Flow resistance of wastewater pumping mains

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Summary

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Wherever a drainage system is located it is likely to include pumping mains for lifting wastewater from low-level areas or for conveying it to sewage works for treatment. In all cases, a key requirement for the effective and economic design of a pumping system is reliable information on the flow resistance of pipes when carrying wastewater. The value of resistance depends on a variety of factors, including the thickness of the biological slimes and grease that build up on the walls of a pipe over a period of time, the size of the pipe, the velocity of the flow and the characteristics of the sewage being pumped through the system.

Surprisingly little information on the in-service flow resistance of pumping mains has previously been collected, and values quoted in standard references (such as the HR Wallingford flow tables) were derived from a very limited amount of data published more than thirty years ago.

This report describes a study carried out by HR Wallingford which had the following objectives:

- To obtain data on the in-service flow resistance of wastewater pumping mains.
- To provide recommended design values of flow resistance for adoption in design manuals, reference documents and computer models of drainage systems.

In order to achieve the above objectives the study was divided into the following stages:

- Determination of the criteria for the selection of test sites in consultation with project partners.
- Identification of test sites.
- Field measurements.
- Analysis of data.
- Recommendation of design values of flow resistance.

The criteria for the selection of test sites were considered in detail by the project Steering Group at the start of the study. Some 2500 sites were available on the Thames Water database alone and a method of selection was required assuming in the first instance that all sites were suitable for use. It was agreed that some 20 sites would be identified and that pipe size would be the most significant factor affecting the choice.

Summary continued

It was further suggested that sites that had reliable records should be chosen and that as wide a range of materials should be tested as possible.

Having set out the criteria against which to choose from the available sites a short list of 26 was drawn up and visited to confirm their suitability. Unfortunately, for various reasons not all were acceptable and throughout the study additional sites were substituted as necessary. In total, tests were performed during the study for 15 sites, test results for an additional seven sites were supplied by United Utilities, and one additional test result was provided by Thames Water. The pipe sizes tested ranged from 75mm to 1000mm in diameter and pipe materials tested included UPVC, ductile iron, steel, asbestos-cement, cast iron, and polyethelene.

A range of data needed to be collected from each field site in order to determine values of pipe roughness with reasonable accuracy. Instrumentation was developed to continuously measure the pressure within the pumping main, the effluent level within the wet well and the temperature of the effluent. The pressure measurements were used to calculate the static and pumping head for the pipeline, while the change in level within the wet well chamber was used to calculate the inflow rate and pumping main flow rate.

All these parameters were recorded during several pumping cycles at each site. Unfortunately, it was not possible to measure directly external / internal diameters of the pumping mains outside the dry well as they were always below ground and not accessible without excavation even for the application of an ultrasonic thickness gauge. Thus, it was necessary to rely on available records of age and material of pipe together with pipe standards to assess the internal pipe diameter.

Analysis of data for each site was carried out and the hydraulic roughness for each test was calculated using the Colebrook-White equation. The k_s calculated from the field measurments is an overall equivalent roughness value for the pipe as it takes into account the effect of sliming, surface texture and loss of area due to slime thickness. Once the range of k_s values had been determined for each site the data were further analysed to assess the influence of flow velocity, pipe diameter and pipe material on k_s. Sensitivity tests were also performed for a number of sites to assess the likely variation in result that could be caused by errors in measurement of various parameters such as pipe diameter and length. The tests showed that calculation of hydraulic roughness was most sensitive to changes in the pipe diameter.

It was found that the most important parameter affecting the hydraulic roughness in pumping mains is the flow velocity. As the flow velocity increased the hydraulic resistance was found to decrease. From the results a predictive equation was developed which relates the flow velocity to the best fit value of hydraulic roughness. The variability of the results due to the effects of sliming and other uncertainties was considered by identifying upper and lower bounds for the data. The effect of parameters such as pipe material and diameter was also investigated but the results showed they had no clear overall effect on the hydraulic roughness values.

The report contains a table of suggested roughness values for design of pumping stations. Values are provided for different pipe conditions; lower, average and upper, which correspond to the results from the predictive equation. Recommendations for further studies are also made.

Contents

Contents continued

1. Introduction

Pumping systems for conveying sewage and wastewater are a vital component of the infrastructure necessary for the safeguarding of public health, and for any country they represent a significant national asset in terms of equipment and investment. In the UK, the capital value of the pumps and associated pipework systems is conservatively estimated to be of the order of £1.5 billion and the overall running costs, in terms of power consumption, are in the region of £150 million per year. One of the largest sewerage undertakers in the UK, Thames Water Utilities, currently operates about 2500 wastewater pumping mains, with the average length of an individual system being of the order of 1km. Around the world, many major wastewater projects are currently under design or are being built to help improve public health and living conditions in large cities

Wherever the drainage system is located it is likely to include pumping mains for lifting wastewater from low-level areas or for conveying it to sewage works for treatment. In all cases, a key requirement for the effective and economic design of a pumping system is reliable information on the flow resistance of pipes when carrying wastewater. The value of resistance depends mainly on the thickness of the biological slimes and grease that build up on the walls of a pipe over a period of time. The thickness of the slime layer may be determined by factors such as the surface texture of the pipe lining, the size of the pipe, the velocity of the flow and the characteristics of the sewage being pumped through the system.

Surprisingly little information on the in-service flow resistance of pumping mains has previously been collected, and values quoted in standard references (such as the HR Wallingford flow tables) were derived from a very limited amount of data published more than thirty years ago. Since then there have been many developments in pipeline technology, with new materials and types of lining being introduced. Reliable values of resistance are very important because an inaccurate assessment of head losses can lead to pumps being incorrectly sized or to uneconomic pipe sizes being selected. Unsatisfactory performance of pumping systems can lead to an increased frequency of burst pipes and pollution incidents due to surface flooding or the premature operation of combined sewer overflows. Existing recommendations on roughness values quoted in the HR Wallingford flow tables (1) were based on a very limited number of relevant studies carried out prior to 1982.

The aim of this study is to improve knowledge on the flow resistance of wastewater pumping mains and the objectives are summarised as follows:

- To obtain data on the in-service flow resistance of wastewater pumping mains.
- To provide recommended design values of flow resistance for adoption in design manuals, reference documents and computer models of drainage systems.

This report is the final output of a study commissioned by the Department of Trade and Industry (DTI), then the Department of the Environment, Transport and the Regions between 1 October 2001 and 31 December 2003. A Steering Group was formed for the project involving the following partners:

- Black and Veatch
- MWH
- Thames Water Utilities
- United Utilities (formerly North West Water)

Following the introduction in Chapter 1, the existing design recommendations are summarised in Chapter 2. Chapter 3 presents the programme of work and chapters 4 to 8 describe other aspects of the study, namely: criteria for selection of test sites (Chapter 4), identification of test sites (Chapter 5), field measurements (Chapter 6), test methodology (chapter 7), analysis method (chapter 8), analysis of data (chapter 9), design values of flow resistance (Chapter 10). Conclusions and recommendations are given in chapter 11. Acknowledgements and references are provided in Chapters 12 and 13 respectively.

2. Previous design recommendations

Design recommendations for the flow resistance (roughness) of sewer pumping mains are given in the 'Tables for the hydraulic design of pipes, sewers and channels' 7th edition (reference 1, subsequently referred to as 'HR Tables'). The data is somewhat limited and is based on work carried out between 1966 and 1979. Although this covered several different pipe materials including spun concrete, spun iron, asbestos-cement, clay and UPVC, recommended roughness values were based only on the velocity of flow. In these tests, pipe diameters ranged from 100mm to 635mm and pipe lengths from 103m to 4350m. Velocity of flow varied between 0.35 and 2.73 m/s

Generally it was concluded that the roughness value (k_s mm) reduced as the velocity of flow increased and, although the data is somewhat scattered, the following equation was utilised to obtain the recommended values given in Reference 1.

$$k_s = 0.303V^{-1.93} \qquad (1)$$

Classification was also based on the assumed condition of the pipe under consideration, be it good, normal or poor. The following table presents the recommended k_s (mm) values given in Reference 1

Table 1 Previous hydraulic roughness values for sewer pumping mains (1)

Mean velocity m/s	**Hydraulic Roughness, k_s (mm) Condition of pipe**		
	Good	Normal	Poor
1.0	0.15	0.3	0.6
1.5	0.06	0.15	0.30
2.0	0.03	0.06	0.15

Designers have found difficulty in applying the values given in Table 1 to the design of pumping mains as the terms good, normal and poor are ambiguous. They do not in fact refer to the pipe condition in terms of jointing or construction but instead principally relate to the build-up of slime within the pipe and therefore the effect of both slime surface characteristics and area reduction on the roughness values.

3. Programme of work

The study involved several stages:

- Determination of the criteria for the selection of test sites in consultation with project partners.
- Identification of test sites.
- Field measurements.
- Analysis of data.
- Recommendations for values of flow resistance.

At the outset it was envisaged that the above programme of work would enable a representative number of combinations of pipe sizes, materials, age and flow conditions to be investigated and the initial discussions / recommendations of the Steering Group are detailed in the following Chapter. However, it soon became evident for numerous reasons that the "ideal" situation would not be possible and the programme and scope had to be modified throughout the study to obtain a reasonably representative set of data within significant constraints of available sites, site information, measurement techniques, and site conditions. Despite this, it has been possible to provide more information on the roughness characteristics of various types and sizes of sewer pumping mains although, as will be explained, the eventual scope of the project was constrained by what was feasible in difficult circumstances.

The stages of the study are described in detail in the next chapters.

4. Determination of the criteria for the selection of test sites

The criteria for the selection of test sites were considered in detail by the Steering Group and after discussion the key conclusions were as follows:

- Around 25 sites should be identified as indicated in the original scope of the project with more added if possible within the available budget for the project.

- Pipe size should be the most significant factor affecting the choice of pumping mains to be tested. This is because there is a strong correlation between pipe size and other factors such as pipe material, type of joint and lining, and type of flow. As an example, plastic pipes are mainly confined to the smaller diameters and so are mainly used for foul water flows. Similarly, concrete and GRP pipes are normally only used at the top end of the size range where large flows from combined systems (foul and surface water) need to be pumped.

- Thames Water (TW) has records of the diameters of nearly all its pumping mains, and this database was used in the first instance in an attempt to ensure that the distribution of pipe sizes tested was representative of industry usage and data needs.

- It was agreed that the purpose of the project was to investigate the effects of sliming on pipe roughness and not the possible additional effects of pipe corrosion. To take account of pipeline age in relation to the degree of sliming, it was considered that it would be sufficient to use three categories, for example: *new* – 0 to 5 years; *medium* – 5 to 20 years; *old* – more than 20 years. It was also agreed that sliming and tuberculation effects in raw water and water supply mains should remain outside the scope of the study (which is specifically concerned with wastewater systems).

- Air in pumping mains causes problems and can lead to misleading measurements of head loss. For this reason, undulating mains (where air could have accumulated at high points and sediment at low points) should be avoided.

- It was agreed that when selecting sites, preference should be given to those where reliable records are available of pipe size, pipe type, length, and levels at the measuring positions and the point of discharge. Test lengths should have only a limited number of pipe fittings such as bends and valves so that the overall head loss is predominantly due to the frictional resistance of the pipes. The geographical location of the pumping main should not be a very significant factor but if possible consideration should be given to the nature of the catchment (e.g., urban, rural, residential, industrial).

- A wide range of pipe materials should be considered for testing including, ductile iron, plastic (UPVC and polyethylene) and spun concrete, with GRP being a possibility at the top end of the size range. Cast iron and asbestos-cement pipes are not an option for new build schemes so are only of limited interest. In the case of plastic pipes, it was thought possible that polyethylene may be more susceptible to slime growth than UPVC.

- Analysis of the Colebrook-White equation indicates that the estimate of k_S is most sensitive to errors in the measurement of pipe diameter, followed in decreasing order of importance by errors in flow rate, head loss gradient and fluid temperature. Table

2 provides information on the effect of a 1% error in the measurement of the key elements based on a ‘typical’ case where the pipe diameter is 200mm, the flow rate is 500 l/s, and the temperature is 15 degrees.

