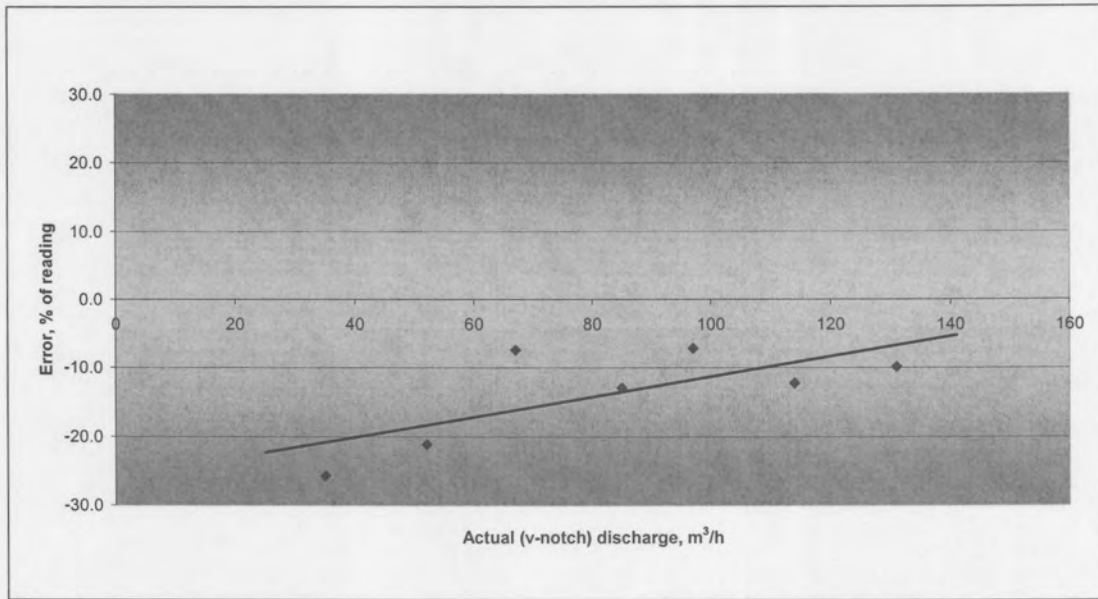


Figure C4a Measurement error (% of reading) due to a 90° bend positioned 200 mm downstream of the transit time meter

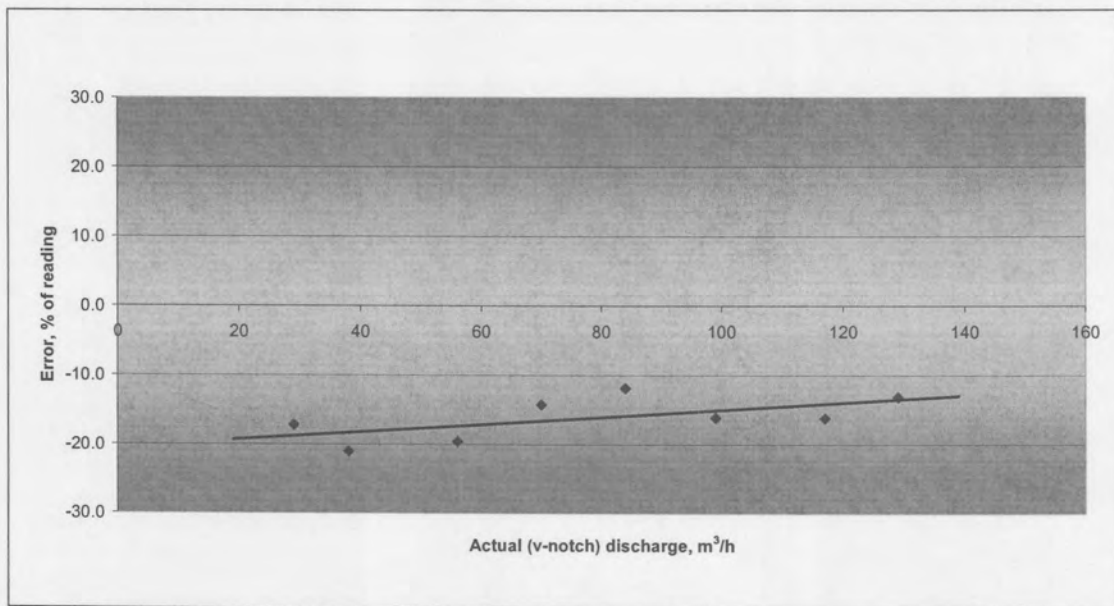


Figure C4b Measurement error (% of reading) due to a 90° bend positioned 200 mm downstream of the transit time meter

Laboratory calibration of Panametrics transit time meter									
21-Nov-02									
I vd Stoep					Pipe diameter = 200 mm (nominal)				
S Bunton					A = 0.0314 m ²				
ILI lab, Silverton									
Panametrics		V-notch			Analysis				
m ³ /h	m/s	cm	m ³ /h	m/s	Error Q	Error Q	Registration	(Ei-Eave) ²	
					%	%	%		
29.2	0.26	41.12	28.33	0.25	3.07	0.55	110.19	7.05	
49.1	0.43	44.04	47.60	0.42	3.15	0.94	104.69	7.51	
61.5	0.54	45.6	60.42	0.53	1.78	0.68	106.40	1.88	
65.5	0.58	46.25	66.32	0.59	-1.23	-0.51	98.79	2.70	
72.8	0.64	46.92	72.74	0.64	0.09	0.04	100.14	0.11	
92.3	0.82	48.86	93.38	0.83	-1.16	-0.68	98.82	2.46	
112.8	1.00	50.64	115.10	1.02	-2.00	-1.45	90.68	5.82	
130.8	1.16	51.94	132.72	1.17	-1.44	-1.21	92.50	3.45	
147.1	1.30	52.78	144.91	1.28	1.51	1.38	95.52	1.21	
151.7	1.34	53.27	152.32	1.35	-0.41	-0.39	92.00	0.67	
160.7	1.42	53.69	158.85	1.41	1.17	1.17	96.33	0.57	
					ave =	0.41	Total =	33.42	
							St. dev. =	1.83	

The tests were performed over a flow range of 20 to 160 m³/h.

