In situ calibration of large water meters

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Abstract

The establishment of a flow reference standard for the cost-effective *in situ* calibration of large in-line water meters consists of the combined accuracy of point velocity measurements within pipes, a velocity-area method and a velocity-profile function.

Tests were carried out in compliance with the requirements of international standards relating to large water meters. Velocity profiles were measured within pipe sections of 250, 300, 400, 500, 600 and 800 mm dia. and compared to the flow measured by Eskom's Flow Laboratory. This flow laboratory has a best measurement capability of 0,1% uncertainty for the 95% confidence level as accredited by the National Laboratory Accreditation Service (NLA).

The physical dimensions of the pipes dictated at which position the turbine insertion meter should be placed within the pipe in accordance with the log-linear method adopted for this research. This resulted in the need to calculate the velocities near the pipe wall within pipes smaller than 700 mm dia. using a first approximation of the ratio of point velocity nearest the pipe wall to the maximum (centre line) velocity. Second approximations of these velocities were derived using the actual position of mean axial velocity and revised constants for the modified Pao equation for each profile, only if the first approximation indicated a positive error.

Flow tests carried out on the 800 mm dia. pipeline were used as a control because all the velocity measuring points dictated by the log-linear method could be reached with the turbine insertion meter. This control exercise was used to establish the meter's calibration factor (K) for the other tests on the 300, 400, 500 and 600 mm dia. pipelines. Another turbine insertion meter was used for flow tests on the 250 mm dia. pipeline and the manufacturer's calibration factor (K) was applied.

Results of this research indicate that the method for the *in situ* calibration of large water meters can achieve accuracies that comply with relevant standards; however, practical limitations of the meters' performance and the limitations of the hydraulic system in which they are installed could restrict the flow range over which they can be tested/calibrated.

The recommendation is that the flow reference standard consisting of insertion flow meter measurements, a velocity-area method and a velocity-profile function detailed in this report be adopted as an accepted test method for the *in situ* calibration of large water meters.

Introduction

The Water Research Commission (WRC) appointed Stewart Scott (CE) Inc. to undertake research to establish a flow reference standard for the cost effective *in situ* calibration of large water meters required for water audits and other test purposes. This flow reference standard can be used to establish the accuracy of permanently installed water meters by means of regular on-site comparisons to ensure that these meters remain within the limits of accuracy prescribed by local and international standards

This research established the accuracy of a flow reference standard consisting of the combined accuracy of insertion point velocity measurements, a velocity-area method and a velocity - profile function which can be effectively applied in the field through the insertion of a velocity probe into a common pipeline in which a permanent large water meter has been installed.

Flow tests were carried out in compliance with the requirements of the specifications relating to large water meters such as the International Standard ISO4064 (1993) and possible future parts of the South African Standard SABS 1529 (1994). Velocity profiles were measured within various pipe sections by means of a single traverse of an insertion flow meter at the depths determined by the relatively more accurate log-linear velocity-area method, with missing values (i.e. near the pipe wall) established with the aid of an iterative process that included the modified Pao equation and actual point velocity measurements.

Flows determined by means of these velocity profile measurements were compared to those established by Eskom's Flow Laboratory, which has been accredited by the National Laboratory Accreditation Service (NLA). Test sections varied in diameter from 250 mm to 800 mm in order to comply with the abovementioned standards. A comprehensive background to this research is provided in Johnson (1995). This research project is essentially as a result of the recommendations of that paper.

Flow laboratory

The Eskom Flow Laboratory used for this research project has been accredited to measure flow rates in closed conduits for a flow range of 20 to 1200 ℓ/s. The total accuracy of the installation is 0.1% of flow rate. This gravimetric flow laboratory can accommodate piping from 150 to 1 000 mm dia. A constant water flow rate is provided either from a constant-head tower (at lower flow rates) or by direct pumping from a constant-head reservoir (at higher flow rates). The flow passes through the meter under test and then through a control valve and into the diverter chute. The diverter changes the flow stream into the weigh tank in 0.1 s without causing any upstream disturbances. The weigh tank has a 200 t capacity and stands on four calibrated load cells. When sufficient water has been diverted to the tank, the flow stream is returned to the normal direction, where it discharges into an open channel and returns to a make-up

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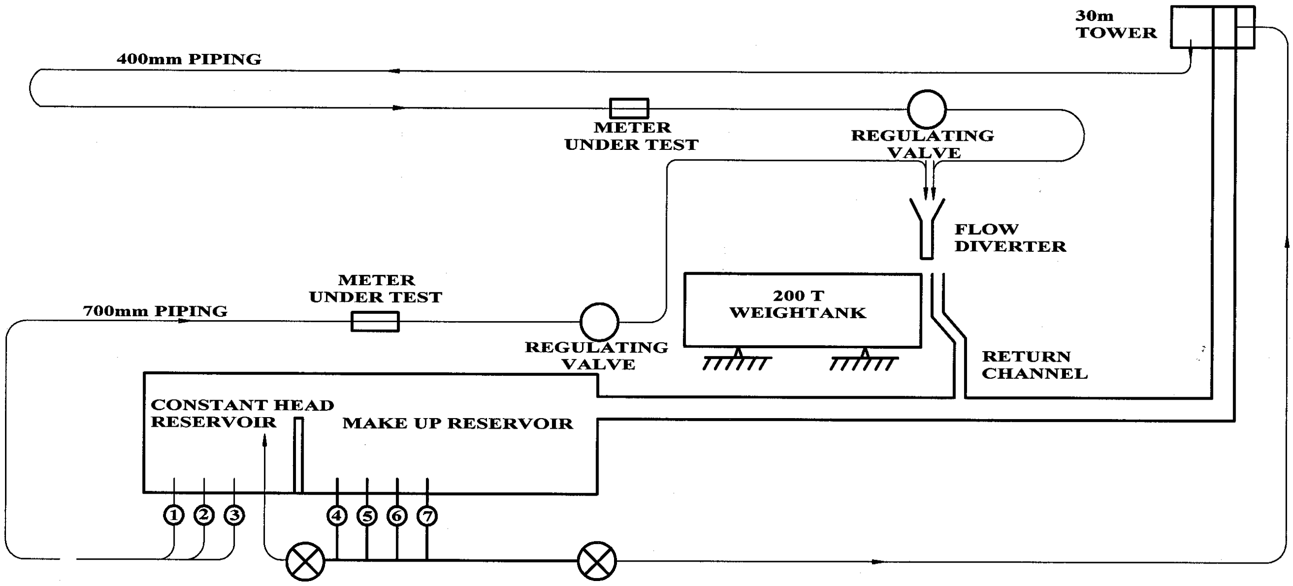