Table 2 Effect of a 1% error in measurement on the key test elements for a typical pumping main (D = 200mm, Q = 500l/s, T = 15°C)

Measurement quantity		Alternative measurement methods	Effect on k_S value of 1% error in measurement quantity	
			Error = measurement – true value	Change in calculated value of k_S
Pipe diameter	D	a. External diameter & wall thickness b. Internal diameter directly c. From specification, e.g. drawings	Δ D = + 2 mm	+ 25.5 %
Flow rate	Q	d. Pipe flow meter (ultrasonic, em) e. Time of fall in wet well	Δ Q = + 0.5 l/s	– 9.2 %
Plan area of wet well	A_o	a. By measurement b. From construction drawings	$\Delta A_o = + 0.01 A_o$ (neglecting any errors in timing)	– 9.2 %
Head loss gradient	i	a. between two measurement points b. between one measurement point and discharge point	Δ i = + 1 / 7700	+ 4.7 %
Pressure head		a. Pressure transducer b. Manometer c. Diaphragm gauge		
Static head		a. Levelling between measurement / discharge points b. From construction drawings		
Level in wet well		a. Manually-read scale or gauge b. Electrical contact / resistance gauge c. Ultrasonic gauge d. Pressure transducer		
Distance between measurement points		a. Chainage / trig survey b. Electronic ranging c. From construction drawings		
Temperature of fluid	T	a. From temperature in wet well b. From temperature in stand pipe	Δ T = + 1.5° C	+ 0.5 %

5. Identification of test sites

Taking on board the agreed criteria described in the previous chapter an “ideal” list of site characteristics was drawn up and is shown in Table 3. As can be seen, this encompassed pipe sizes in the range 100mm to above 350mm, and materials of iron, polyethylene, concrete, and GRP. This list of requirements of test sites was then matched against the details provided in the Thames Water database which contained some 2529 pumping mains. Table 4 is a copy of the record shown for the shortlist of 26 sites initially chosen. Considerable time and effort was taken visiting the proposed sites to confirm that they would be suitable for tests to be carried out. Unfortunately, for various reasons, not all the proposed sites were acceptable and, based on advice from Thames Water, other sites were substituted. The new sites were visited and their suitability confirmed.

Table 3 Initial Criteria for selecting suitable field-test sites.

Factor	Availability / Range							Comments from SG
Pipe size (mm)	100	150	200	225	300	350	450	Determines many other factors
Pipe material	Ductile iron	Cast iron	Spun concrete	GRP	UPVC	HDPE / MDPE	Steel	
Pipe lining	None Spun concrete Polyethylene Polyurethane	None Spun concrete Polyethylene Polyurethane	None	None	None	None	None Spun concrete Polyethylene Polyurethane	Not likely to be very significant
Flow velocity in pipes	V < 1.0 m/s	1.0 ≤ V < 2.0 m/s	V ≥ 2.0 m/s					Dominant factor according to HR Tables
Age	New	≤ 5 years	5 < years ≤ 10	10 < years ≤ 25	25 < years ≤ 50	> 50 years		Slime growth is likely to occur quickly. Corrosion aspects outside scope.
Flow type	Foul water	Surface water	Combined					Grit from surface water likely to have an effect
Ratio of static/total pumping head	< 25 %	25 % – 75 %	> 75 %					Not considered to be very significant
Pump operation	Continuous	Stop-start (on/off time ?)	Variable speed	1 No duty pump	2 No duty pumps			May be significant
Pipe fittings in test length	Bends	Tees	Gate valves	Air valves	Reflux valves			Relatively few away from pumping stations

Table 4 Initial shortlist of field-test sites

Pipe diameter	Velocity range	Site name	Area	Receiving STW	Pipe material	Pipe length
0.05m	<1m/s	Spooner Close, Headington	Oxford City	Sandford	UPVC	45m
	1-2m/s	Pedley Hill, Studham	South Bedfordshire	Studham	UPVC	445m
	>2m/s	Ashendon Main	Aylesbury	Ashendon	NA	90m
		Bierton Rowshaw Rd	Aylesbury	Aylesbury	NA	475m
0.1m	<1m/s	Stansfields Close	Oxford	Sandford	UPVC	43m
		Isis Close	Aylesbury	Aylesbury	UPVC	NA
		Rectory Close Wendlebury	Cherwell	Bicester	UPVC	975m
		Dorcester Way	Hart	Hartley Whitney	Cast iron	210m
		Brill the firs	Aylesbury	Worminghall	Cast iron	190m
	1-2m/s	Nether Winchendon	Aylesbury	Cuddington	MDPE	904m
		Fraser Gardens Wallingford	South Oxfordshire	Cholsey	Ductile iron	340m
		Reading Road Wallingford	South Oxfordshire	Cholsey	Ductile iron	300m
		Hithercroft	South Oxfordshire	Cholsey	UPVC	350m
	>2m/s	Middle Green	South Buckingham -shire	Slough	Cast iron	570m
		Osney Mead	Oxford	Sandford	Cast iron	284m
		Blackhall Charlbury	Oxford	Sandford	UPVC	114m
		Larkfields Rd	Oxford	Oxford	Spun iron	31m
0.15m	<1m/s	Thyme Close Swindon	Swindon	Swindon	Cast iron	180m
	1-2m/s	Rippington Drive	Oxford	Sandford	UPVC	100m
		St Johns New	South Oxfordshire	Cholsey	Ductile iron	520m
		Cheddington South End	Aylesbury	Aylesbury	Cast iron	1700m
0.2 to 0.3m	unknown	Swindon Honda	Swindon	Swindon	GRP	530m
	unknown	Croft Villas	South Oxfordshire	Cholsey	Ductile iron	310m
	unknown	St Johns Main	South Oxfordshire	Cholsey	Ductile iron	Unknown
>0.35m	unknown	County Oak Crawley	Crawley	Crawley	Ductile iron	400m
	unknown	Gallions	Newham	Beckton	Concrete	700m

Later in the project an agreement was also reached with United Utilities to incorporate two of their sites in the north west of England, which enabled data to be obtained for larger pipe diameters (>350mm) than originally proposed.

A full list of sites at which tests were carried out is given in Table 5. Six additional sites are also included. Previously collated test data from these six sites were provided by United Utilities. Further details of each site are contained in Appendix A.

Table 5 List of sites where field tests were carried out

RECEIVING STW (Pumping main)	Material	Diameter (mm)	Length (m)	Static Head (m)	Total Operational Head (m)	Maximum Operational flow (l/s)	Maximum Operational velocity (m/s)
CHOLSEY (Hithercroft)	UPVC	100	NA	NA	12.6	14.3	1.70
CHOLSEY (St John's New)	Ductile iron	150	520	NA	16.1	19.8	1.23
CHOLSEY (Fairmile)	Steel	150	788	12.5	27.3	22.0	1.21
HARWELL (Dene Hollow)	Asbestos cement	125	2880	12.5	22.0	7.3	0.54
WHITCHURCH (Whitchurch Hill)	Steel	100	1440	12.4	24.0	6.2	0.69
READING (Bradfield Farm)	Ductile iron	150	980	49.5	59.5	22.4	1.36
BOURTON-ON-THE-WATER (Rissington)	Ductile iron	250	570	7.14	13.3	51.0	1.07
OXFORD (Garsington)	UPVC	100	950	24.2	30.7	6.8	0.82
BIBURY (Bibury)	UPVC	125	1100	34.9	42.8	12.1	0.95
GREAT COXWELL (Great Coxwell)	UPVC	125	1445	19.3	48.5	15.6	1.23
STADHAMPTON (Stadhampton)	Cast iron	100	780	3.4	13.8	6.1	0.75
AYLESBURY (Nether Winchendon)	MDPE	100	904	4.5	22.5	8.9	1.12
SWINDON (Bishopstone)	Cast iron	100	1286	1.9	11.8	11.7	0.86

Table 5 List of sites where field tests were carried out (continued)

RECEIVING STW (Pumping main)	Material	Diameter (mm)	Length (m)	Static Head (m)	Total Operational Head (m)	Maximum Operational flow (l/s)	Maximum Operational velocity (m/s)
AYLESBURY (Cheddington South End)	Ductile iron	150	1700	1.2	40.0	33.7	2.05
CLIFTON MARSH (Freckleton)	HDPE	600	2450	11.3	16.0	320	0.99
CLIFTON MARSH (Lea Gate)	Ductile iron	1000	3600	6.2	10.0	738	0.92
Additional United Utility Sites							
CLIFTON MARSH (Lea Gate)	Ductile iron	1000	3600	NA	10.7	NA	NA
UNKNOWN (Alum Bridge)	Cast iron	175	500	5.8	13.0	37	1.85
UNKNOWN (Highway Lane)	Cast iron	125	620	14.7	24.8	15.2	1.54
UNKNOWN (Church St)	Ductile iron	250	620	15.4	21.0	42.9	1.30
UNKNOWN (Hedben Green)	Cast iron	150	382	1.2	9.0	24.9	1.23
UNKNOWN (The Dell)	Cast iron	75	233	17.2	23.6	8.3	1.67
UNKNOWN (Heskin Lane)	Cast iron	150	215	6.4	16.8	47.4	2.35

6. Field measurements

The field data needed to be collected at each site to determine, with accuracy, the value of pipe roughness was agreed at the start of the project. For each site, suitable measurements were required to obtain the following data: pipe diameter, flow rate, head loss gradient, and temperature. It was originally envisaged that all these data would be obtained by direct measurement using specialist instrumentation. Unfortunately, this was not possible in all cases and some compromise had to be made.

A detailed description of the instrumentation and measurements made in each case follows:

- Pipe diameter
  It was not possible to measure directly the pipe diameter. This would have necessitated in each case either exposing a length of pipe (outside the wet well) and removing it or using some form of ultrasonic thickness gauge on the exposed pipe. Instead, an alternative method had to be used. From available records of the pipe material and age and using pipe standards and catalogues a best estimate of internal diameter was obtained in each case.

- Flow rate
  Two methods of measuring flow rate were originally considered: either direct measurement using a strap on ultrasonic pipe flow meter; or, if available, an in–line electromagnetic meter; or by the pumping well method. The pumping well method involves measuring the changing liquid levels in the wet well and based on the dimensions of the wet well, the flow rate can be calculated. From an inspection of the various sites it was evident that in almost all cases there was not enough exposed pipe within the dry well to utilise the direct method. This resulted in all flow measurement (apart from sites having suitable in-line instrumentation already installed) being obtained from the pumping well method. In each case ultrasonic level recorders were mounted in the wet well to continuously monitor the liquid surface level. Care had to be taken in the siting of these transducers to ensure satisfactory operation. In some cases this was not possible due to the fouled condition of the wet well and alternative instrumentation (of a similar type) installed by Thames Water had to be used.

  For each test pumping the elapsed time for the liquid level in the well to reduce a known distance was recorded and with the pump switched off the time to recover to the original level was noted. With these measurements and the plan area of the wet well, the inflow (pump at rest) and outflow could be calculated. Care was taken to ensure that the range of depth measurement within the wet well during individual tests did not result in backing up of the incoming sewer and resultant error in discharge calculation.

- Head loss gradient
  In order to obtain a measurement of the head loss gradient it was necessary to obtain data on the pressure head, static head and pipe length. To do this an arrangement of Druck PMP 1400 pressure transducers was mounted on a short length of pipe attached to a male Bauer pipe connector. The pressure range of the three transducers used at each site was chosen with reference to the expected head from available records. Thus, continuous records of pressure within the pipe under test were recorded (both under pumping and static conditions). The vertical distance between the pressure sensors and the elevation of the pipe at the pressure sensing position

was recorded. The length of pipe under test was obtained from pipe layout drawings of individual sites or measured on site where possible.

An example of the Bauer connector and connected pressure sensors is shown in Plate 1.

- Temperature
  The temperature of the liquid in the wet well was obtained using a Comark electronic thermometer attached to a thermocouple.

- Data Recording
  The readings from the pressure transducers and ultrasonic level recorders were collected during each test by a type DT50 “Datataker” connected to a laptop computer. The associated software incorporated a time base and allowed interrogation during testing to ensure correct operation of instruments. All other measurements (temperature, dimensions of well etc) were recorded by hand.