Evaluation of the effect of flow disturbances on the transit time meter						
25-27 Nov 02						
I v d Stoep		d =	200	mm		
S Buntun		A =	0.028339	m ²		
ILI-lab, Silverton		Steel pipe				
Test 1: Gate valve 2 pipe diameters downstream from transit time meter						
Panametrics		V-notch		Analysis		
m ³ /h	m/s	m ³ /h	m/s	Error %	FS Error %	
28	0.27	30	0.29	-6.7	-1.3	
44	0.43	47	0.46	-6.4	-1.9	
56	0.55	54	0.53	3.7	1.3	
69	0.68	69	0.68	0.0	0.0	
90	0.88	90	0.88	0.0	0.0	
103	1.01	106	1.04	-2.8	-1.9	
126	1.24	128	1.25	-1.6	-1.3	
Test 2: Gate valve 2 pipe diameters upstream from transit time meter						
Panametrics		V-notch		Analysis		
m ³ /h	m/s	m ³ /h	m/s	Error %	FS error %	
55	0.54	51	0.50	7.8	2.5	
75	0.74	73	0.72	2.7	1.3	
93	0.91	89	0.87	4.5	2.5	
109	1.07	105	1.03	3.8	2.5	
130	1.27	122	1.20	6.6	5.0	
137	1.34	132	1.29	3.8	3.1	
Test 3: 90 degree bend 2 pipe diameters downstream from transit time meter						
Panametrics		V-notch		Analysis		
m ³ /h	m/s	m ³ /h	m/s	Error %	FS error %	
26	0.25	35	0.34	-25.7	-5.7	
41	0.40	52	0.51	-21.2	-6.9	
62	0.61	67	0.66	-7.5	-3.1	
74	0.73	85	0.83	-12.9	-6.9	
90	0.88	97	0.95	-7.2	-4.4	
100	0.98	114	1.12	-12.3	-8.8	
118	1.16	131	1.28	-9.9	-8.2	
Test 4: 90 degree bend 2 pipe diameter+A1s upstream from transit time meter						
Panametrics		V-notch		Analysis		
m ³ /h	m/s	m ³ /h	m/s	Error %	FS Error %	
24	0.24	29	0.28	-17.2	-3.1	
30	0.29	38	0.37	-21.1	-5.0	
45	0.44	56	0.55	-19.6	-6.9	
60	0.59	70	0.69	-14.3	-6.3	
74	0.73	84	0.82	-11.9	-6.3	
83	0.81	99	0.97	-16.2	-10.1	
98	0.96	117	1.15	-16.2	-12.0	
112	1.10	129	1.26	-13.2	-10.7	

Appendix D: Data from laboratory tests

PUMP TEST 1											
Cape Technicon											
EVT	TIME	FLOW		PRESSURES			delta p	KWH	KVAR	RPM	RPM/10
		mA	m ³ /h	DEL	SUCTION	Suc corr.	m				
1	14:41:10	3.98	0.000	60.5	5.5	2	58.5			2979	297.9
2	14:43:34	4.098	1.531	60.7	5.5	2	58.7			2980	298
0	14:38:00	4.115	1.797	60.7	5.5	2	58.7			-	
4	14:46:45	4.191	2.984	60.7	5.5	2	58.7			2978	297.8
3	14:45:20	4.194	3.031	60.6	5.5	2	58.6			2982	298.2
5	14:48:46	4.194	3.031	60.6	5	1.5	59.1			2977	297.7
6	14:50:10	4.213	3.328	60.7	4.9	1.4	59.3			2979	297.9
8	14:55:10	4.281	4.391	60.7	5.5	2	58.7	10.76	0.033	2979	297.9
7	14:52:15	4.357	5.578	60.6	4.8	1.3	59.3			2975	297.5
9	14:56:30	4.357	5.578	60.5	5.5	2	58.5	17.1	0.53	2976	297.6
10	15:00:00	4.5	7.813	60.5	5.2	1.7	58.8	33.37	1.04	2976	297.6
11	15:01:10	4.653	10.203	60.4	5	1.5	58.9	38.88	1.22	2975	297.5
12	15:02:30	4.875	13.672	60.4	5	1.5	58.9	44.38	1.39	2973	297.3
13	15:03:48	5.085	16.953	60.4	4.75	1.25	59.2	50.16	1.57	2973	297.3
39	15:40:15	5.32	20.625	60.2	4.5	1	59.2	225.82	7.9	2969	296.9
14	15:04:51	5.445	22.578	60.4	4.5	1	59.4	36.21	1.75	2973	297.3
15	15:06:15	5.643	25.672	60.5	4.25	0.75	59.8	62.52	1.96	2975	297.5
16	15:07:34	6.1	32.813	60.1	4	0.5	59.6	69.64	2.19	2972	297.2
17	15:08:55	6.512	39.250	60.1	4	0.5	59.6	76.2	2.39	2967	296.7
18	15:11:25	6.727	42.609	59.9	3.5	0	59.9	88.46	2.79	2967	296.7
19	15:12:30	7.15	49.219	59.7	3.5	0	59.7	93.63	2.96	2966	296.6
20	15:13:35	7.35	52.344	59.3	3.5	0	59.3	98.78	3.13	2966	296.6
21	15:14:45	7.65	57.031	59.2	3.5	0	59.2	104.2	3.33	2966	296.6
22	15:15:50	7.73	58.281	58.7	3.25	-0.25	59.0	109.88	3.5	2966	296.6
38	15:38:37	7.86	60.313	58.3	3	-0.5	58.8	217.89	7.63	2959	295.9