Figure 1
Schematic layout of the laboratory

TABLE 1
CLASS/VELOCITY MATRIX IN COMPLIANCE WITH ISO 4064 (1993)

Flow range points* q_{min}	Class C (0.006 q_p)		Class B (0.03 q_p)	Class A (0.08 q_p)			Velocity @ permanent flow All classes	Velocity @ overload flow All classes
q_t		Class C (0.015 q_p)			Class B (0.20 q_p)	Class A (0.3 q_p)		
q_p							q_p	
q_s								q_s
Dia. (mm)								
250	0.0136	0.0340	0.068	0.1811	0.4527	0.6791	2.2635	4.5270
300	0.0141	0.0354	0.071	0.1886	0.4716	0.7074	2.3579	4.7158
400	0.0133	0.0332	0.066	0.1768	0.4421	0.6632	2.2105	4.4210
500	0.0127	0.0318	0.064	0.1698	0.4244	0.6366	2.1221	4.2442
600	0.0147	0.0368	0.0737	0.1965	0.4912	0.7368	2.4561	4.9122
800	0.0133	0.0332	0.066	0.1768	0.4421	0.6632	2.2105	4.4210

*Note: q_{min} = minimum flow rate; q_t = transitional flow rate; q_p = permanent flow rate; q_s = overload flow rate

Water meter metrological classes
Class A: Value of $q_{min} = 0.08\ q_p$ Value of $q_t = 0.3\ q_p$
Class B: Value of $q_{min} = 0.03\ q_p$ Value of $q_t = 0.2\ q_p$
Class C: Value of $q_{min} = 0.006\ q_p$ Value of $q_t = 0.015\ q_p$

reservoir. A schematic layout of the laboratory situated at Rosherville, Johannesburg is given in Fig. 1.

The quantity of water collected is obtained from the tank weight before and after the diversion period. The time period is obtained from a digital timer which is activated by sensing units attached to the diverter chute.

Flow standards and ranges for large water meters

Water meters have a flow range over which they have been designed to operate; from their minimum flow rate (q_{min}) up to their maximum or overload flow rate (q_s).

- q_{min} is the lowest flow rate at which the meter is required to give indications within the permissible tolerance and is specified as a ratio of the permanent flow rate (q_p) for various metrological classes of water meters.

TABLE 2 METHOD-ACCURACY COMPARISON				
Method	**Log-linear**		**Tangential**	
Traverse points per diameter	6	10	6	10
% Error	-0.24	-0.15	+1.03	+0.56
SD (%)	±0.171	±0.107	±0.245	±0.107
Accuracy @ 95% Conf. (%)	±0.367	±0.242	±0.554	±0.242
SD: Standard deviation				

- q_p is the flow rate for which the meter is designed and at which the meter is required to give indications within the permissible tolerance under normal conditions of use.
- q_s is the rate that is equal to $2q_p$ and also represents the highest flow rate at which the meter is required to operate in a satisfactory manner for a short period of time without deterioration. This short period of time is specified by some manufacturers as 24 h in the life of the meter.
- Between q_{min} and q_p, a transitional flow rate (q_t) is specified dividing the flow range into two separate permissible tolerance zones.
- q_t is also specified as a ratio of q_p for various metrological classes of water meters.

International Standards ISO 4064 (1993) specify the flow for each nominal diameter and for each point on the flow range. The velocities for the various diameters, flow range points and metrological classes are given in Table 1.

Practitioners involved with the testing of large water meters on permanent test facilities generally do not test electronic water meters below 0.1 m/s and mechanical water meters below 0.3 m/s, although Class B and C meters are specified to measure much lower velocities as indicated in Table 1.

The relevance of these findings to this research is that it would be practical to undertake *in situ* calibration of in-line flow meters over the flow range from q_t for Class B meters up to q_s as site testing would not necessarily achieve the high performance standards of a permanent test facility.

The log-linear velocity-area method

Velocity-area methods require that the velocity sensor should be inserted at predetermined points across the flow plane for the measurement of the local velocity. The mean of these local velocities is the average (or mean axial velocity) of the water flow in the pipe. Previous overseas research examined and mentioned in the paper by Johnson (1995), shows that the greater the number of measuring points per traverse the more accurate the flow determination for that method. It was, however, found that the log-linear method is more efficient in its application as it requires fewer measuring points to achieve accuracies better than other velocity-area methods with a greater number of measuring points. Another important aspect of the aforementioned overseas research is that it emphasised the relative accuracy of the various velocity-area methods rather than the overall accuracy of the measurement as in this project.

Six velocity measurement positions (defined by the log-linear method), per traverse across the pipe diameter were selected for this project. Analysis of Salami's (1971) data given in Table 2 indicates that six velocity measurements per traverse of the diameter should achieve an accuracy of ±0.4% for the 95% confidence level. (i.e. the accuracy of a six-measuring-point log-linear method is ± 0.4%).