7. Test methodology

The methodology of testing was to an extent site dependent. Tests carried out in the Thames Water area were generally on smaller pipes < 200mm diameter whilst those that were situated in the United Utilities area were 600mm and 1.0m diameter pipes. In the case of the Thames Water sites the method of flow measurement was the pumping well method. At one of the United Utilities sites there was an electromagnetic flow meter within the pumping main and the flow measurements were continuously recorded and displayed on screen at the station. For the second site there was an electromagnetic flow meter within the pumping main; this was monitored at the receiving sewage treatment works (STW) and flow information during the test was obtained via phone from the receiving STW.

7.1 THAMES WATER SITES

At each of the Thames Water (TW) sites the test procedure was as follows:

- The Bauer connector containing the pressure transducers was fixed to the over pumping tee within the dry well of the pumping station. The dry well was generally located beside the wet well. With the over pumping connector valve shut the inlet / fill valve at the top of the pressure transducer manifold was opened and it was filled with clean water. The valve was then closed. This procedure helped to prevent raw sewage from coming into direct contact with the pressure sensors. It also served to prevent an “air cushion” forming between the sewage/water and the diaphragm of the pressure transducer. The cables from the pressure transducers were then coupled, via the datataker, to the computer. At this point the valve on the over pumping tee was slowly opened to allow the pressure in the pumping main to be monitored/recorded.
- Two ultrasonic level sensors were mounted above the surface of the liquid in the wet well to provide a simultaneous record of level during the pumping test. The output from these level recorders was also logged on the computer.
- A temperature sensor was used within the wet well to periodically record the temperature of the liquid during the testing. This data was manually recorded.
- From an inspection of the wet well an assessment was then made of the available draw down that could be utilised for each pumping test. This depended on the shape of the well (consistent cross section through the depth required) and to some extent the likely time to recover to the start level after a pumping test. Too great a draw down depth and slow filling resulted in a significant delay between test cycles. On average a drawdown of between 0.5m and 1.0m was used in most cases. The switch-on and switch-off levels for the pump under test was pre-programmed by TW personnel into the pump control panel prior to the commencement of testing.
- At sites where reflux (non-return) valves were incorporated in the pumping lines upstream of the pressure transducer connector, the valves were opened manually to allow the measurement of static head to be recorded when the pumps were not operational.
- A stopwatch was used to manually record times for drawdown and fill for each pump test; these measurements complemented the computer record.
- A number of tests were then carried out utilising each pump in turn (if more than one was operational.) In each case the duty pump was automatically operated between the upper and lower levels that had been pre-set in the pump control panel. Usually around 6 tests were carried out but this depended to some extent on the fill rate of the wet well as described above. If it was possible to override the operating system a final test was carried out with both pumps operating.

- Photographs of the site were taken during each test and any relevant records of pipe runs and configuration noted. This latter information was often contained in a file within the equipment cabinet on site.
- Sufficient dimensions of the wet well were recorded such that the volume utilised for each test could be calculated.
- On completion of the required number of test cycles all equipment was removed and cleaned prior to leaving the site.

7.2 UNITED UTILITIES SITES

- At the two United Utilities (UU) sites the test methodology was slightly different. The pipelines at both sites were significantly larger than those used in the Thames Region (the main reason for using them) and the sites were generally more automated. However, whilst there was access to the dry wells and in one case the incoming flow chamber, there was no access to the wet wells. In both cases, therefore, reliance for flow measurement was on UU instrumentation/data. In one case this consisted of an inline electro–magnetic flow meter with readout at the pumping station. In the second case flows were obtained from the readout at the STW as the tests proceeded.
- Both these sites had existing pressure tapings in the pipes connected to gauges. During the period of testing these gauges were replaced with HR Wallingford (HRW) pressure transducers coupled via the datataker to the computer. This enabled a continuous record of pressure to be made during each test cycle as with the TW sites.
- Using the automated level sensing instrumentation, suitable cut-in and cut-out levels within the wet wells were programmed into the system
- Each of the UU sites had four dry weather flow pumps and one or two stormwater pumps; each one was operated in turn and both the static and dynamic pressures were recorded.
- Photographs of the site were taken during testing and relevant data on pipe size, length and material obtained. An inspection was also made of the discharge points at the STW, for example see Plate 2.

Plate 1 Example of the Bauer connector and pressure sensors used for the field tests.

Plate 2 View of the pumping main bellmouth discharge points at the Clifton Marsh wastewater treatment plant.

8. Analysis method

8.1 PUMP RATES

The test procedure used to measure the inflow and outflow rates is called a ‘pump down test’. As described in section 7.1, the level in the wet well was continuously recorded during the test, both before and after the pump was operated.

The data recorded was plotted as the level in the wet well versus time. From the slope of the graphs it was possible to calculate the inflow or outflow rate in m/s for each test. The inflow rate while a pump was operating was assumed to be the average of the inflow rates before and after the test. These results were then combined with the measured wet well areas to give inflow rates to the wet well and flow rates in the pumping main (in m^3/s) for each test.

It was found that in the majority of tests the inflow and outflow rates did not vary during a test. If there was found to be some variation in inflow or outflow rate then the average value over the test was used to calculate the hydraulic roughness. Instantaneous flow rates were used in the sensitivity analysis to assess the affect of pumping head changes on hydraulic roughness values.

For five tests it was not possible to continuously monitor the level of the wet well. This was due to difficulties in obtaining a return signal from the level sensor in the well. The presence of grease or other materials on the surface of the liquid in the wet well prevented the signal from the sensor from being correctly reflected back to the sensor. In these instances, the time required to fill and empty the wet well over the pre-set distance was recorded. The change in level over time for a test was then combined with the area of the wet well to provide a value for the average inflow or outflow rate during the test.

The method of timing the change in level in the wet well was used at all the UU sites. Continuous measurements of the level in the wet well were not made.

8.2 PRESSURE HEAD MEASUREMENTS

The pressure head on the pumping main was monitored continuously throughout the tests. This allowed the determination of both the static head on the pumping main and the pumping head used.

The static head was recorded when the pumps were not operating. At some sites it was necessary to hold open the non-return valve on the pumping main to enable this measurement to be recorded. If the static head could not be recorded it was estimated from the levels of the start and end points of the pumping main. In both cases, where the pumping main discharged to a manhole rather than to another pumping station or treatment works, an additional allowance of one pipe diameter was added to the static head level to account for changes in liquid level at the discharge point.

The pumping head for the pipe was recorded while the pump(s) was operating. It was found that there was often a decrease in pressure head during the course of a test as the level in wet well reduced.

For the calculation of hydraulic roughness, the average pressure head during a test was used as the pumping head value. Sensitivity tests were carried out using the maximum and minimum head during a test and the corresponding outflow rate to determine what effect this has on the calculated hydraulic roughness.

For the test information provided from UU and TW the static head was estimated from the levels of the start and end of the pumping main. The pumping head given in the results was either the average pumping head recorded during a test or the average value for all the tests at a particular site.

8.3 MINOR LOSSES

Minor losses along the pumping main, due to bends and valves, were estimated from the available information on the pumping main for each site. For many of the Thames Water sites a plan of the pumping main was obtained from their GIS system. For the UU sites detailed plans of each pumping main were supplied. Standard loss coefficients for different types of bends and valves were used. Details of the minor losses are given, along with the test results, in Appendix B.

8.4 CALCULATION OF HYDRAULIC ROUGHNESS

For each test the hydraulic roughness k_s was calculated using the Colebrook-White equation, which for pipe-full conditions has this form:

$$\frac{1}{\sqrt{\lambda}} = -2\log\left\{\frac{k_s}{3.71D} + \frac{2.51}{\mathrm{Re}\sqrt{\lambda}}\right\} \tag{2}$$

where λ = friction factor, Re = Reynolds number (=VD/ν), V = flow velocity (m/s), D = pipe diameter (m), ν = kinematic viscosity (m^2/s), and k_s = hydraulic roughness (m).

The hydraulic roughness k_s was calculated based on the average pumping head for each test. The results for each site are given in Appendix B. At each site a minimum of four tests was performed and k_s was calculated for each test. A range of k_s values was therefore obtained for each site. Once the k_s value had been calculated the data was analysed to assess the influence of flow velocity, pipe diameter and pipe material on k_s values. This is described in Section 9.

Sensitivity tests were also performed for a number of sites using the maximum and minimum pumping head measurements.

For the six additional sites provided by UU, the test results were reanalysed using the method above if all the required test information was available. Measurements of hydraulic roughness in pumping mains were also found in the literature (references 2, 3, 4, 5, 6). These results have also been included in the present analysis.

9. Analysis of data

9.1 RESULTS OF FIELD TESTS

The test results for all the field tests were analysed to determine the hydraulic roughness of each test. Table 6 gives details of the results of all the field tests along with data from other studies that has been incorporated in the analysis. For each site information on the test methodology has been included. The velocity and roughness values have been rounded to two decimal places (or two significant figures), however the full values were use in the analysis.

Table 6 List of hydraulic roughness results used in the present analysis

Test site name or data source	Pipe material	Pipe internal diameter (m)	Test methodology	Average velocity during the test (m/s)	Hydraulic roughness k_s (mm)
			Present study		
Fairmile	Steel	0.1518	M	1.10	2.15
			M	1.24	1.04
			M	1.25	1.00
			M	1.21	1.25
			M	1.25	1.80
Dene Hollow	Asbestos cement	0.1319	MT	0.49	1.00
			MT	0.49	1.00
			MT	0.42	1.42
			MT	0.48	1.08
			MT	0.44	1.09
			MT	0.54	0.47
			MT	0.48	0.52
Whitchurch Hill	Steel	0.1071	M	0.68	0.77
			M	0.60	1.54
			M	0.63	0.83
			M	0.68	0.51
			M	0.61	0.99
			M	0.64	0.81
			M	0.64	0.93
Bradfield farm	Ductile iron	0.1574	M	0.92	0.30
			MT	0.91	0.22
			MT	1.23	0.02
			MT	0.65	6.21
Bourton-on-the-Water	Ductile iron	0.2472	TW	1.07	3.26
			TW	0.93	3.91
South end Garsington	UPVC	0.1032	M	0.74	0.26
			M	0.80	0.055
			M	0.80	0.047
			M	0.82	0.057
Bibury	UPVC	0.1276	MT	0.88	0.092
			MT	0.92	0.013
			MT	0.90	0.053
			MT	0.95	0.010
			MT	0.88	0.081
Great Coxwell	UPVC	0.1276	MT	1.05	2.10
			MT	1.17	0.98
			MT	1.22	0.83
			MT	1.17	1.00
			MT	1.23	0.76
			MT	1.18	0.99

Table 6 List of hydraulic roughness results used in the present analysis (continued)

Test site name or data source	Pipe material	Pipe internal diameter (m)	Test methodology	Average velocity during the test (m/s)	Hydraulic roughness k_s (mm)
Stadhampton	Cast iron	0.102	M	0.67	2.11*
			M	0.75	1.61*
			M	0.75	1.92*
			M	0.73	2.55*
			M	0.73	2.92*
			M	0.72	3.62*
			M	0.74	2.55*
Nether Winchendon	Polyethylene (MDPE)	0.101	M	1.08	0.70
			M	1.11	0.57
			M	1.11	0.54
			M	1.11	0.51
			M	1.14	0.41
Bishopstone	Cast iron	0.1312	M	0.79	0.27
			M	0.63	1.79
			M	0.72	0.62
			M	0.82	0.24
			M	0.86	0.31
Cheddington	Ductile iron	0.1448	MT	1.90	0.076
			MT	1.95	0.053
			MT	2.03	0.020
			MT	2.05	0.015
			MT	1.60	0.358
			MT	2.02	0.001
			MT	1.96	0.021
			MT	1.67	0.22
Freckleton	Polyethylene (HDPE)	0.5818	MR	0.91	0.26
			MR	0.84	0.29
			MR	0.83	0.33
			MR	0.99	0.17
Lea Gate	Cement mortar lined ductile iron	1.0106	MR	0.88	1.88
			MR	0.89	1.58
			MR	0.91	1.34
			MR	0.91	1.31
			MR	0.92	1.28
			MR	0.92	1.15
			MR	0.85	2.50
			MR	0.89	1.59
			Test data provided by UU		
Heskin Lane	Cast iron	0.1602	UM	2.23	0.40
			UM	2.35	0.34
The Dell	Cast iron	0.0808	UM	0.91	1.74
			UM	0.90	1.82
			UM	0.90	1.76
			UM	0.86	2.07
			UM	0.89	1.91
			UM	0.90	1.82
			UM	1.67	0.24
			UM	1.62	0.31
			UM	1.58	0.38
Hebden Green	Cast iron	0.1605	UM	1.23	1.74
			UM	1.19	2.18
			UM	1.23	1.74
			UM	0.44	25.63**
			UM	0.47	21.38**
			UM	0.45	24.54**