23	15:16:00	8.35	67.969	57.9	3	-0.5	58.4	115	3.68	2963	296.3
24	15:18:16	8.55	71.094	57.1	3	-0.5	57.6	121.43	3.92	2962	296.2
44	15:47:35	8.72	73.750	50.1	-4	-7.5	57.6	261.34	9.14	2953	295.3
43	15:46:30	8.85	75.781	52.2	-2	-5.5	57.7	254.89	8.91	2953	295.3
45	15:48:55	8.85	75.781	53.1	-1	-4.5	57.6	267.24	9.55	2954	295.4
42	15:45:30	8.976	77.750	54.8	1	-2.5	57.3	250.32	8.75	2954	295.4
41	15:43:45	9.1	79.688	56.2	2.75	-0.75	57.0	243.08	8.49	2951	295.1
25	15:19:45	9.12	80.000	56.2	2.75	-0.75	57.0	128.17	4.14	2956	295.6
40	15:41:50	9.53	86.406	54.6	2.5	-1	55.6	233.39	8.15	2948	294.8
26	15:21:45	9.75	89.844	54.9	2.5	-1	55.9	139.41	4.53	2953	295.3
37	15:37:15	10.46	100.938	52.0	2	-1.5	53.5	211.44	7.41	2945	294.5
28	15:24:50	10.85	107.031	47.9	1.5	-2	49.9	152.71	5.02	2946	294.6
36	15:35:50	11.65	119.531	43.5	0.5	-3	46.5	206.4	7.22	2936	293.6
29	15:26:10	11.71	120.469	43.9	0.25	-3.25	47.2	158.52	5.26	2939	293.9
30	15:27:15	12.22	128.438	40.5	0	-3.5	44.0	164.57	5.49	2935	293.5
31	15:28:30	12.902	139.094	35.6	-1	-4.5	40.1	169.81	5.71	2933	293.3
32	15:29:45	13.67	151.094	31.7	-1.25	-4.75	36.5	175.3	5.94	2929	292.9
33	15:31:00	14	156.250	27.7	-2	-5.5	33.2	181.29	6.18	2926	292.6
34	15:32:10	14.25	160.156	24.5	-2.5	-6	30.5	186.23	6.4	2925	292.5
35	15:33:15	14.7	167.188	23.3	-3	-6.5	29.8	191.68	6.63	2923	292.3

PUMP TEST 2										
EVT	TIME	FLOW		PRESSURES			Total pressure	KWH	KVAR	RPM
		mA	m ³ /h	DEL	SUCTION	Suc corr				
				0	5,8		Δp	0	0	
0	10:58:48	3.982	0.0	61	6	2.5	58.5	3,06	0,3	2981
37	12:02:33	4.474	7.4	61	6	2.5	58.5	309,28	11,03	2973
1	11:02:15	4.536	8.4	61	6	2.5	58.5	20,13	0,63	2971
2	11:03:55	4.794	12.4	61	5.5	2	59	28,11	0,87	2982
28	11:49:21	4.951	14.9	61	5	1.5	59.5	246,45	8,62	2978
36	12:01:25	4.981	15.3	61	5.5	2	59	303,21	10,58	2970
3	11:05:10	5.491	23.3	61	4.9	1.4	59.6	33,18	1,02	2977
27	11:48:10	5.658	25.9	61	4	0.5	60.5	240,68	8,44	2975
4	11:06:25	6.124	33.2	61	4.5	1	60	39,89	1,25	2975
26	11:47:10	6.392	37.4	60.5	3	-0.5	61	235,76	8,27	2972
6	11:16:01	7.195	49.9	61	4	0.5	60.5	87,01	2,81	2961
24	11:45:45	7.447	53.9	58	1	-2.5	60.5	228,95	8,03	2966
7	11:17:15	7.820	59.7	60	3.5	0	60	92,69	3,02	2965
23	11:44:57	7.891	60.8	56.5	0	-3.5	60	224,89	7,90	2960
22	11:43:40	8.365	68.2	55	-1	-4.5	59.5	219,50	7,70	2961
8	11:22:25	8.652	72.7	59	3.4	-0.1	59.1	117,41	3,91	2958
21	11:42:40	8.950	77.3	53	-2	-5.5	58.5	214,39	7,52	2959
20	11:41:35	9.289	82.6	51.5	-3	-6.5	58	208,76	7,32	2957
19	11:39:30	9.613	87.7	49.5	-4	-7.5	57	198,86	6,96	2955
12	11:29:10	9.875	91.8	54.4	2	-1.5	55.9	149,72	5,12	2954
35	11:59:45	10.370	99.5	52	2.2	-1.3	53.3	295,28	10,39	2949
29	11:51:41	11.120	111.3	48	1.5	-2	50	257,50	9,04	2947
30	11:52:45	11.801	121.9	45	1	-2.5	47.5	262,24	9,23	2938
31	11:53:37	12.650	135.2	40	0	-3.5	43.5	266,71	9,41	2933
33	11:56:28	13.390	146.7	32	-2	-5.5	37.5	279,93	9,97	2972
32	11:54:49	13.475	148.0	33	-1	-4.5	37.5	271,93	9,63	2932
34	11:57:40	14.260	160.3	26	-2	-5.5	31.5	285,75	10,22	2929