Research equipment, methodology and findings

Turbine insertion flow meters

The insertion flow meters used for this project were turbine insertion meters that provide a frequency output proportional to the velocity of the flowing water. The measuring head consists of a small turbine of 32 mm dia. mounted in a cage together with a magnetic pick-up that is used to count the turbine blade's revolutions. The manufacturer provided two of these meters for this project. It is important to note that this research is aimed at establishing a standard test method and not at establishing the accuracy of the meter type *per se*, although in order to establish the overall accuracy of the measurements, the accuracy of the meters also needed to be established. The measuring head is mounted on the end of a retractable probe, which is inserted through a 45 mm dia. access tee and isolating valve into the pipeline operating under normal conditions. The exact dimensions of the meter, the access tee, valve, as well as the internal and external pipe diameters were established in order to insert the centre of the turbine to the positions prescribed by the log-linear method. External measurement reference points on the meter's probe were used in conjunction with a steel measuring rule (that had a resolution of 0.5 mm), to establish the prescribed depths of penetration. In accordance with the British Standard BS1042 (Section 2.2, 1983) the diameter of the turbine dictates the minimum pipe diameter within which the velocity profile can be measured which, in this case is 300 mm.

A Certificate of Calibration provided by Eskom's Flow Laboratory for each flow test included the measured meter frequency for each insertion depth.

The further the probe is inserted into the pipe the greater is the area of pipe blocked, causing a greater velocity of the water passing through the remaining unrestricted area. In order to establish the actual point velocity each velocity measurement was corrected by means of blockage and velocity factors that used a ratio of areas to correct these local velocities. These corrections were made during the analysis of the data as given in **Appendix A**.

Initial flow results as well as examination of the turbine indicated problems with 'sticking' of the turbine at the lower velocities The turbine cage was stripped and hair-like fibres were found to be fouling the turbine's small bearings. In an attempt to minimise the effect of this problem on the results of this research

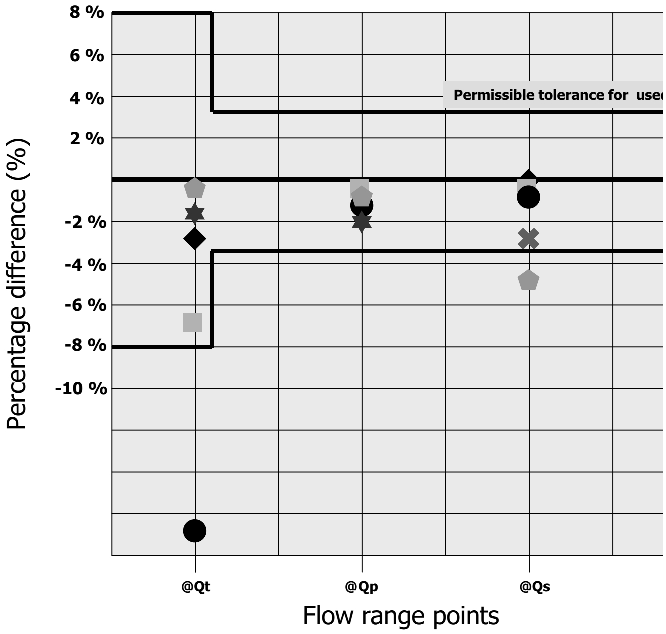

Figure 2
Test results

TABLE 3
SUMMARY OF RESULTS

	Nominal dia. (mm)	Internal dia. (mm)	Percentage difference in measured flow to laboratory flow standard			
			% @ q_t	% @ q_p	% @ q_s	Mean difference (%)
	800	793.0	-3.111	-0.174	1.044	-0.7471
	600	597.8	-6.305	-0.435	1.137	-1.8677
	500	492.3	-0.336	-0.517	-5.455	-2.1027
	400	396.0	-3.496	-0.533	-3.329	-2.4527
	300	306.06	-1.168	-1.959	0.447	-0.8933
	250	257.8	-16.344*	-1.333	0.494	-0.4195
Mean			-2.8833	-0.8252	-0.9436	**-1.4723**
SD			2.322	0.6782	2.7686	2.1842
Student's t			2.7765	2.5706	2.5706	2.1199
Accuracy (%)			6.447	1.743	7.117	**4.630**

* Notes: Outlier and therefore, omitted from further analysis.

the meter (No.30193/90) was only used for the measurements on the 250 mm dia. pipeline and was not used again.

Meter No. 31901/96 was used for measuring flows on the 300, 400, 500, 600 and 800 mm dia. pipelines. This meter was also stripped, oiled and its bearings cleaned by removing hair-like fibres. As all the measuring points could be measured on the 800 mm dia. pipe these flow tests were used to establish the meter's calibration (K) factor. (See **Appendix A1**).

Methodology

As previously mentioned the aim was to measure the six positions dictated by the log-linear velocity area method. Two additional point velocity measurements were taken and these were at the centre line of the pipe and at a rough approximation of the depth of the mean axial velocity as described in previous research (Johnson, 1995). The reason for taking these two additional velocity measurements was that they facilitate the process of establishing revised constants for the modified Pao equation in order to establish an approximation for velocity measurements of the inaccessible measurement positions on the pipes smaller than 700 mm dia. Greater details of the velocity profile function known as the modified Pao equation are provided in Johnson (1995) where it is noted that the equation is independent of temperature changes. Although this research was conducted on horizontal pipes it is applicable to pipes installed on a slope because the geometry of the velocity profile is related to the roughness of the inside pipe wall and Reynolds number and not the gradient of the pipe *per se*. The relevant criteria are that the probe is inserted perpendicular to the flow stream and within the tolerances dictated by the British Standard BS1042 (Section 2.2 1983).

The access point was situated at a position between 18 and 30 diameters of straight length of pipeline downstream from any turbulence-causing devices such as 90° bends and tapers. These positions were indicated on the Calibration Certificates provided by Eskom.

Where possible flow tests were conducted at q_t, q_p and q_s but not at q_{min} because of the extremely low velocities. In accordance with International Standards ISO4064 (1983) tests were conducted within 10% of these specified flow rates.