Table 6 List of hydraulic roughness results used in the present analysis (continued)

Test site name or data source	Pipe material	Pipe internal diameter (m)	Test methodology	Average velocity during the test (m/s)	Hydraulic roughness k_s (mm)
Church St	Ductile iron	0.2054	UM	1.15	0.037
			UM	1.30	0.030
			UM	1.24	0.16
Highway Lane	Cast iron	0.1124	UM	1.05	0.33
			UM	1.08	0.25
			UM	1.06	0.28
			UM	1.25	0.012
Lea Gate	Cement mortar lined ductile iron	0.9626	UU	-	0.57
Previous test results					
Bland, Bayley & Thomas (1983)	Unglazed clay	0.100	NA	0.76	3.52
			NA	1.1	0.98
			NA	1.15	0.16
			NA	2.1	0.11
	UPVC	0.100	NA	0.76	3.97
			NA	1.1	1.07
			NA	1.5	0.22
			NA	2.1	0.06
Clay (1966)	Spun concrete	0.635	NA	1.45	0.088
			NA	1.60	0.043
		0.470	NA	0.78	0.195
			NA	1.69	0.36
		0.279	NA	1.49	0.073
			NA	1.53	0.076
			NA	2.66	0.085
			NA	2.69	0.076
			NA	2.73	0.067
Flaxman (1966)	Asbestos cement	0.229	NA	0.82	0.61
			NA	0.82	0.91
	Spun iron	0.127	NA	1.03	0.91
			NA	1.03	0.91
HRS (1979)	UPVC	0.385	M	1.38	0.060
			M	1.38	0.20
Green pers. comm.	UPVC	0.250	NA	0.74	0.70
			NA	2.00	0.020

M – the pressure head and the inflow and outflow rates were measured continuously during the test.
MT – the pressure head was measured continuously. The inflow and outflow rates were calculated from timing the rate of rise and fall of the wet well for the test.
MR – the pressure head was measured continuously. The flowrate in the pumping main was monitored at the treatment works or pumping station and an average flow rate for the test was estimated.
TW – test data from a pump down test was provided by Thames Water. Inflow and outflow rates were calculated from timing the rate of rise and fall of the wet well for the test. Static head levels were estimated from the levels of the pumping station and the outflow location. The average pumping head measured on site was used.
UM – test data from a pump down test was provided by United Utilities. Inflow and outflow rates were calculated from timing the rate of rise and fall of the wet well for the test. Static head levels were calculated from the levels of the pumping station and the outflow location although there is some uncertainty as to the correct values. The average pumping head measured on site was used.
UU – hydraulic roughness data was provided by United Utilities. Not enough information was provided to enable recalculation of the hydraulic roughness value. The data was not included in the analysis.
NA – the actual test data was unavailable. The values given in the table are the test results as given in the reference.

* There is uncertainty in the static head measurements obtained for these tests.

**There is some uncertainty in the measurements obtained for these tests and the results have not been included in the present analysis.

In the present analysis the results for the sites of Hithercroft and St Johns Main were not included due to uncertainty over the static head measurements and the discharge locations. The static head could not be measured on site and actual discharge location of each pipe could not be confirmed. For these reasons they have not been included in the data table.

Also, previously measured hydraulic roughness data was provided by UU for the Lea Gate site and Alum Bridge site. This was not included in the analysis as insufficient information was provided to enable the hydraulic roughness value to be checked.

9.2 FLOW VELOCITY EFFECTS

Data from previous studies indicates that the velocity in the pipe is the dominant factor affecting the hydraulic roughness produced by sliming in wastewater pumping mains. This was also found for the present study results. Figure 1 plots the flow velocity versus hydraulic roughness for all the field tests in the present study along with the additional UU test results and data from the available literature.

Clearly, as the flow velocity increases the hydraulic roughness of the pumping main decreases. Around half of the HRW field tests were performed with flow velocities around 1m/s or less because these were the normal operating velocities for the sites. In the HR Tables (1) the recommended k_s values for pumping mains are given for flow velocities of 1m/s or greater. There is therefore an assumption that pumping mains are operated at velocities of 1m/s or greater which is not supported by the results of the present study.

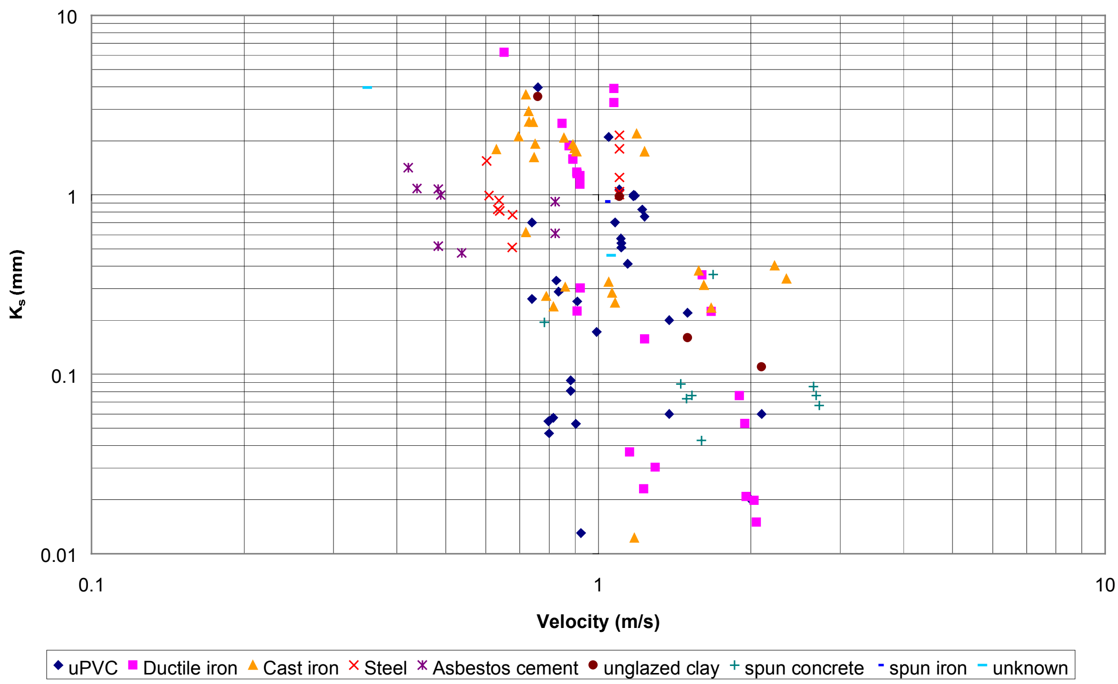

Figure 1 Hydraulic roughness versus velocity for all available data

9.3 THE EFFECT OF PIPE MATERIAL AND DIAMETER

9.3.1 Pipe diameter

An attempt was made to quantify the effect of pipe material and pipe diameter on the hydraulic roughness. Figures 2 to 5 show the hydraulic roughness versus velocity for different pipe sizes and materials. Only those pipe diameters are shown where results for more than one type of pipe material were available. The results show that there does appear to be a difference in k_s for the different pipe diameters although there is no clear overall trend visible in the data. For example, the results for cast iron pipe of different diameters are given in Figure 6. Due to the variability of the data it was decided not to differentiate between the different pipe diameters.

9.3.2 Pipe material

Figure 1 shows all of the test results identified according to pipe material. The results of an analysis of pipe material effects on k_s values are given in Table 7. The predicted k_s value is that given by the prediction equation in Section 9.6.

Table 7 Result of analysis of pipe material influence on roughness values

Material	Number of pipelines tested	Average $\left(\frac{\text{measured } k_s}{\text{predicted } k_s}\right)$	Standard deviation ratio
Steel	2	1.54	2.95
Asbestos-cement	2	0.44	1.75
Ductile/Spun iron	5	0.59	5.56
Cement mortar lining in DI	1	2.65	1.21
Cast iron	6	2.09	3.14
UPVC	6	0.49	5.96
Polyethylene	2	0.88	1.97
Spun concrete	1	0.77	2.51
All data	26	1.00	4.10

There is a general pattern in the results which shows that the pipe materials which for clean water applications have been shown to have lower k_s values also follow this trend in these wastewater flow applications, however the differences are less clear than in the clean water case. The actual variation between the materials is small when compared to the standard deviation of the data. For instance, for many of the pipe materials commonly used in wastewater applications the measured k_s value is within 25% of the predicted value.

Therefore this variability of data supports the decision not to differentiate between pipe materials in the recommended values discussed in Section 9.6.