PUMP TEST 3										
EVT	TIME	FLOW		PRESSURES				KW	KVAR	RPM
		mA	m ³ /h	DEL	SUCTION	Suc corr	delta p			
				m	m	m	m			
0	15:18:00	4	0.0	61	6	2.5	58.5	17.71	19.8	2981
1	15:22:00	4.67	10.5	61	6	2.5	58.5	16.27	20	2981
35	16:00:37	4.89	13.9	61	5	1.5	59.5	16.18	20.45	2976
2	15:22:54	5.5	23.4	61	4.5	1	60	14.32	20.25	2977
3	15:24:04	6.35	36.7	61	4	0.5	60.5	11.86	20.45	2973
4	15:25:03	7.35	52.3	60	2.5	-1	61	8.62	21.25	2968
33	15:57:47	7.45	53.9	60.5	2.5	-1	61.5	7.96	20.95	2962
32	15:56:57	7.51	54.8	60	2	-1.5	61.5	7.87	21.1	2964
5	15:25:58	8.03	63.0	60	3	-0.5	60.5	5.98	21.7	2963
6	15:26:52	8.64	72.5	59.5	3	-0.5	60	3.82	21.75	2963
27	15:52:10	9.1	79.7	54	-1	-4.5	58.5	3.1	22	2953
7	15:27:40	9.35	83.6	57	3	-0.5	57.5	2.08	22	2961
26	15:51:10	9.55	86.7	51	-2	-5.5	56.5	0.85	22.3	2955
9	15:29:53	10.36	99.4	53	2	-1.5	54.5	98.66	22.94	2955
24	15:48:19	10.4	100.0	44.5	-4	-7.5	52	97.4	22.94	2945
23	15:47:28	10.43	100.5	45.5	-3	-6.5	52	97.37	22.89	2946
25	15:50:04	10.5	101.6	48	-3	-6.5	54.5	99.05	22.49	2947
21	15:45:21	10.56	102.5	48	-1	-4.5	52.5	97.22	22.99	2947
22	15:46:24	10.69	104.5	46.5	-2.4	-5.9	52.4	97.31	22.89	2946
19	15:42:45	10.7	104.7	50	1	-2.5	52.5	96.92	23.04	2945
20	15:44:05	10.75	105.5	48.5	0	-3.5	52	96.98	23.14	2948
18	15:41:10	10.8	106.3	50	1.5	-2	52	96.8	23.09	2946
11	15:33:48	11.6	118.8	45	1	-2.5	47.5	94.28	23.99	2941
17	15:39:41	12.1	126.6	42	0	-3.5	45.5	92.84	24.34	2937
12	15:34:49	12.5	132.8	40	0	-3.5	43.5	91.82	24.84	2939
13	15:35:50	13.4	146.9	34	-1	-4.5	38.5	89.75	25.24	2934
14	15:36:53	14	156.3	30	-2	-5.5	35.5	88.31	25.74	2931
15	15:37:53	14.6	165.6	25	-2.5	-6	31	86.99	26.19	2929



Pump test 1									
Q meas.	V	Diff head	Q calc	Error	(Xave-Xi)^2				
m ³ /h	m/s	m	m ³ /h	%					
			(combo poly)	(combo poly)	(3rd poly)				
0.00									
11.15	0.48	59.67	47.70	327.8	108790.9				
30.33	1.30	61.00	23.68	-21.9	394.8				
30.50	1.30	61.10	21.61	-29.2	733.6				
30.70	1.31	61.20	19.50	-36.5	1182.8				
39.33	1.68	61.40	15.21	-61.3	3512.6				
48.80	2.09	60.38	35.43	-27.4	641.3				
74.37	3.18	59.16	76.08	2.3	17.7				
80.83	3.45	58.75	77.67	-3.9	4.0				
107.57	4.60	52.22	101.78	-5.4	12.1				
135.60	5.79	42.94	131.54	-3.0	1.2				
136.00	5.81	43.04	131.24	-3.5	2.5				
158.67	6.78	33.46	156.48	-1.4	0.3				
168.40	7.20	28.05	168.20	-0.1	3.2				
172.00	7.35	26.32	171.59	-0.2	2.8				
				-1.9	43.7	S =	2.50	%	
Pump test 2									
Q meas.	V	Diff head	Q calc	Error	(Xave-Xi)^2				
m ³ /h	m/s	m	m ³ /h	%					
			(combo poly)	(combo poly)	(3rd poly)				
0.00									
11.15	0.48	59.67	66.09	492.7	244797.4				
30.33	1.30	61.00	39.52	30.3	1047.4				
30.50	1.30	61.10	36.96	21.2	540.9				
30.70	1.31	61.20	34.33	11.8	192.9				
39.33	1.68	61.40	28.84	-26.7	605.6				
48.80	2.09	60.38	53.33	9.3	129.0				
74.37	3.18	59.16	72.98	-1.9	0.0				
80.83	3.45	58.75	77.17	-4.5	6.0				
107.57	4.60	52.22	105.02	-2.4	0.1				
135.60	5.79	42.94	134.48	-0.8	1.6				
136.00	5.81	43.04	134.20	-1.3	0.6				
158.67	6.78	33.46	156.49	-1.4	0.5				
168.40	7.20	28.05	165.37	-1.8	0.1				
172.00	7.35	26.32	167.66	-2.5	0.2				
				-2.1	9.1	S =	1.14	%	



Pump test 3								
Q meas.	V	Diff head	Q calc	Error	(Xave-Xi)^2			
m ³ /h	m/s	m	m ³ /h	%				
			(combo poly)	(combo poly)	(3rd poly)			
0.00								
11.15	0.48	59.67	72.68	551.9	306843.3			
30.33	1.30	61.00	60.27	98.7	9702.0			
30.50	1.30	61.10	59.15	93.9	8789.0			
30.70	1.31	61.20	58.01	89.0	7880.2			
39.33	1.68	61.40	55.66	41.5	1707.2			
48.80	2.09	60.38	66.49	36.2	1299.6			
74.37	3.18	59.16	76.41	2.7	6.5			
80.83	3.45	58.75	78.98	-2.3	6.2			
107.57	4.60	52.22	104.19	-3.1	11.1			
135.60	5.79	42.94	134.16	-1.1	1.6			
136.00	5.81	43.04	133.85	-1.6	3.1			
158.67	6.78	33.46	160.33	1.0	0.7			
168.40	7.20	28.05	173.23	2.9	7.2			
172.00	7.35	26.32	177.06	2.9	7.6			
				0.2	44.0	S =	2.51	%