Research findings

Analysis of the results for the tests carried out on the 800 mm dia. pipeline and for the velocity range of 0.4654 to 2.1455 m/s was used to establish the meter's calibration constant of 113.2170 pulses/m. As Eskom's Flow Laboratory has NLA accreditation for a maximum flow of 1 200 ℓ/s, q_s for an 800 mm dia. pipeline with a flow rate of 2 222.2 ℓ/s could not be reached. However, two flow tests were carried out at q_p (see **Appendix A1**).

The calibration factor (K) was then applied to all flow tests for the 300 mm, 400 mm, 500 mm, 600 mm and 800 mm dia. pipelines. The calibration factor originally provided with the turbine meter by the manufacturer and used for flow tests on the 250 mm dia. pipeline was adopted. However, because of the problems encountered with the turbine 'sticking' at low flows, the results from the q_{min} test were considered an outlier and omitted from further analysis.

Analysis of the data for the flow tests on the 800 mm dia. pipeline included the establishment of the ratios of each point velocity to the maximum (centre line) velocity. The means of these ratios nearest the pipe wall were then used to establish a first approximation of these velocities for the pipes smaller than the 800 mm dia. pipe.

The position of mean axial velocity as well as the constants for the modified Pao equation were established for every velocity profile measured. Where necessary these derived constants were used to establish a second approximation of the velocities near the pipe wall (i.e. if the percentage error for the first approximation of flow determination was positive).

The percentage difference in the flow measured by the Flow Laboratory and that derived from the velocity profiles was established for each flow test. (See **Appendices A2 to A7**). A summary of these results is given in Table 3 and Fig. 2.

Examination of these results indicates that the mean percentage difference for all the tests is –1.4623%, which translates to an accuracy of ±4.630% (i.e. SD x Student's t). The best result at a particular flow rate for all the pipe sizes was that for the permanent flow rate (q_p) with an accuracy of ±1.743%.

When undertaking flow tests in the field with the pipeline operating under normal conditions the flow within the pipe will rarely be at one of the prescribed flow rates for testing. Probably the best situation for *in situ* testing would require a throttling of a valve on the pipeline to achieve the desired flow rate so that there would be minimum interference with the supply. As it probably would be very unlikely that q_s could be achieved in the field at a predetermined time, flow tests could be practically conducted only in the region of the in-line meter's q_t and q_p.

It is interesting to note that the South African Standard SABS 1529-1 (1994) allows for the verification of used water meters (not exceeding 100 mm dia.) when tested in the installation in which they are used in trade at q_{min},q_t and q_s. The permissible tolerances given by SABS 1529-1 (1994) for these tests are 8% for flow rates less than q_t and 3,5% for flow rates not less than q_t. These specifications would need modifying to be relevant for future Parts of SABS 1529 applicable to water meters larger than 100 mm dia. because of the previous observation that the *in situ* testing cannot necessarily replicate the performance standards of a permanent test facility.

Practical application of site calibration and site testing

The practical application of the *in situ* calibration of large flow meters will require the organisations offering this service to be accredited for site calibration and site testing by an agency such as the NLA if there is to be any credibility in the field tests as well as to ensure traceability.

The United Kingdom Accreditation Service (UKAS) has published the *NAMAS M18 Accreditation for Site Calibration and Site Testing -Assessment Procedures and Criteria of Competence* (1996). This publication details the various site calibration/ testing categories together with their respective criteria and assessment procedures. Site calibration or testing performed on site by organisations (or individuals) that do not have a permanent calibration or testing laboratory (Category III) may perform calibration or testing according to the following methods:

- using portable calibration or testing equipment;
- in a site laboratory;
- in a mobile laboratory; or
- using equipment from a mobile or site laboratory.

Criteria of competence to be met by applicants for accreditation include aspects such as keeping and maintaining a quality manual; documented detailed procedures that are available for regular auditing; ensuring staff are properly trained and competent; procedures for operating, maintaining and calibrating of equipment used; the holding of reference standards; having calibration/ test procedures; maintenance of a record system as well as the requirements for test results and issuing of certificates.

The flow range over which the water meter can be calibrated/ tested in the field is limited by practical limitations such as the maximum operating capacity of the hydraulic system at the time of testing and the ability of the system to be throttled to the lower flows without interrupting the supply.

Other types of insertion flow meters with smaller measuring heads would be able to measure at the velocity measurement positions near the pipe wall on pipes smaller than 700 mm dia. and thereby possibly achieve an improvement in the accuracy of the method.

Conclusion and recommendations

The *in situ* calibration of large in-line water meters with the aid of a portable insertion flow meter can achieve accuracies that comply with relevant standards. However, practical limitations of the meter's performance and the limitations of the hydraulic system in which they are installed could restrict the flow range over which they can be tested/calibrated, to between q_t and q_p. The findings of this project are, that when testing at q_t, q_p and q_s for diameters 250, 300, 400, 500, 600 and 800 mm, accuracies of better than ±5% were achieved. Tests carried out at q_p for all the pipe diameters achieved accuracies of better than ±2%.

It is therefore recommended that the flow reference standard consisting of insertion flow meter measurements, a velocity-area method and a velocity profile function detailed in this report be adopted as an accepted test method for the *in situ* calibration of large water meters. The following specific aspects are also recommended:

- The flow range over which the tests/calibrations are carried out should correspond with the performance capabilities of the portable meter adopted for *in situ* testing and the limitations of the hydraulic system in which the tests are conducted, which, would generally be from q_t up to the water meter's q_p as defined by ISO 4064 (1993).
- The organisation or individual carrying out such site testing/calibration should be accredited by NLA in a manner similar to that detailed in the UKAS NAMAS M18 manual (1996) to provide such a service.
- Future parts of SABS 1529 (1994) applicable to water meters larger than 100 mm dia. should incorporate the recommendations of this research.