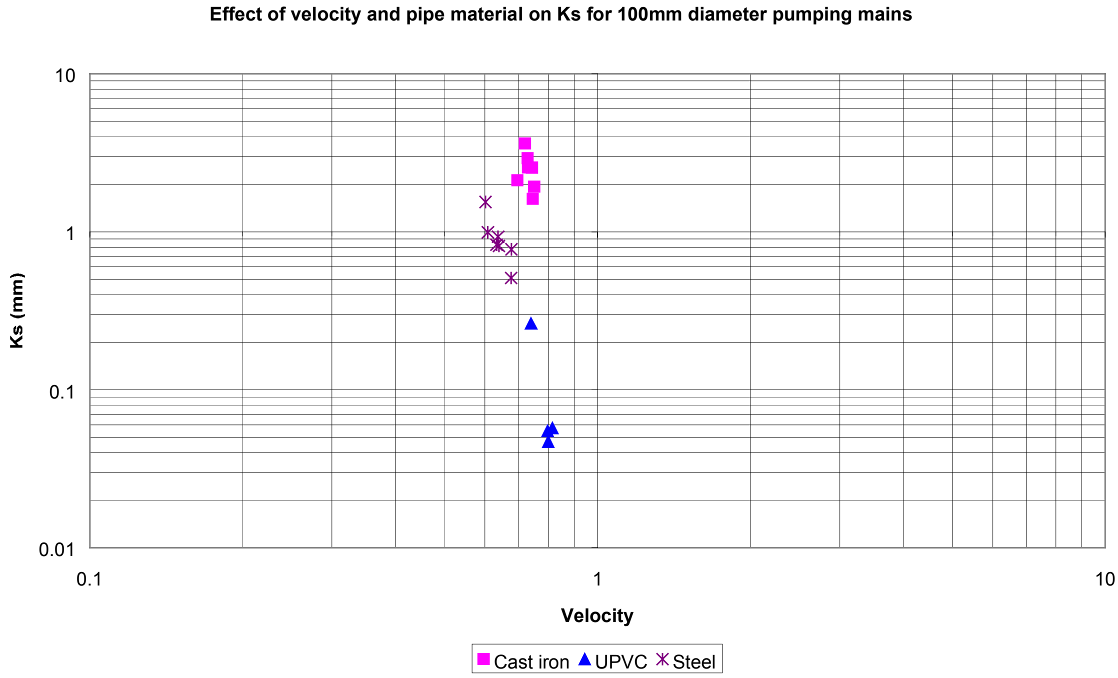

Figure 2 Hydraulic roughness versus velocity for 100mm diameter pipes

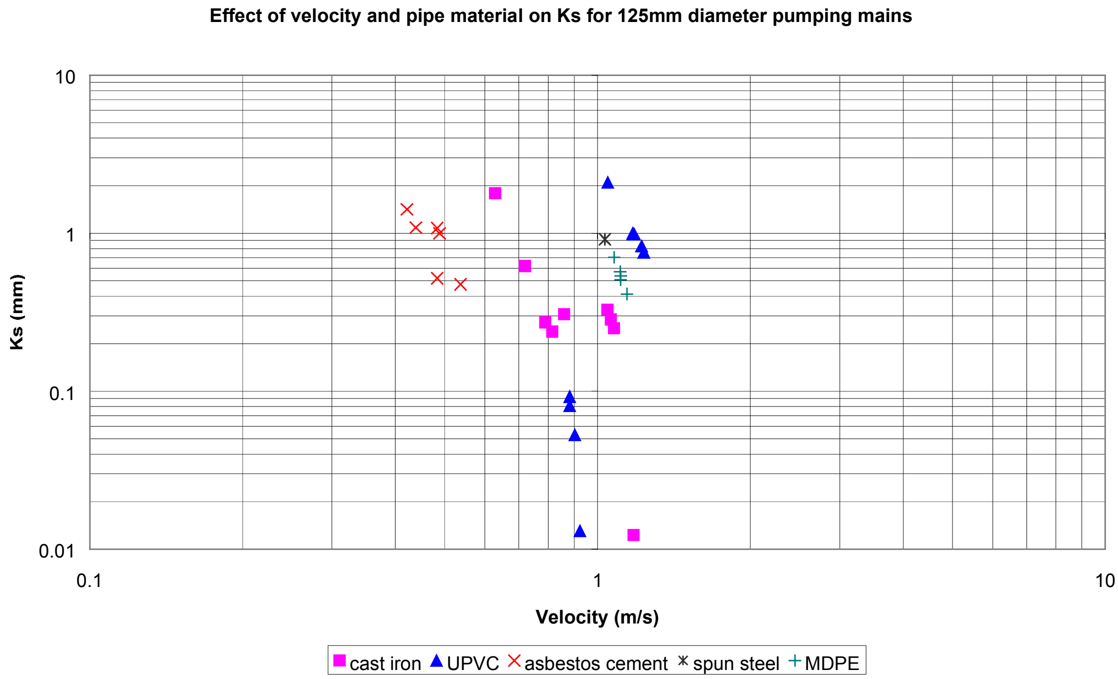

Figure 3 Hydraulic roughness versus velocity for 125mm diameter pipes

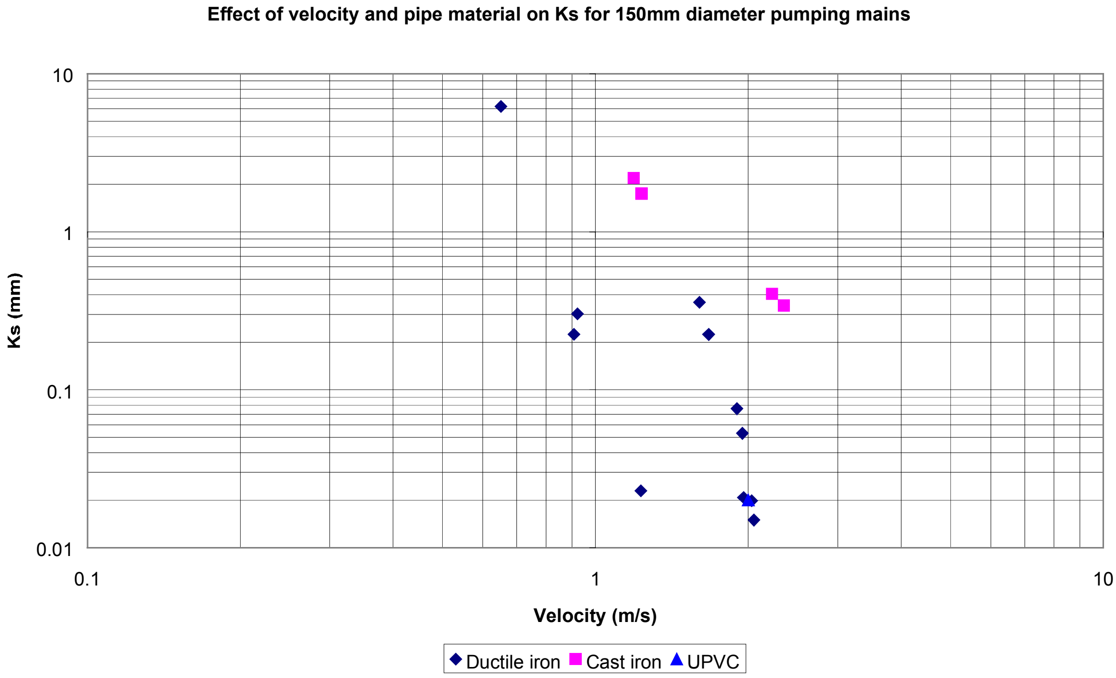

Figure 4 Hydraulic roughness versus velocity for 150mm diameter pipes

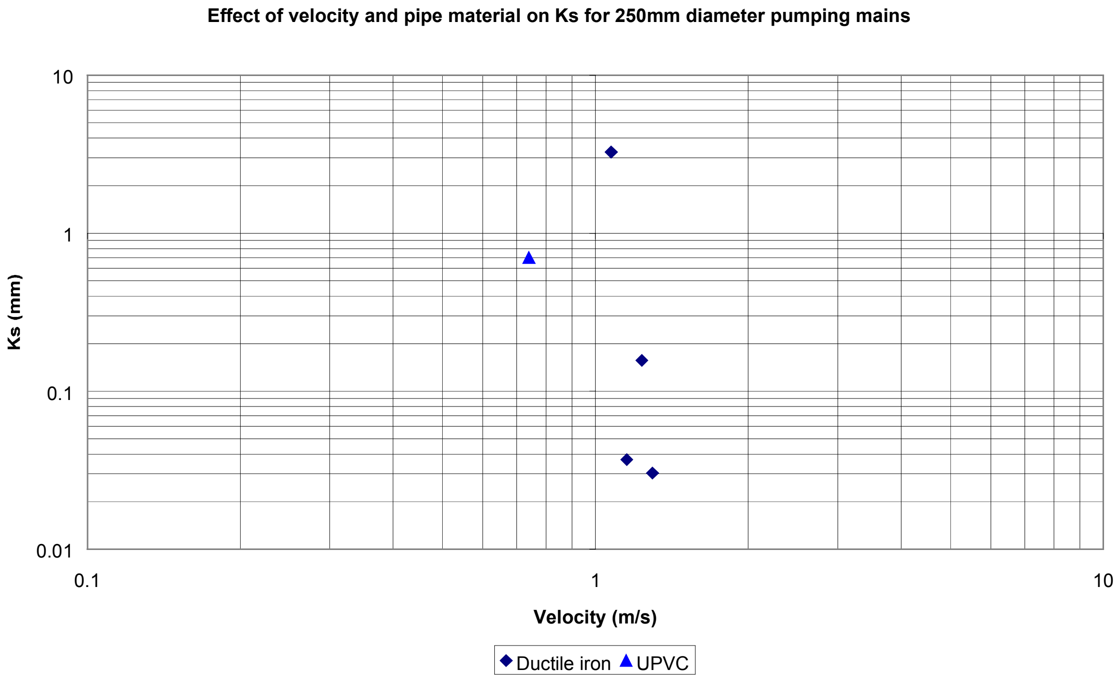

Figure 5 Hydraulic roughness versus velocity for 250mm diameter pipes

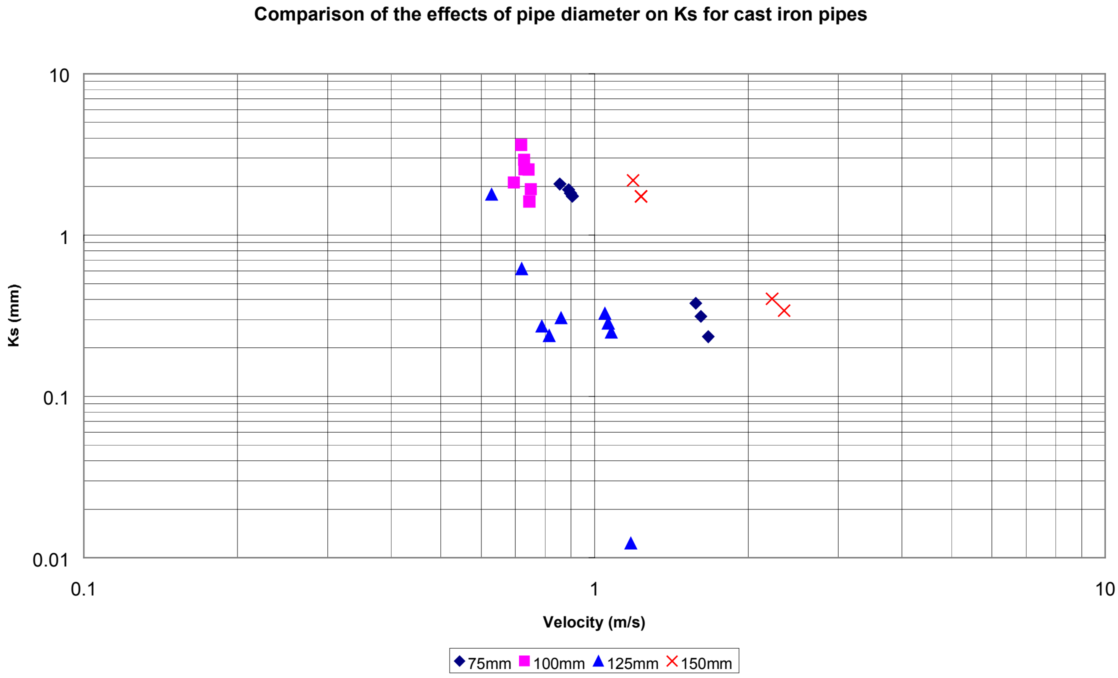

Figure 6 Hydraulic roughness versus velocity for cast iron pipes of different diameters

9.4 EFFECTS OF PIPE SLIMING

The test results have clearly shown a relationship between hydraulic roughness and the flow velocity. However, for the same velocity quite a range of roughness values has been measured. Part of this apparent scatter in the results can possibly be attributed to the effects of pipe sliming.

Previous studies, described in Bland et al (1975) and Perkins and Gardiner (1985), have investigated the growth of slime in sewer pipes and the effect these growths have on hydraulic roughness.

Bland et al (1975) found that the growth of slime under pressurised flow was independent of the pipe material but was dependent on the flow velocity. At low velocities (0.76m/s) the slime appeared to grow for a period of 15-40 days and then was carried off the internal surfaces. This resulted in a cyclic increase and decrease in hydraulic roughness.

Parkins and Gardiner (1985) describe tests on gravity sewer pipes. They found that the slime built up very quickly on the pipes but once the initial sliming has taken place then there was no further evidence of subsequent continuous increase. This indicated that there is a continuous process of sliming growth and removal occurring. Contrary to Bland et al they also found that pipe material did have an affect on roughness values.

Clearly, there is a relationship between the growth and decay of slime in sewers and the hydraulic roughness of the pipes. It is also likely that the slime layer characteristics will vary along the length of the pipe. Some of the factors that may affect the development and growth of slime layers in sewer pipes include:

- The antecedent rainfall conditions
- Seasonal variations in temperature and rainfall
- Presence of sediment
- Type of liquid – foul sewers, storm sewers or combined sewers
- Use of dosing chemicals for odour control

Unfortunately, in the present study it was not possible to assess the slimed condition of the pipes tested. However, the results from some of the field test sites give an indication that the slime may have a dynamic behaviour that is related to the flow conditions in the pipe.

An example is shown in Figure 7, where the field test results for the Bishopstone pumping main are plotted. The tests are labelled test 1 to test 5, which represent the order in which the tests were performed. Clearly, there is a relationship between the flow velocity and the hydraulic roughness value.

It was postulated when the tests were being designed that the hydraulic roughness of the pumping main might vary during a series of tests due to the slime being sloughed off the sides of the pipe by the flows. However, the results in Figure 7 show that the hydraulic roughness varied with flow velocity independently of when the test was performed. For instance, test 2 had a flow velocity of 0.63m/s and a calculated k_s of 1.87 mm whereas test 1 had a flow velocity of 0.79m/s and a calculated k_s of 0.36mm. The slime may therefore be responding dynamically to the change in flow velocity.