Appendix E: Data from long term field tests: Q- Δp relationship

Ramdam Site		
Manual readings taken on day of installation		
Q-delta p relationship		
Reading	Transit time	Pressure transd.
	Q	P diff
	m3/h	kPa
1	181	280
2	182	279
3	176	283
4	168	290
5	159	297
6	86	339
7	177	280
8	183	274
9	42	355
10	43	348
11	43	351
12	43	349.5
13	43	354.5
14	141	316
15	142	314.5
16	143	314.5
17	142	318
18	143	312.5
19	128	317



Differential pressure and discharge readings at three duty points: Ramdam site								
Unit I.D.: 208715								(suction)
		Del P	Suc P	Diff P	Q (Panam)	Q (Kent)	Q (Electro)	v (Panam)
		kPa	kPa	kPa	m ³ /h	m ³ /h	m ³ /h	m/s
Both pivots	10:00:05	224	-66	290	182.75	214.2857	180.5	0.98
	10:00:15	225	-66	291	183.52			0.99
	10:00:25	225	-66	291	183.98			0.99
	10:00:35	225	-66	291	182.88			0.98
	10:00:45	225	-64	289	182.87			0.98
	10:00:55	225	-67	292	183.65			0.99
	10:01:05	223	-66	289	183			0.98
	10:01:15	223	-65	288	184.08			0.99
	10:01:25	224	-66	290	180.98			0.97
	10:01:35	223	-66	289	178.11			0.96
	10:01:45	224	-64	288	178.78			0.96
	10:01:55	224	-66	290	182.73			0.98
	10:02:05	224	-66	290	187.19			1
	10:02:15	222	-67	289	186			1
	10:02:25	222	-66	288	175.32			0.94
	10:02:35	222	-64	286	180.8			0.97
	10:02:45	222	-66	288	180.18			0.97
	10:02:55	223	-66	289	197.57			1.06
	10:03:05	223	-67	290	185.73			1
	10:03:15	223	-63	286	171.31			0.92
	10:03:25	222	-65	287	179.33			0.96
	10:03:35	224	-66	290	177.74			0.95
	10:03:45	223	-65	288	177.61			0.95
	10:03:55	224	-65	289	177.61			0.95
	10:04:05	221	-66	287	183.61			0.99
	10:04:15	222	-67	289	182.27			0.98
	10:04:25	222	-66	288	183.41			0.98
	10:04:35	222	-63	285	183.33			0.98
	10:04:45	223	-65	288	183.8			0.99
	10:04:55	223	-67	290	185.6			1
	10:05:05	221	-67	288	181.36			0.97
	10:05:15	222	-64	286	180.61			0.97
	10:05:25	221	-67	288	182.53			0.98
	10:05:35	221	-66	287	181.21			0.97
	10:05:45	221	-66	287	182.85			0.98
	10:05:55	221	-63	284	181.97			0.98
	10:06:05	221	-66	287	181.73			0.98
	10:06:15	221	-65	286	182.9			0.98
	10:06:25	222	-65	287	185.1			0.99
	10:06:35	220	-66	286	184.67			0.99
	10:06:45	221	-66	287	183.55			0.99
	10:06:55	222	-65	287	185.96			1
	10:07:05	221	-66	287	184.54			0.99
	10:07:15	222	-66	288	184.26			0.99
	10:07:25	221	-65	286	183.24			0.98



	10:07:35	222	-66	288	185.23			0.99
	10:07:45	222	-65	287	186			1
	10:07:55	222	-66	288	185.44			1
	10:08:05	222	-65	287	184.71			0.99
	10:08:15	221	-66	287	182.85			0.98
	10:08:25	221	-67	288	182.14			0.98
	10:08:35	219	-66	285	181.37			0.97
	10:08:45	220	-66	286	181.1			0.97
	10:08:55	221	-65	286	183.03			0.98
	10:09:05	220	-65	285	184.78			0.99
	10:09:15	221	-67	288	183.09			0.98
	10:09:25	220	-65	285	190.19			1.02
	10:09:35	221	-66	287	185.98			1
	10:09:45	221	-67	288	177.37			0.95
	10:09:55	220	-64	284	176.92			0.95
	10:10:05	222	-64	286	178.51			0.96
					182.6382			
10 ha pivot	10:21:05	338	-14	352	42.78	56.69291	36	0.23
	10:21:15	337	-14	351	42.35			0.23
	10:21:25	336	-14	350	42.46			0.23
	10:21:35	337	-14	351	41.1			0.22
	10:21:45	334	-14	348	41.75			0.22
	10:21:55	336	-14	350	42.55			0.23
	10:22:05	335	-14	349	42.8			0.23
	10:22:15	332	-15	347	42.85			0.23
	10:22:25	335	-14	349	43.28			0.23
	10:22:35	334	-14	348	42.03			0.23
	10:22:45	336	-14	350	42.78			0.23
	10:22:55	337	-14	351	43.22			0.23
	10:23:05	337	-14	351	42.67			0.23
	10:23:15	335	-15	350	43.11			0.23
	10:23:25	336	-14	350	42.61			0.23
	10:23:35	336	-14	350	42.68			0.23
	10:23:45	334	-15	349	42.13			0.23
	10:23:55	332	-14	346	42.5			0.23
	10:24:05	337	-14	351	42.78			0.23
	10:24:15	339	-14	353	42.98			0.23
	10:24:25	338	-14	352	42.91			0.23
	10:24:35	336	-14	350	43.5			0.23
	10:24:45	333	-14	347	43.54			0.23
	10:24:55	333	-14	347	42.78			0.23
	10:25:05	335	-14	349	43.24			0.23
	10:25:15	333	-14	347	42.31			0.23
	10:25:25	336	-14	350	42.29			0.23
	10:25:35	335	-14	349	43.22			0.23
	10:25:45	336	-14	350	43.65			0.23
	10:25:55	334	-14	348	43.39			0.23
	10:26:05	335	-14	349	42.76			0.23
	10:26:15	333	-14	347	42.44			0.23
	10:26:25	335	-14	349	42.01			0.23
	10:26:35	335	-14	349	42.29			0.23
	10:26:45	335	-14	349	42.85			0.23