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- BEP Bestobell South Africa
- KDG Mobrey Limited UK

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Appendix A1

In situ calibration of large water meters

Determination of constants and calibration factors

Reference flow(m³/s)	Reference mean vel(m/s)	Pipe dia.	Depth of meter(mm)	Distance from top pipe wall	Measured frequency(Hz)	Blockage factor	Velocity factor	Adjusted frequency(Hz)	Turbine meter K factor	Point velocity	Position of mean vel.	Constant A	Constant B	Position of mean vel:dia.	Ratio of Pt vel:mean	Ratio of Pt vel:max
0.16742	0.3390	793	145.8	25.46	32.15	0.2207	1.0022	32.0790		0.2924					0.8627	0.7873
			227.3	106.98	38.64	0.6306	1.0063	38.3963		0.3500	91.33		0.1503	0.1152	1.0326	0.9423
			262.2	141.95	39.71	0.8076	1.0081	39.3893		0.3591					1.0593	0.9667
			374.6	254.32	43.03	1.3764	1.0140	42.4377		0.3869					1.1413	1.0415
			516.8	396.50	41.62	2.0961	1.0214	40.7476		0.3715					1.0958	1.0000
			659.0	538.68	42.43	2.8158	1.0290	41.2353		0.3759					1.1090	1.0120
			806.3	686.02	39.34	3.5616	1.0369	37.9389		0.3459	98.09		0.1580	0.1237	1.0203	0.9311
			887.8	767.54	32.30	3.9742	1.0414	31.0163		0.2828					0.8341	0.7612
									109.6943	0.3390		1.0958				
0.229862	0.4654		145.8	25.46	45.24	0.2207	1.0022	45.1401		0.3994					0.8582	0.7748
			227.3	106.98	54.84	0.6306	1.0063	54.4942		0.4822	90.47		0.1678	0.1141	1.0360	0.9353
			262.2	141.95	55.13	0.8076	1.0081	54.6848		0.4839					1.0396	0.9386
			374.6	254.32	59.62	1.3764	1.0140	58.7994		0.5203					1.1179	1.0092
			516.8	396.50	59.51	2.0961	1.0214	58.2626		0.5155					1.1077	1.0000
			659.0	538.68	59.15	2.8158	1.0290	57.4845		0.5086					1.0929	0.9866
			806.3	686.02	55.19	3.5616	1.0369	53.2244		0.4709	99.45		0.1792	0.1254	1.0119	0.9135
			887.8	767.54	48.38	3.9742	1.0414	46.4573		0.4111					0.8832	0.7974
									113.0198	0.4654		1.1077				
1.059677	2.1455		145.8	25.46	215.67	0.2207	1.0022	215.1939		1.8811					0.8767	0.7805
			227.3	106.98	249.97	0.6306	1.0063	248.3938		2.1713	99.75		0.2057	0.1258	1.0120	0.9009
			262.2	141.95	262.48	0.8076	1.0081	260.3602		2.2759					1.0608	0.9443
			374.6	254.32	277.11	1.3764	1.0140	273.2959		2.3890					1.1135	0.9913
			516.8	396.50	281.61	2.0961	1.0214	275.7072		2.4100					1.1233	1.0000
			659.0	538.68	276.69	2.8158	1.0290	268.8990		2.3505					1.0955	0.9753
			806.3	686.02	259.63	3.5616	1.0369	250.3830		2.1887	95.09		0.1988	0.1199	1.0201	0.9081
			887.8	767.54	225.49	3.9742	1.0414	216.5285		1.8927					0.8822	0.7854
									114.3995	2.1455		1.1233				
1.0588	2.1438		145.8	25.46	206.15	0.2207	1.0022	205.6949		1.8328					0.8549	0.7514
			227.3	106.98	250.10	0.6306	1.0063	248.5229		2.2144	91.89		0.2171	0.1159	1.0329	0.9078
			262.2	141.95	25646	0.8076	1.0081	25438.8848		226.6639					105.7316	92.9244
			374.6	254.32	275.82	1.3764	1.0140	272.0237		2.4238					1.1306	0.9937
			516.8	396.50	279.62	2.0961	1.0214	273.7589		2.4392					1.1378	1.0000
			659.0	538.68	278.43	2.8158	1.0290	270.5900		2.4110					1.1247	0.9884
			806.3	686.02	246.91	3.5616	1.0369	238.1161		2.1216	116.23		0.2586	0.1466	0.9897	0.8698
			887.8	767.54	217.28	3.9742	1.0414	208.6448		1.8591					0.8672	0.7621
									112.2317	2.1438		1.1378				
								MEAN FACTOR :	113.2170		**TOP PROF.**	1.1161	0.1852	0.1177	0.8631	0.8183
								STD DEVIATION:	1.0972	3.182449291	**TOP PROF.**	0.0183	0.0314	0.0054	0.0096	0.0997
								NUMBER OF VAL:	3			4	4	4		
											BOT PROF.		0.1987	0.1289	0.8667	0.7765
											BOT PROF.		0.0433	0.0120	0.0229	0.0178