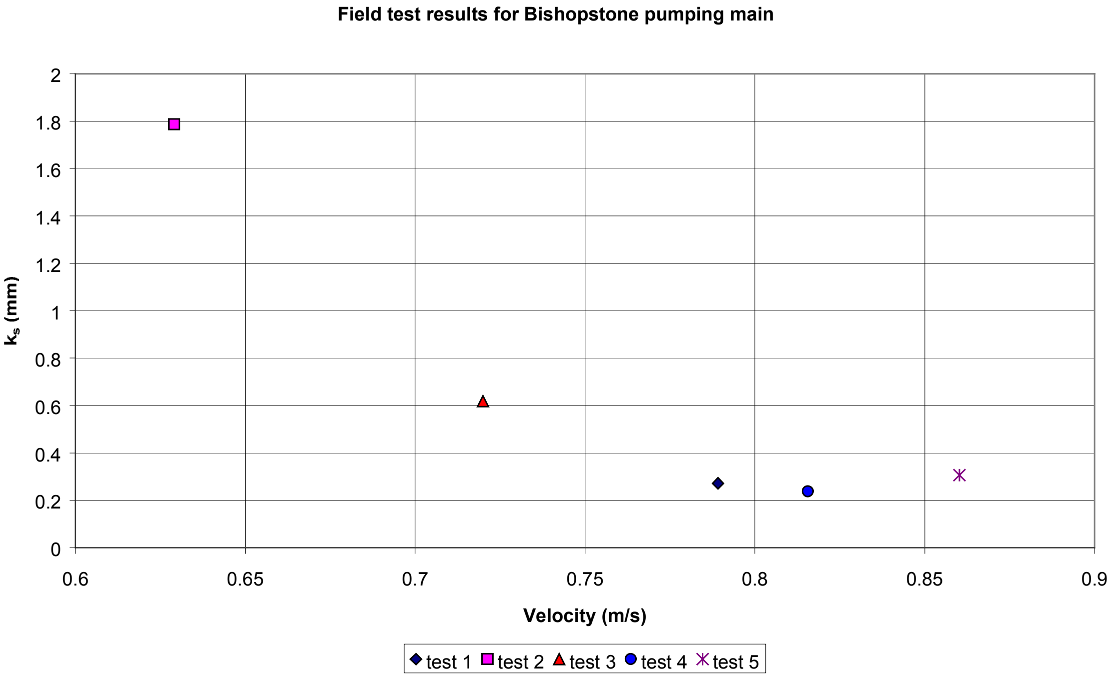

Figure 7 Field test results for the Bishopstone pumping main

Further work on assessing the slime growth in pumping mains, in particular the relationship between slime thickness and growth to the above-mentioned factors, is needed to improve the understanding of sliming affects on hydraulic roughness.

However, by providing upper and lower bands on the design curves for hydraulic roughness (as described in the following section) it is thought that allowance is being made for the affect of sliming on pumping mains.

9.5 EFFECT OF SHEAR STRESS ON ROUGHNESS

An analysis was performed to relate the shear stress and the hydraulic roughness of the pipe. It was expected that there would be a relationship between the parameters whereby the higher the shear stress the smaller would be the hydraulic roughness. This would therefore provide a possible way of predicting the thickness of the slime layer.

Figure 8 shows the results of the analysis. The shear stress is defined as:

$$\tau_o = \rho g R i \qquad (3)$$

where R is the hydraulic radius and i is the hydraulic gradient of the pipe.

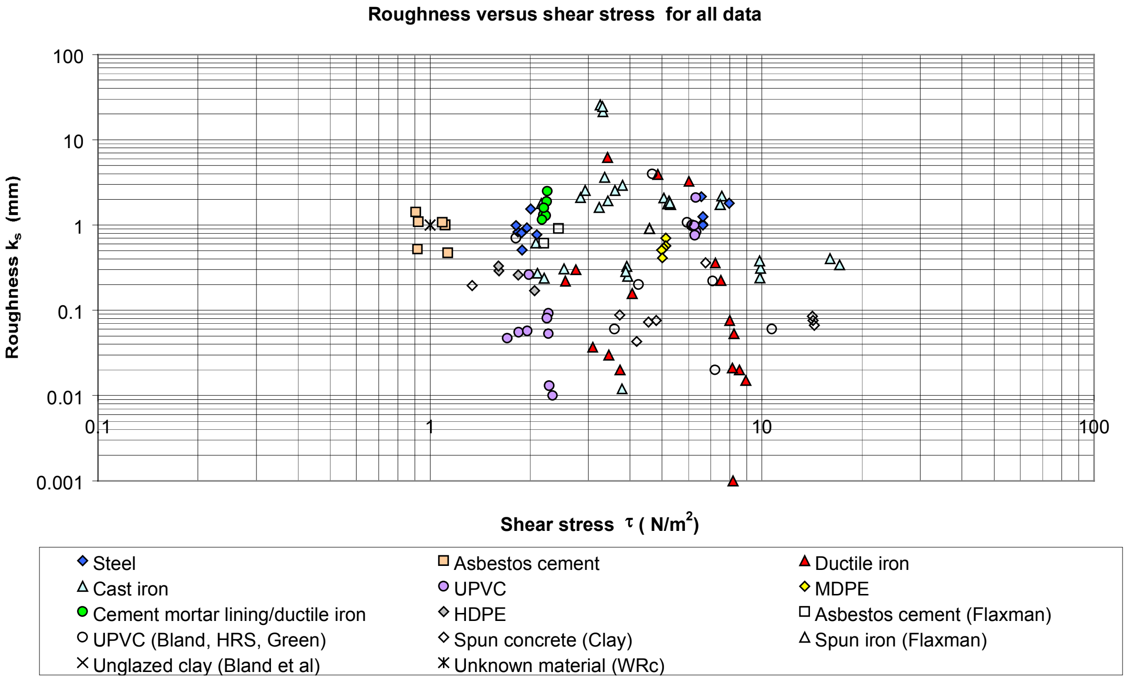

Figure 8 Roughness versus shear stress for all data

Clearly, there is no apparent correlation between the parameters and therefore it does not provide a useful way of predicting hydraulic roughness values.

9.6 PREDICTION OF HYDRAULIC ROUGHNESS BASED ON TEST RESULTS

As shown in the previous sections, the data provided by the field tests shows the dependency of k_s on velocity. In order to provided a prediction method for estimating k_s at different velocities the following best fit equation was developed along with upper and lower bounds.

$$k_s = \alpha V^{-2.34} \tag{4}$$

with k_s in mm, and V in m/s. $\alpha = 0.446$ is the average value (i.e. mean), $\alpha = 0.054$ is the lower bound value, and $\alpha = 3.66$ is the upper bound value. The upper and lower bound values have been calculated from a statistical analysis of the data and represent predicted k_s values two standard deviations about the average value. Therefore 95% of the measured k_s values are within the upper and lower bounds (assuming the data is normally distributed).

The prediction equation is plotted along with the test results in Figures 9 to 15. Only pipe diameters for which there was more than one test are plotted. The additional lines labelled upper and lower are the predicted upper and lower bounds for the k_s values.

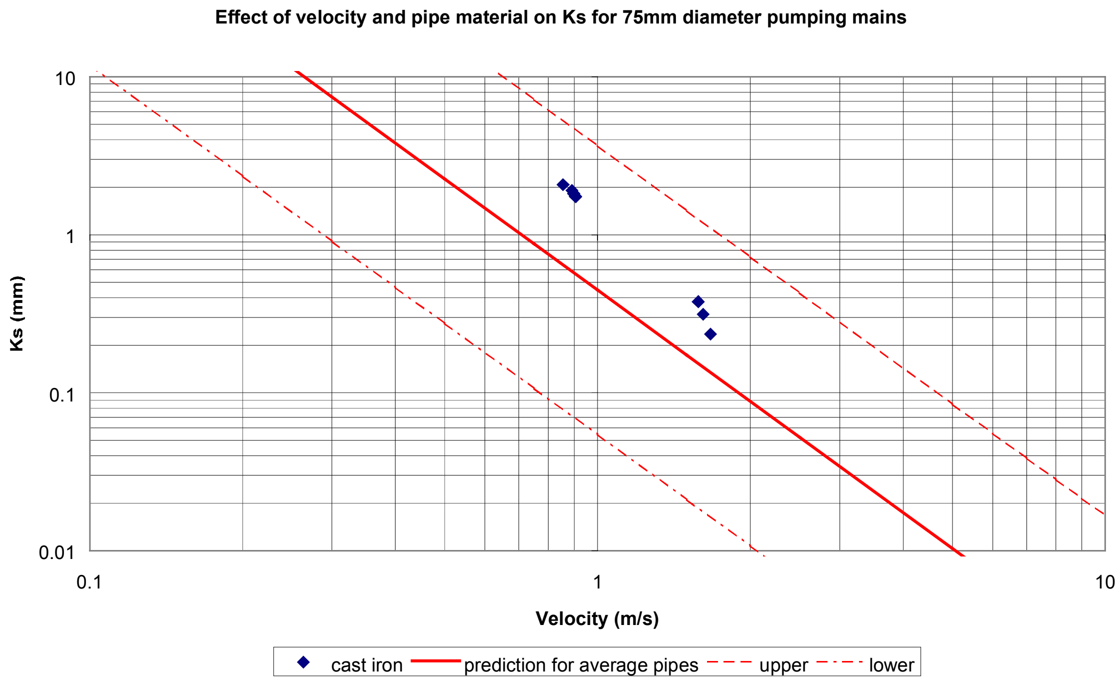

Figure 9 Test results for 75mm diameter pipes compared with the k_s prediction equation

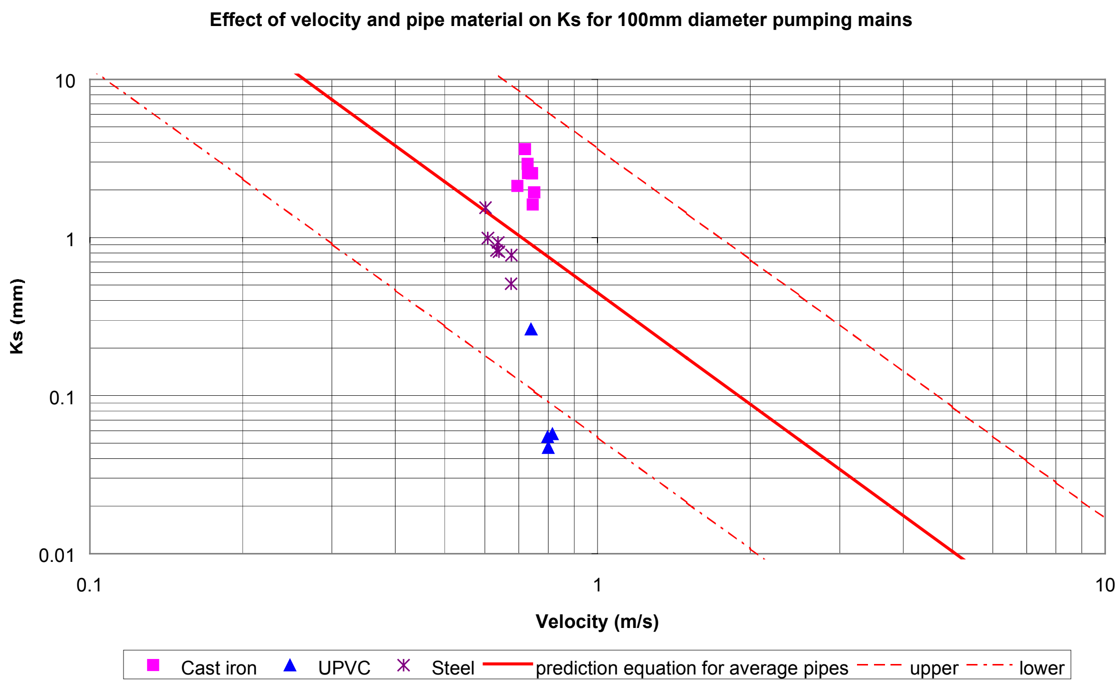

Figure 10 Tests results for 100mm diameter pipes compared with the k_s prediction equation