	10:26:55	334	-14	348	43			0.23
	10:27:05	334	-14	348	42.2			0.23
	10:27:15	333	-14	347	42.83			0.23
	10:27:25	332	-14	346	42.87			0.23
	10:27:35	335	-14	349	42.33			0.23
	10:27:45	335	-14	349	42.29			0.23
	10:27:55	338	-14	352	42.8			0.23
	10:28:05	338	-14	352	43.49			0.23
	10:28:15	334	-14	348	43.91			0.24
	10:28:25	333	-14	347	43.6			0.23
	10:28:35	335	-14	349	43.49			0.23
	10:28:45	335	-14	349	43.26			0.23
	10:28:55	333	-14	347	42.59			0.23
	10:29:05	334	-14	348	43.3			0.23
	10:29:15	334	-14	348	43.32			0.23
	10:29:25	333	-14	347	42.96			0.23
	10:29:35	335	-15	350	42.61			0.23
	10:29:45	335	-14	349	43.19			0.23
	10:29:55	332	-15	347	43.15			0.23
	10:30:05	336	-14	350	43.73			0.23
	10:30:15	334	-14	348	42.93			0.23
	10:30:25	334	-14	348	43.13			0.23
	10:30:35	337	-14	351	42.91			0.23
	10:30:45	333	-14	347	42.54			0.23
	10:30:55	336	-14	350	42.18			0.23
	10:31:05	333	-14	347	42.27			0.23
					42.81098			
30 ha pivot	10:46:05	270	-43	313	140.68	167.4419	139	0.76
	10:46:15	272	-43	315	140.78			0.76
	10:46:25	270	-43	313	141.78			0.76
	10:46:35	271	-43	314	141.06			0.76
	10:46:45	271	-43	314	139.96			0.75
	10:46:55	271	-43	314	140.05			0.75
	10:47:05	270	-43	313	140.44			0.75
	10:47:15	270	-43	313	142.31			0.76
	10:47:25	271	-43	314	143.16			0.77
	10:47:35	271	-43	314	139.21			0.75
	10:47:45	270	-43	313	139.57			0.75
	10:47:55	268	-43	311	141.43			0.76
	10:48:05	269	-43	312	142.21			0.76
	10:48:15	270	-43	313	142.31			0.76
	10:48:25	269	-44	313	145.1			0.78
	10:48:35	269	-44	313	143.33			0.77
	10:48:45	269	-44	313	143.68			0.77
	10:48:55	269	-43	312	142.6			0.77
	10:49:05	268	-43	311	143.22			0.77
	10:49:15	269	-43	312	142.42			0.76
	10:49:25	270	-43	313	143.57			0.77
	10:49:35	269	-43	312	144.06			0.77
	10:49:45	269	-44	313	142.99			0.77
	10:49:55	269	-43	312	142.38			0.76
	10:50:05	269	-44	313	142.83			0.77



	10:50:15	270	-43	313	142.16			0.76
	10:50:25	270	-43	313	142.19			0.76
	10:50:35	270	-43	313	143.35			0.77
	10:50:45	270	-43	313	141.49			0.76
	10:50:55	270	-43	313	142.64			0.77
	10:51:05	270	-43	313	142.53			0.77
	10:51:15	270	-43	313	141.95			0.76
	10:51:25	270	-43	313	141.17			0.76
	10:51:35	270	-43	313	140.22			0.75
	10:51:45	271	-43	314	140.44			0.75
	10:51:55	270	-43	313	142.38			0.76
	10:52:05	269	-43	312	143.42			0.77
	10:52:15	270	-43	313	141.62			0.76
	10:52:25	270	-43	313	142.75			0.77
	10:52:35	269	-43	312	145.12			0.78
	10:52:45	269	-43	312	142.57			0.77
	10:52:55	269	-44	313	143.14			0.77
	10:53:05	270	-43	313	142.25			0.76
	10:53:15	269	-43	312	142.25			0.76
	10:53:25	269	-43	312	142.06			0.76
	10:53:35	269	-43	312	142.47			0.76
	10:53:45	269	-44	313	141.86			0.76
	10:53:55	270	-43	313	141.93			0.76
	10:54:05	270	-43	313	142.64			0.77
	10:54:15	271	-43	314	141.13			0.76
	10:54:25	273	-43	316	141.8			0.76
	10:54:35	270	-43	313	140.31			0.75
	10:54:45	272	-43	315	141.39			0.76
	10:54:55	272	-43	315	141.52			0.76
	10:55:05	272	-43	315	143.03			0.77
	10:55:15	270	-43	313	142.17			0.76
	10:55:25	270	-43	313	142.08			0.76
	10:55:35	270	-43	313	143.27			0.77
	10:55:45	271	-43	314	140.03			0.75
	10:55:55	271	-43	314	141.35			0.76
	10:56:05	271	-43	314	141.08			0.76
					142.0474			