Appendix A2

***In situ* calibration of large water meters**

Analysis of flow tests for 800 mm diameter

Reference flow(m^3/s)	Reference mean vel(m/s)	Pipe dia.	Depth of meter(mm)	Distance from top pipe wall	Measured frequency(Hz)	Blockage factor	Velocity factor	Turbine meter K factor	Point velocity	% Error of measured Q
0.16742	0.3390	793	145.8	25.46	32.15	0.2207	1.0022		0.2833	
			227.3	106.98	38.64	0.6306	1.0063		0.3391	
			262.2	141.95	39.71	0.8076	1.0081		0.3479	
			374.6	254.32	43.03	1.3764	1.0140		0.3748	
			516.8	396.50	41.62	2.0961	1.0214		0.3599	
			659.0	538.68	42.43	2.8158	1.0290		0.3642	
			806.3	686.02	39.34	3.5616	1.0369		0.3351	
			887.8	767.54	32.30	3.9742	1.0414		0.2740	
								113.2170	0.3284	-3.1114
0.229862	0.4654		145.8	25.46	45.24	0.2207	1.0022		0.3987	
			227.3	106.98	54.84	0.6306	1.0063		0.4813	
			262.2	141.95	55.13	0.8076	1.0081		0.4830	
			374.6	254.32	59.62	1.3764	1.0140		0.5194	
			516.8	396.50	59.51	2.0961	1.0214		0.5146	
			659.0	538.68	59.15	2.8158	1.0290		0.5077	
			806.3	686.02	55.19	3.5616	1.0369		0.4701	
			887.8	767.54	48.38	3.9742	1.0414		0.4103	
									0.4646	-0.1742
1.059677	2.1455		145.8	25.46	215.67	0.2207	1.0022		1.9007	
			227.3	106.98	249.97	0.6306	1.0063		2.1940	
			262.2	141.95	262.48	0.8076	1.0081		2.2997	
			374.6	254.32	277.11	1.3764	1.0140		2.4139	
			516.8	396.50	281.61	2.0961	1.0214		2.4352	
			659.0	538.68	276.69	2.8158	1.0290		2.3751	
			806.3	686.02	259.63	3.5616	1.0369		2.2115	
			887.8	767.54	225.49	3.9742	1.0414		1.9125	
									2.1680	1.0444
1.0588	2.1438		145.8	25.46	206.15	0.2207	1.0022		1.8168	
			227.3	106.98	250.10	0.6306	1.0063		2.1951	
			262.2	141.95	256.46	0.8076	1.0081		2.2469	
			374.6	254.32	275.82	1.3764	1.0140		2.4027	
			516.8	396.50	279.62	2.0961	1.0214		2.4180	
			659.0	538.68	278.43	2.8158	1.0290		2.3900	
			806.3	686.02	246.91	3.5616	1.0369		2.1032	
			887.8	767.54	217.28	3.9742	1.0414		1.8429	
									2.1251	-0.8703
								MEAN		-0.7779
								STDEV		1.7454

Appendix A3

***In situ* calibration of large water meters**

Analysis of flow tests for 600 mm diameter

Reference flow(m^3/s)	Reference mean vel(m/s)	Pipe dia. (mm)	Depth of meter(mm)	Distance from top pipe wall	Measured frequency(H-z)	Blockage factor	Velocity factor	Turbine meter K factor	Point velocity	Calculated velocity	Position of mean vel.	Constant A	Constant B	Calculated velocity(m/s)	% Error of measured Q
0.150417	0.5359	597.8	123.4	19.19	47.00	0.3382	1.0034	113.2170	0.4137	0.4137					
			184.8	80.64	58.84	0.8751	1.0088		0.5152		72.74		0.2755		
			211.2	107.01	61.95	1.1099	1.0112		0.5411						
			295.9	191.71	67.98	1.8644	1.0190		0.5892						
			403.1	298.90	68.39	2.8191	1.0290		0.5870						
			510.3	406.09	67.17	3.7738	1.0392		0.5709						
			621.4	517.16	55.60	4.7632	1.0500		0.4677		117.69		0.4178		
			625.0	520.74	56.02	4.7951	1.0504		0.4711	0.4560		1.1691		0.4560	
								Mean velocity	1st Approx.=	0.5021				0.5021	
								Calc.flow(m^3/s)	1st Approx.=	0.1409					-6.305
0.669703	2.3861		123.4	19.19	226.96	0.3382	1.0034		1.9979						
			184.8	80.64	294.09	0.8751	1.0088		2.5748		59.43		0.1707		
			211.2	107.01	288.79	1.1099	1.0112		2.5225						
			295.9	191.71	316.76	1.8644	1.0190		2.7457						
			403.1	298.90	309.92	2.8191	1.0290		2.6602						
			510.3	406.09	299.89	3.7738	1.0392		2.5488						
			621.4	517.16	275.88	4.7632	1.0500		2.3207		107.44		0.2695		
			625.0	520.74	275.76	4.7951	1.0504		2.3189	2.0665				2.0665	
								Mean velocity	1st Approx.=	2.3757		1.1198		2.3757	
								Calc.flow(m^3/s)	1st Approx.=	0.6668					-0.435
1.078514	3.8426		123.4	19.19	369.35	0.3382	1.0034		3.2513						
			184.8	80.64	459.01	0.8751	1.0088		4.0188		69.90		0.1924		
			211.2	107.01	474.84	1.1099	1.0112		4.1475						
			295.9	191.71	495.48	1.8644	1.0190		4.2948						
			403.1	298.90	507.52	2.8191	1.0290		4.3563						
			510.3	406.09	517.63	3.7738	1.0392		4.3995						
			621.4	517.16	470.72	4.7632	1.0500		3.9596		77.84		0.2078		
			625.0	520.74	459.48	4.7951	1.0504		3.8638	3.3840		1.1214		3.3938	
								Mean velocity	1st Approx.=	3.8847			2nd Approx.=	3.8863	
								Calc.fow(m^3/s)	1st Approx.=	1.0903			2nd Approx.=	1.0908	1.137
													OVERALL	MEAN error	-1.868
													STDEV		3.923