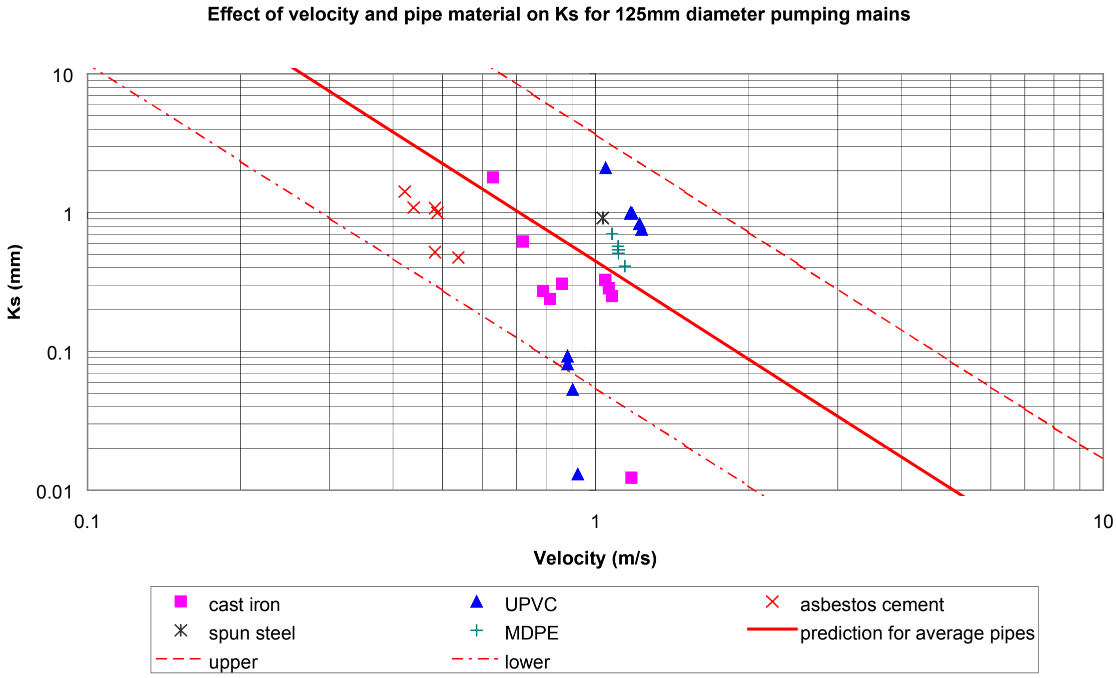

Figure 11 Test results for 125mm diameter pipes compared with the k_s prediction equation

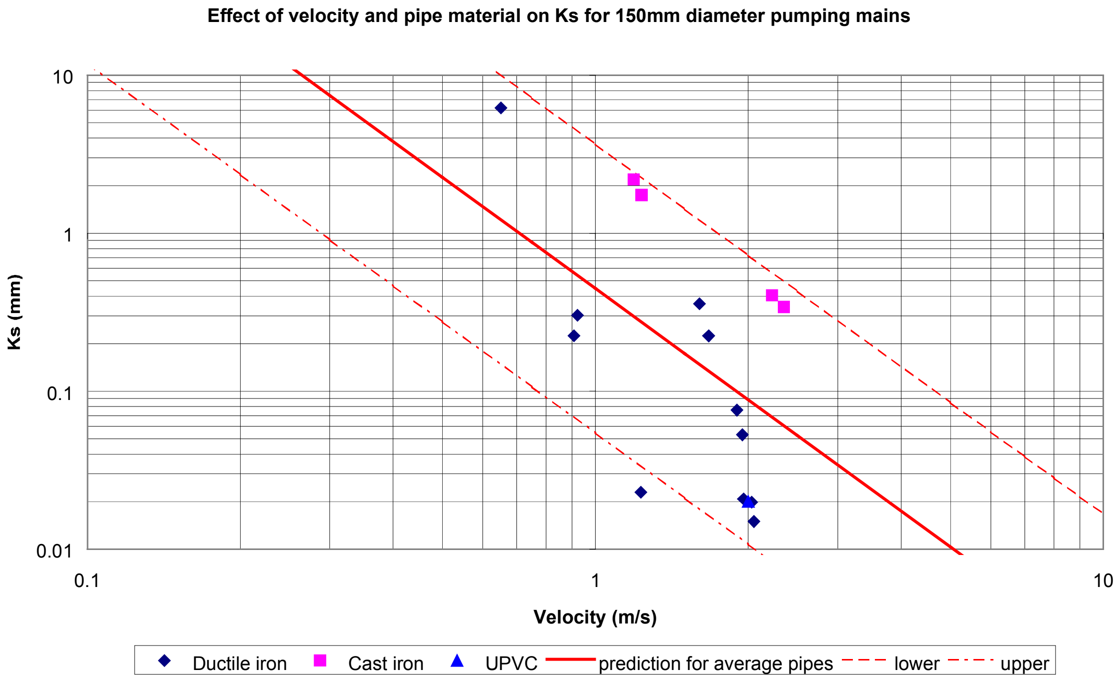

Figure 12 Test results for 150mm diameter pipes compared with the k_s prediction equation

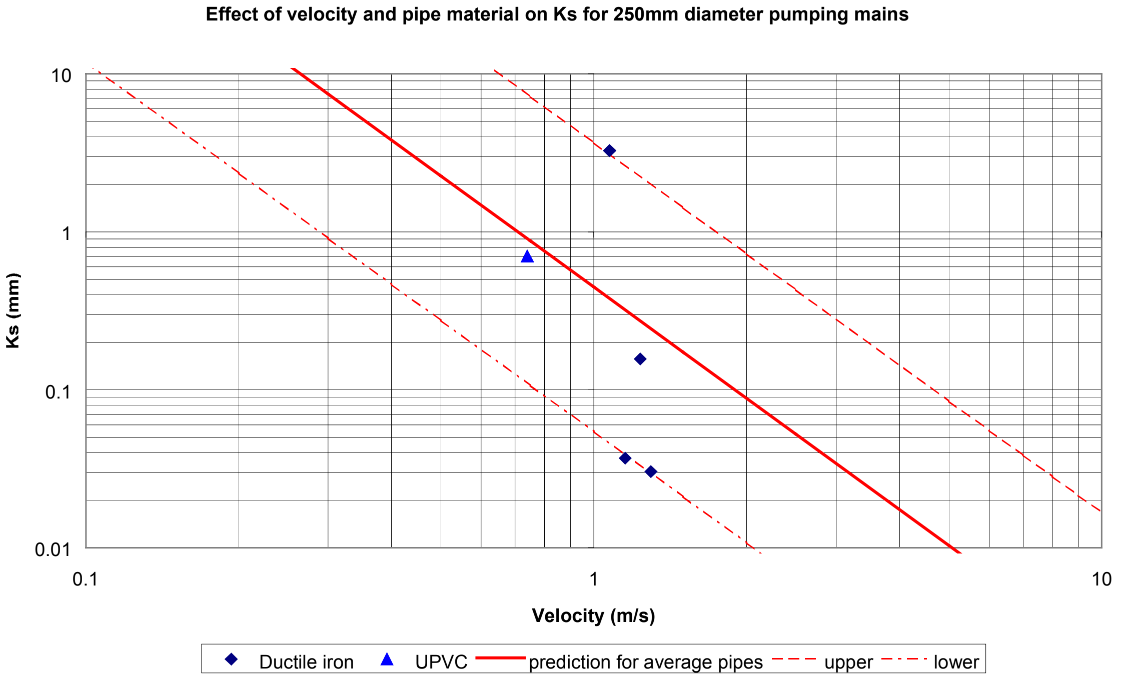

Figure 13 Test results for 250mm diameter pipes compared with the k_s prediction equation

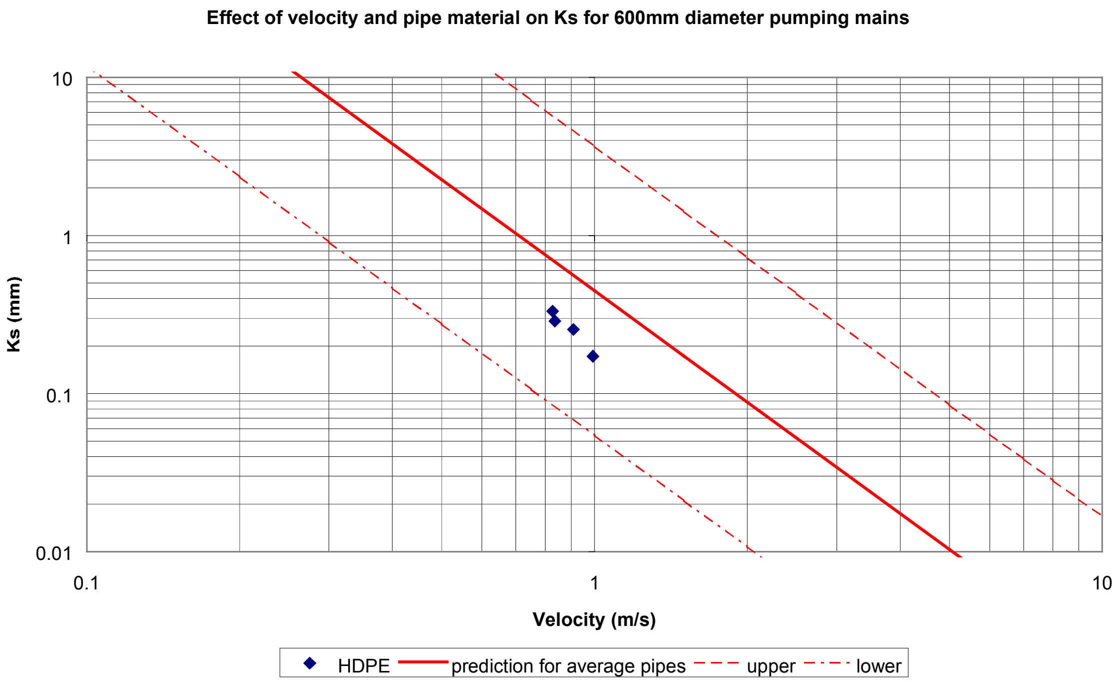

Figure 14 Test results for 600mm diameter pipes compared with the k_s prediction equation

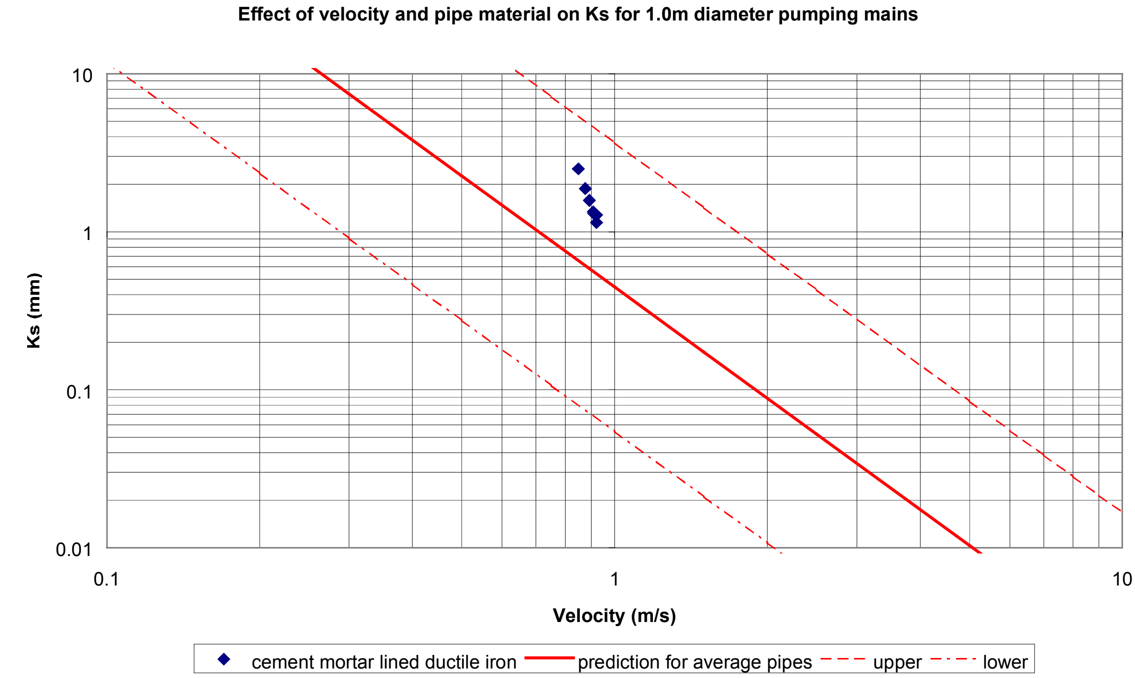

Figure 15 Test results for 1.0m diameter pipes compared with the k_s prediction equation