Frequency analysis: both pivots			
		Diff pressure	
Bin		Bin	Frequency
284		284	2
285		285	4
286		286	9
287		287	13
288		288	15
289		289	7
290		290	7
291		291	3
292		292	1
		More	0
		Discharge	
		Bin	Frequency
175		175	1
176		176	1
177		177	1
178		178	4
179		179	3
180		180	1
181		181	4
182		182	6
183		183	11
184		184	11
185		185	6
186		186	9
187		187	0
188		188	1
189		189	0
190		190	0
		More	2



Frequency analysis: 10 ha pivot			
Diff pressure			
Bin		Bin	Frequency
		347	14
347		348	10
348		349	14
349		350	12
350		351	6
351		352	4
352		353	1
353	More		0
Discharge			
Bin		Bin	Frequency
41		41	0
41.5		41.5	1
42		42	1
42.5		42.5	15
43		43	24
43.5		43.5	15
44		44	5
	More		0

Frequency analysis: 30 ha pivot			
Diff pressure			
Bin		Bin	Frequency
		311	2
311		312	11
312		313	33
313		314	10
314		315	4
315		316	1
316	More		0
Discharge			
Bin		Bin	Frequency
139		139	0
140		140	3
141		141	8
142		142	15
143		143	22
144		144	10
145		145	1
146		146	2
	More		0

Appendix F: Data from long term field tests: Monitoring



Sample of results from long term field tests (total of 6270 data rows)							
Date & Time	P delivery (gauge)	P suction (Absolute)	P suction (gauge)	P diff	Q	Q	Volume
	kPa	kPa	kPa	kPa	m ³ /h	m ³ /min	m ³ (cum.)
2003/08/03 09:52	325	91	-9	334	42.8	0.713333	0.71
2003/08/03 09:53	282	83	-17	299	142.1	2.368333	3.08
2003/08/03 09:54	288	83	-17	305	142.1	2.368333	5.45
2003/08/03 09:55	300	85	-15	315	142.1	2.368333	7.82
2003/08/03 09:56	302	85	-15	317	142.1	2.368333	10.19
2003/08/03 09:57	259	80	-20	279	182.6	3.043333	13.23
2003/08/03 09:58	257	80	-20	277	182.6	3.043333	16.27
2003/08/03 09:59	268	81	-19	287	182.6	3.043333	19.32
2003/08/03 10:00	337	90	-10	347	42.8	0.713333	20.03
2003/08/03 10:01	280	82	-18	298	142.1	2.368333	22.40
2003/08/03 10:02	298	85	-15	313	142.1	2.368333	24.77
2003/08/03 10:03	299	85	-15	314	142.1	2.368333	27.14
2003/08/03 10:04	276	83	-17	293	182.6	3.043333	30.18
2003/08/03 10:05	253	79	-21	274	182.6	3.043333	33.22
2003/08/03 10:06	256	80	-20	276	182.6	3.043333	36.27
2003/08/03 10:07	264	80	-20	284	182.6	3.043333	39.31
2003/08/03 10:08	263	80	-20	283	182.6	3.043333	42.35
2003/08/03 10:09	264	80	-20	284	182.6	3.043333	45.40
2003/08/03 10:10	263	80	-20	283	182.6	3.043333	48.44
2003/08/03 10:11	264	80	-20	284	182.6	3.043333	51.48
2003/08/03 10:12	264	81	-19	283	182.6	3.043333	54.53
2003/08/03 10:13	263	80	-20	283	182.6	3.043333	57.57
2003/08/03 10:14	264	80	-20	284	182.6	3.043333	60.61
2003/08/03 10:15	263	81	-19	282	182.6	3.043333	63.66
2003/08/03 10:16	263	81	-19	282	182.6	3.043333	66.70
2003/08/03 10:17	263	80	-20	283	182.6	3.043333	69.74
2003/08/03 10:18	262	80	-20	282	182.6	3.043333	72.79
2003/08/03 10:19	263	80	-20	283	182.6	3.043333	75.83
2003/08/03 10:20	262	81	-19	281	182.6	3.043333	78.87
2003/08/03 10:21	334	92	-8	342	42.8	0.713333	79.59
2003/08/03 10:22	340	91	-9	349	42.8	0.713333	80.30
2003/08/03 10:23	340	91	-9	349	42.8	0.713333	81.01
2003/08/03 10:24	341	91	-9	350	42.8	0.713333	81.73
2003/08/03 10:25	341	91	-9	350	42.8	0.713333	82.44
2003/08/03 10:26	342	91	-9	351	42.8	0.713333	83.15
2003/08/03 10:27	342	91	-9	351	42.8	0.713333	83.87
2003/08/03 10:28	341	91	-9	350	42.8	0.713333	84.58
2003/08/03 10:29	341	91	-9	350	42.8	0.713333	85.29
2003/08/03 10:30	341	91	-9	350	42.8	0.713333	86.01
2003/08/03 10:31	341	91	-9	350	42.8	0.713333	86.72
2003/08/03 10:32	339	91	-9	348	42.8	0.713333	87.43
2003/08/03 10:33	341	91	-9	350	42.8	0.713333	88.15
2003/08/03 10:34	339	91	-9	348	42.8	0.713333	88.86
2003/08/03 10:35	339	91	-9	348	42.8	0.713333	89.57
2003/08/03 10:36	339	91	-9	348	42.8	0.713333	90.29
2003/08/03 10:37	339	91	-9	348	42.8	0.713333	91.00
2003/08/03 10:38	339	91	-9	348	42.8	0.713333	91.71
2003/08/03 10:39	340	91	-9	349	42.8	0.713333	92.43