Appendix A4

In situ calibration of large water meters

Analysis of flow tests for 500 mm diameter

Reference flow(m^3/s)	Reference mean vel(m/s)	Pipe dia. (mm)	Depth of meter(mm)	Distance from top pipe wall	Measured frequency (Hz)	Blockage factor	Velocity factor	Turbine Meter K factor	Point velocity	Calculated velocity	Position of mean vel.	Constant A	Constant B	Calculated velocity(m/s)	% Error of measured Q
0.099302	0.5217	492.3	0	15.80	0.0	0.4587	1.0046	113.2170	0.0000	0.4851				0.4851	
			170.1	66.41	57.32	1.1034	1.0112		0.5007		128.96		0.4996		
			191.8	88.12	60.54	1.3885	1.0141		0.5273						
			261.6	157.88	68.89	2.3047	1.0236		0.5945						
			349.9	246.15	69.53	3.4640	1.0359		0.5929						
			438.1	334.42	68.98	4.6234	1.0485		0.5811						
			529.6	425.89	59.83	5.8247	1.0618		0.4977		90.82		0.3239		
			0.0	476.50	0.0	6.4894	1.0694		0.0000	0.4605		1.1403		0.4605	
								Mean velocity	1st Approx.=	0.5199				0.5199	
								Calc.flow(m^3/s)	1st Approx.=	0.0990				0.0990	-0.336
0.411006	2.1592		0	15.80	0.0	0.4587	1.0046		0.0000	1.9099				1.9099	
			170.1	66.41	250.49	1.1034	1.0112		2.1881		59.13		0.1398		
			191.8	88.12	261.57	1.3885	1.0141		2.2783						
			261.6	157.88	293.06	2.3047	1.0236		2.5288						
			349.9	246.15	273.73	3.4640	1.0359		2.3340						
			438.1	334.42	278.13	4.6234	1.0485		2.3430						
			529.6	425.89	253.12	5.8247	1.0618		2.1055		82.81		0.1829		
			0.0	476.50	0	6.4894	1.0694		0.0000	1.8130		1.0866		1.8130	
								Mean velocity	1st Approx.=	2.1481				2.1481	
								Calc.flow(m^3/s)	1st Approx.=	0.4089				0.4089	-0.517
0.815783	4.2857		0	15.80	0	0.4587	1.0046		0.0000	3.9390				3.9390	
			170.1	66.41	428.02	1.1034	1.0112		3.7388		44.36		0.2526		
			191.8	88.12	446.47	1.3885	1.0141		3.8887						
			261.6	157.88	474.66	2.3047	1.0236		4.0959						
			349.9	246.15	564.54	3.4640	1.0359		4.8136						
			438.1	334.42	547.72	4.6234	1.0485		4.6141						
			529.6	425.89	503.08	5.8247	1.0618		4.1847		64.81		0.3243		
			0.0	476.50	0	6.4894	1.0694		0.0000	3.7392		1.1880		3.7392	
								Mean velocity	1st Approx.=	4.0519			2nd Approx.=	4.0519	
								Calc.flow(m^3/s)	1st Approx.=	0.7713			2nd Approx.=	0.7713	-5.455
													OVERALL	MEAN error	-2.103
													STDEV		2.905

Appendix A5

***In situ* calibration of large water meters**

Analysis of flow tests for 400 mm diameter

Reference flow(m^3/s)	Reference mean vel(m/s)	Pipe dia. (mm)	Depth of meter(mm)	Distance from top pipe wall	Measured frequency (Hz)	Blockage factor	Velocity factor	Turbine meter K factor	Point velocity	Calculated velocity	Position of mean vel.	Constant A	Constant B	Calculated velocity (m/s)	% Error of measured Q
0.055338	0.4493	396	0	12.71	0.00	0.6524	1.0066	113.2170	0.0000	0.4193				0.4193	
			154.3	53.42	48.66	1.4416	1.0146		0.4236		149.37		1.4858		
			171.8	70.88	52.15	1.7961	1.0183		0.4523						
			227.9	127.00	58.19	2.9351	1.0302		0.4989						
			298.9	198.00	60.67	4.3763	1.0458		0.5125						
			369.9	269.00	55.15	5.8176	1.0618		0.4588						
			443.5	342.58	49.21	7.3110	1.0789		0.4029		93.85		0.5609		
			0.0	383.29	0.00	8.1374	1.0886		0.0000	0.3981		1.1819		0.3981	
								Mean velocity	**1st Approx.=**	0.4336				0.4336	
								Calc.flow(m^3/s)	**1st Approx.=**	0.0534				0.0534	-3.496
0.277309	2.2516		0	12.71	0.00	0.6524	1.0066		0.0000	2.0738				2.0738	
			154.3	53.42	269.13	1.4416	1.0146		2.3428		37.80		0.1830		
			171.8	70.88	283.54	1.7961	1.0183		2.4594						
			227.9	127.00	302.87	2.9351	1.0302		2.5966						
			298.9	198.00	300.05	4.3763	1.0458		2.5342						
			369.9	269.00	279.98	5.8176	1.0618		2.3291						
			443.5	342.58	259.74	7.3110	1.0789		2.1264		94.49		0.4096		
			0.0	383.29	0.00	8.1374	1.0886		0.0000	1.9686		1.1316		1.9686	
								Mean velocity	**1st Approx.=**	2.2396				2.2396	
								Calc.flow(m^3/s)	**1st Approx.=**	0.2758				0.2758	-0.533
0.498442	4.0470		0	12.71	0.00	0.6524	1.0066		0.0000	3.5564				3.5564	
			154.3	53.42	478.72	1.4416	1.0146		4.1674		36.42		0.1508		
			171.8	70.88	491.58	1.7961	1.0183		4.2640						
			227.9	127.00	519.42	2.9351	1.0302		4.4531						
			298.9	198.00	514.57	4.3763	1.0458		4.3460						
			369.9	269.00	498.67	5.8176	1.0618		4.1483						
			443.5	342.58	460.81	7.3110	1.0789		3.7726		80.78		0.2847		
			0.0	383.29	0.00	8.1374	1.0886		0.0000	3.3760		1.1109		3.3760	
								Mean velocity	**1st Approx.=**	3.9123			**2nd Approx.=**	3.9123	
								Calc.flow(m^3/s)	**1st Approx.=**	0.4819			**2nd Approx.=**	0.4819	-3.329
													OVERALL	MEAN error	-2.453
													STDEV		1.664

Appendix A6

***In situ* calibration of large water meters**

Analysis of flow tests for 300 mm diameter

Reference Flow (m^3/s)	Reference mean vel(m/s)	Pipe dia. (mm)	Depth of meter(mm)	Distance from top pipe wall	Measured frequency (Hz)	Blockage factor	Velocity factor	Turbine meter K factor	Point velocity	Calculated velocity	Position of mean vel.	Constant A	Constant B	Calculated velocity(m-/s)	% Error of measured Q
0.030094	0.4091	306.06	0	9.82	0.00	1.0039	1.0101	113.2170	0.0000	0.3665				0.3665	
			144.9	41.29	45.50	2.0011	1.0204		0.3938		53.36		0.2359		
			158.4	54.78	47.18	2.4597	1.0252		0.4065						
			201.8	98.15	52.46	3.9334	1.0409		0.4451						
			256.6	153.03	53.83	5.7982	1.0616		0.4479						
			311.5	207.91	54.86	7.6630	1.0830		0.4475						
			368.4	264.77	53.19	9.5953	1.1061		0.4248		26.13		0.1406		
			0.0	296.24	0.00	10.6645	1.1194		0.0000	0.3479		1.1080		0.3479	
								Mean velocity	**1st Approx.=**	0.4043				0.4043	
								Calc.flow(m^3/s)	**1st Approx.=**	0.0297				0.0297	-1.168
0.165488	2.2494		0	9.82	0.00	1.0039	1.0101		0.0000	2.1696				1.9539	
			144.9	41.29	264.07	2.0011	1.0204		2.2857		47.21		0.2918		
			158.4	54.78	283.10	2.4597	1.0252		2.4390						
			201.8	98.15	310.08	3.9334	1.0409		2.6311						
			256.6	153.03	318.66	5.7982	1.0616		2.6514						
			311.5	207.91	312.87	7.6630	1.0830		2.5517						
			368.4	264.77	268.96	9.5953	1.1061		2.1476		63.79		0.3921		
			0.0	296.24	0.00	10.6645	1.1194		0.0000	2.0596		1.1490		1.6620	
								Mean velocity	**1st Approx.=**	2.3076				2.2053	
								Calc.flow(m^3/s)	**1st Approx.=**	0.1698				0.1622	-1.959
0.332284	4.5165		0	9.82	0.00	1.0039	1.0101		0.0000	4.3007				3.4851	
			144.9	41.29	510.49	2.0011	1.0204		4.4188		50.19		0.3273		
			158.4	54.78	533.66	2.4597	1.0252		4.5977						
			201.8	98.15	610.51	3.9334	1.0409		5.1803						
			256.6	153.03	631.65	5.7982	1.0616		5.2556						
			311.5	207.91	603.64	7.6630	1.0830		4.9232						
			368.4	264.77	540.38	9.5953	1.1061		4.3150		62.02		0.4040		
			0.0	296.24	0.00	10.6645	1.1194		0.0000	4.0826		1.1585		3.0700	
								Mean velocity	**1st Approx.=**	4.5367			**2nd Approx.=**	4.2321	
								Calc.flow(m^3/s)	**1st Approx.=**	0.3338			**2nd Approx.=**	0.3114	0.447
													OVERALL	MEAN error	-0.893
													STD DEV		1.226

Appendix A7

In situ calibration of large water meters | **Analysis of flow tests for 250 mm diameter**

Reference flow(m^3/s)	Reference mean vel(m/s)	Pipe dia. (mm)	Depth of meter(mm)	Distance from top pipe wall	Measured frequency (Hz)	Blockage factor	Velocity factor	Turbine meter K factor	Point velocity	Calculated velocity	Position of mean vel.	Constant A	Constant B	Calculated velocity (m/s)	% Error of measured Q
0.046487	0.8906	257.8	0	8.28	0.00	1.3481	1.0137	112.3938	0.0000	0.7043				0.7043	
			142.6	34.78	80.03	2.5086	1.0257		0.6942		-98.15				
			153.9	46.15	81.33	3.0531	1.0315		0.7015						
			190.5	82.68	100.45	4.8027	1.0504		0.8508						
			236.7	128.90	104.04	7.0165	1.0755		0.8607						
			282.9	175.12	103.14	9.2304	1.1017		0.8329						
			330.8	223.02	91.38	11.5245	1.1303		0.7194		59.01		0.4575		
			0.0	249.52	0.00	12.7938	1.1467		0.0000	0.6686		1.1553		0.6686	
								Mean velocity	**1st Approx.=**	0.7450				0.7450	
								Calc.flow(m^3/s)	**1st Approx.=**	0.0389				0.0389	-16.344
0.111188	2.1301		0	8.28	0.00	1.3481	1.0137		0.0000	2.0258				2.0258	
			142.6	34.78	236.77	2.5086	1.0257		2.0538		80.22		0.8638		
			153.9	46.15	246.94	3.0531	1.0315		2.1300						
			190.5	82.68	281.62	4.8027	1.0504		2.3853						
			236.7	128.90	299.25	7.0165	1.0755		2.4757						
			282.9	175.12	280.71	9.2304	1.1017		2.2670						
			330.8	223.02	248.37	11.5245	1.1303		1.9552		57.29		0.5052		
			0.0	249.52	0.00	12.7938	1.1467		0.0000	1.9231		1.1779		1.9231	
								Mean velocity	**1st Approx.=**	2.1017			**2nd Approx.=**	**2.1017**	
								Calc.flow(m^3/s)	**1st Approx.=**	0.1097			**2nd Approx.=**	**0.1097**	-1.333
0.221725	4.2478		0	8.28	0.00	1.3481	1.0137		0.0000	4.0543				4.0543	
			142.6	34.78	490.72	2.5086	1.0257		4.2566		35.51		0.2869		
			153.9	46.15	515.32	3.0531	1.0315		4.4450						
			190.5	82.68	570.28	4.8027	1.0504		4.8303						
			236.7	128.90	598.87	7.0165	1.0755		4.9545						
			282.9	175.12	572.97	9.2304	1.1017		4.6273						
			330.8	223.02	507.55	11.5245	1.1303		3.9954		55.50		0.4390		
			0.0	249.52	0.00	12.7938	1.1467		0.0000	3.8486		1.1606		3.8486	
								Mean velocity	**1st Approx.=**	4.2687			**2nd Approx.=**	4.2687	
								Calc.flow(m^3/s)	**1st Approx.=**	0.2228			**2nd Approx.=**	0.2228	0.494
													OVERALL	MEAN error	-5.728
													STDEV		9.239