2003/08/03 10:40	341	91	-9	350	42.8	0.713333	93.14
2003/08/03 10:41	342	91	-9	351	42.8	0.713333	93.85
2003/08/03 10:42	342	91	-9	351	42.8	0.713333	94.57
2003/08/03 10:43	339	91	-9	348	42.8	0.713333	95.28
2003/08/03 10:44	341	91	-9	350	42.8	0.713333	95.99
2003/08/03 10:45	338	91	-9	347	42.8	0.713333	96.71
2003/08/03 10:46	339	91	-9	348	42.8	0.713333	97.42
2003/08/03 10:47	340	91	-9	349	42.8	0.713333	98.13
2003/08/03 10:48	343	91	-9	352	42.8	0.713333	98.85



SAPWAT calculations for theoretical irrigation requirement						
Crop	Wheat-med					
Option	Early June					
Planting Region	N.Cape/Karoo					
Planting Month	June					
PIDay	15			Total Available Moisture (mm/m)		
				140		
Weather Station	ORANIA:BEKER LOOP-					
Day of Growth	Date	Kc	Avg Et0 (mm)	Et (mm)	Rain (mm)	
1	16-Jun-03	0.7	2	1.4	0	
2	17-Jun-03	0.7	2	1.4	0	
3	18-Jun-03	0.7	2	1.4	0	
4	19-Jun-03	0.7	2	1.4	0	
5	20-Jun-03	0.7	2	1.4	0	
6	21-Jun-03	0.7	2.1	1.4	0	
7	22-Jun-03	0.7	2.1	1.5	0	
8	23-Jun-03	0.7	2.1	1.5	0	
9	24-Jun-03	0.7	2.1	1.5	0	
10	25-Jun-03	0.7	2.1	1.5	0	
11	26-Jun-03	0.7	2.1	1.5	0	
12	27-Jun-03	0.7	2.1	1.5	0	
13	28-Jun-03	0.7	2.1	1.5	0	
14	29-Jun-03	0.7	2.1	1.5	0	
15	30-Jun-03	0.7	2.1	1.5	0	
16	01-Jul-03	0.7	2.2	1.5	0	
17	02-Jul-03	0.7	2.2	1.5	0	
18	03-Jul-03	0.7	2.2	1.5	0	
19	04-Jul-03	0.7	2.2	1.5	0	
20	05-Jul-03	0.7	2.2	1.5	0	
21	06-Jul-03	0.7	2.2	1.5	0	
22	07-Jul-03	0.7	2.2	1.6	0	
23	08-Jul-03	0.7	2.2	1.6	0	
24	09-Jul-03	0.7	2.2	1.6	0	
25	10-Jul-03	0.7	2.2	1.6	0	
26	11-Jul-03	0.7	2.3	1.6	0	
27	12-Jul-03	0.7	2.3	1.6	0	
28	13-Jul-03	0.7	2.3	1.6	0	
29	14-Jul-03	0.7	2.3	1.6	0	
30	15-Jul-03	0.7	2.3	1.6	0	
31	16-Jul-03	0.71	2.3	1.7	0	
32	17-Jul-03	0.72	2.4	1.7	0	
33	18-Jul-03	0.72	2.4	1.7	0	
34	19-Jul-03	0.73	2.4	1.8	0	
35	20-Jul-03	0.74	2.5	1.8	0	
36	21-Jul-03	0.74	2.5	1.9	0	
37	22-Jul-03	0.75	2.5	1.9	0	
38	23-Jul-03	0.76	2.6	2	0	
39	24-Jul-03	0.77	2.6	2	0	
40	25-Jul-03	0.77	2.7	2.1	0	
41	26-Jul-03	0.78	2.7	2.1	0	
42	27-Jul-03	0.79	2.7	2.1	0	
43	28-Jul-03	0.79	2.8	2.2	0	
44	29-Jul-03	0.8	2.8	2.2	0	



45	30-Jul-03	0.81	2.8	2.3	0		
46	31-Jul-03	0.81	2.9	2.3	0		
47	01-Aug-03	0.82	2.9	2.4	0		
48	02-Aug-03	0.83	2.9	2.4	0		
49	03-Aug-03	0.83	3	2.5	0		
50	04-Aug-03	0.84	3	2.5	0		
51	05-Aug-03	0.85	3	2.6	0		
52	06-Aug-03	0.85	3.1	2.6	0		
53	07-Aug-03	0.86	3.1	2.7	0		
54	08-Aug-03	0.87	3.1	2.7	0		
55	09-Aug-03	0.88	3.2	2.8	0		
56	10-Aug-03	0.88	3.2	2.8	0		
57	11-Aug-03	0.89	3.3	2.9	0		
58	12-Aug-03	0.9	3.3	2.9	0		
59	13-Aug-03	0.9	3.3	3	0		
60	14-Aug-03	0.91	3.4	3.1	0		
61	15-Aug-03	0.92	3.4	3.1	0		
62	16-Aug-03	0.92	3.4	3.2	0	NIR =	44.2mm
63	17-Aug-03	0.93	3.5	3.2	0	NA =	16796m3
64	18-Aug-03	0.94	3.5	3.3	0		
65	19-Aug-03	0.94	3.5	3.3	0		
66	20-Aug-03	0.95	3.6	3.4	0		
67	21-Aug-03	0.96	3.6	3.4	0		
68	22-Aug-03	0.96	3.6	3.5	0		
69	23-Aug-03	0.97	3.7	3.5	0		
70	24-Aug-03	0.98	3.7	3.6	0		
71	25-Aug-03	0.98	3.7	3.7	0		
72	26-Aug-03	0.99	3.7	3.7	0		
73	27-Aug-03	1	3.8	3.8	0		
74	28-Aug-03	1.01	3.8	3.8	0		
75	29-Aug-03	1.01	3.8	3.9	0		
76	30-Aug-03	1.02	3.9	3.9	0		
77	31-Aug-03	1.03	3.9	4	0		