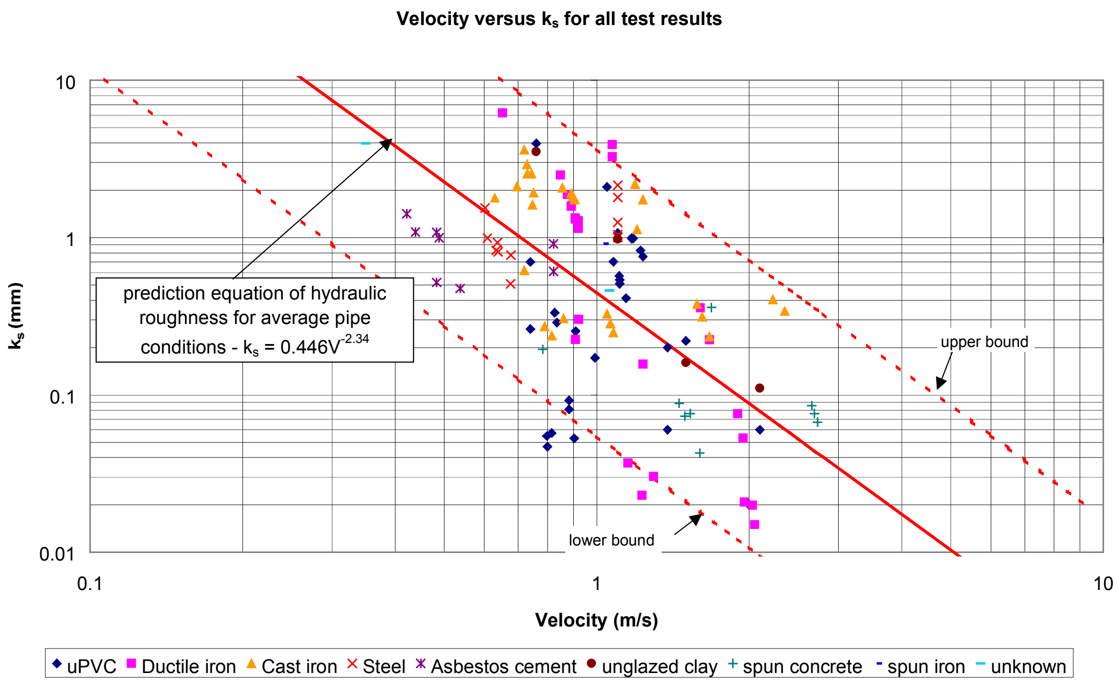

Figure 16 All test results per pipe material compared with the k_s prediction equation

The final figure (Figure 16) shows the prediction equations with all the test data collected during the study. It can be seen from these graphs that the prediction equation for average condition pipes does fit the general trend in the data of decreasing k_s as V increases. The scatter of the test results is generally confined to the range given by the upper and lower bound lines.

Table 8 gives a comparison of the hydraulic roughness values predicted by the new equation and those given previously by the HR Tables (1). The comparison shows that the new equation gives slightly increased hydraulic roughness values for average condition pipes, reduced hydraulic roughness for pipes in good condition (lower bound), and increased hydraulic roughness for pipes in poor condition (upper bound).

Hydraulic roughness values are also provided for flow velocities of 0.75m/s and 0.5m/s. These show that as the flow velocity decreases below 1m/s the hydraulic roughness increases substantially. These values were included because the field tests showed that many of the pumping mains were operated at velocities less than 1m/s.

Table 8 Comparison of hydraulic roughness values between the HR Tables (1) and the new prediction equation

	Hydraulic roughness values k_s (mm)					
Velocity	HR Tables (1)			Prediction equation		
	good	normal	poor	Lower	average	upper
0.50	-	-	-	0.28	2.26	18.5
0.75	-	-	-	0.11	0.88	7.18
1.0	0.15	0.3	0.6	0.054	0.45	3.66
1.5	0.06	0.15	0.3	0.021	0.17	1.42
2.0	0.03	0.06	0.15	0.011	0.088	0.72

9.7 SENSITIVITY TESTS

During the analysis the following assumptions were made about the field data.

- The internal pipe diameter could not be measured and therefore a best estimate of the internal diameter had to be used in the calculations.
- The maximum pumping head changes over the course of each test as the level in the wet well varied. For the analysis the average pumping head and flow rate for each test was used.
- Where the length of each pumping main could not be measured on site it had to be taken off plans of the pumping main.
- The temperature in all but 3-4 tests was measured on site. The probe only measured the temperature in the wet well and it was assumed that this was representative of the overall temperature of the flow in the pumping main.

Sensitivity tests were performed on the test results to assess the impact of the assumptions above.

9.7.1 Effect of changes in pipe diameter

Pipe internal diameter has been identified as the most sensitive parameter affecting the calculation of hydraulic roughness from field test results. To test the effect of changes in pipe diameter a number of field test results were selected and the pipe internal diameter varied to assess its impact. It was found that a 2% change in pipe diameter resulted in a 25% to 35% change in the calculated hydraulic roughness. This is similar to the initial estimate of parameter sensitivity, Table 2. Therefore changes in the internal diameter of the pipe do affect the calculation of hydraulic roughness and it is important to be as accurate as possible in estimating or measuring this parameter.

It is recommended that where new pumping mains are installed the exact internal diameter of the pipe be recorded. Also, when repairs to sections of pipe are undertaken, the internal diameter should be measured where possible.

9.7.2 Effect of changes in pumping head

It was found that during the majority of tests the pumping head of the pumping main decreased as the level in the wet well fell. The change was generally in the order of up to ± 2% about the average value. The k_s values were calculated for a number of sites using the maximum and minimum head values during each test. It was found that this resulted in an average change in k_s of up to 20% during a test.

During the field-tests the pump down time of the wet well in the majority of cases was less than 3 minutes. The length of time the pumping head was at the maximum or minimum values was quite short, in the order of 30 seconds or less.

Also, the measurements of pump down rate of the wet well did not show any significant variation over a test cycle, which indicates that the flow rate in the pumping main did not vary during a test. Based on these results the average flow rate and similarly the average pumping head over a test are the most appropriate values to use in analysis of hydraulic roughness.

9.7.3 Effect of pumping main length

It was not possible to measure the length of the pumping main at several of the sites. The data was therefore estimated based on available records. To assess the effect of changes in length on the hydraulic roughness the assumed length of the pumping main was varied for a number of sites. It was found that changes in length of the pumping main of up to 2% resulted in changes in k_s of up to 8%.

This shows that the calculation of hydraulic roughness is sensitive to the accuracy with which the length of the pumping main is known. However, significant changes in length are required before there is a substantial change in the k_s value.

9.7.4 Effect of temperature

Temperature of the water in the wet well was measured during each test. It was possible that heat could have been added to the system as the liquid passed through the pump. To test the sensitivity of k_s to temperature, the assumed temperature at a number of sites was varied. It was found that a 100% change in temperature resulted in only a 0.1% change in k_s value. It was therefore concluded that the effect of temperature on the analysis was minimal.

10. Recommended values of flow resistance

It is proposed that Equation (4), be used to estimate the hydraulic roughness of wastewater pumping mains.

$$k_s = \alpha V^{-2.34} \tag{5}$$

where α = 0.446 is the average value, α = 0.054 is the lower bound, and α = 3.66 is the upper bound. Refer to Section 9.6 for a definition of the lower and upper bound values.

Table 9 summarises the results of Equation (5) as given in Table 8 for different velocities and conditions.

Table 9 Recommended values for hydraulic roughness of wastewater pumping mains

Velocity	Hydraulic roughness values k_s (mm)		
	Lower	Average	Upper
0.5	0.28	2.26	18.54
0.75	0.11	0.88	7.18
1.0	0.054	0.45	3.66
1.5	0.021	0.17	1.42
2.0	0.011	0.088	0.72

11. Conclusions and recommendations

A study was carried out to improve the knowledge of the flow resistance of wastewater pumping mains. The methodology used was to obtain data on the in-service flow resistance of pumping mains by carrying out a number of field tests on live mains of various sizes and pipe materials. The collected data was then subjected to analysis of the hydraulic roughness k_s of the pipes in each test. The purpose of the analysis was to provide more comprehensive and up-to-date recommendations for values of hydraulic roughness to be used in design manuals and reference documents. Significant conclusions from the study were as follows:

1. In agreement with previous field and laboratory tests it was concluded that velocity of flow within the pipe is the dominant factor affecting the flow resistance of wastewater pumping mains.

2. The k_s calculated from the field test results is a composite value, taking into consideration both the effect of the slimes surface texture and the loss of area due to the slimes thickness on the hydraulic roughness.

3. As with previous studies k_s was seen to reduce as velocity within the pipe increased. In the present study the most common operating velocity of the pumping main was found to be around 1m/s.

4. A prediction equation for hydraulic roughness based on flow velocity has been developed (see chapter 10) which provides a method of calculating average values of hydraulic roughness, and also likely upper and lower bounds. Comparison with previous recommendations indicates slightly increased values of k_s for average pipe conditions; reduced values for the lower bound (good pipe conditions), and increased values for the upper bound (poor pipe condition).

5. At velocities less than 1m/s predicted k_s values were significantly higher than previously determined for the higher velocity range (1 to 2m/s). The increase was particularly noticeable for the upper bound condition.

6. Results indicate that k_s may vary with pipe diameter but the behaviour was not consistent for different pipe materials. As a result no clear overall trend could be determined from the available data.

7. Sensitivity tests were made to assess the effects of possible errors in pipe diameter and pumping head measurement. Assuming a 2% variation in pipe diameter would result in a 25 to 35% change in the calculated hydraulic roughness. Similarly, assuming a 2% variation in the value of pumping head would result in a 20% variation of the calculated k_s. However, these changes are within the upper and lower bounds predicted for the roughness values.

8. Accuracy in the determination of the length of the pumping main had significantly less effect on the calculated value of k_s as did variation of the temperature of the sewage.

9. It is recommended that further tests be carried out over a wider range of velocities and pipe sizes for each material in order to investigate the variation of k_s with pipe size and material.

10. It is very difficult to obtain accurate definitive values of internal pipe diameter for existing live rising mains either from records or measurement. Therefore every opportunity should be taken to accurately record the diameter of new or existing pumping mains whenever possible since this is by far the most significant factor when determining their hydraulic roughness.

11. Care should be taken to preserve records of all new and existing pipe networks especially when the "Responsible Authority" changes since recovery of such data (if at all possible) can be a time consuming and costly exercise. Good records are essential for both the drainage engineer and researcher alike.

12. Acknowledgements

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MWH– Mr Bernard Poole
Thames Water Utilities – Mr Don Ridgers
United Utilities – Mr Steve Whipp

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Appendices

Appendix A Details of field test sites

Site 1 - General Site Description

Site name:	Alum Bridge
Receiving STW:	NA
Operating Utility:	United Utilities

Pumping Main Characteristics

Pipe nominal diameter	0.175m
Pipe internal diameter (estimated)	NA
Pipe length	500m
Pipe material	Cast iron

Pumping Station Characteristics

Wet well area	7.55m^2
No. of pumps	2
Maximum flow rate	32 l/s pump 1, 21 l/s pump 2
Maximum pumping head	11.7m
Maximum static head	5.75m

Test details

Date of test	05/07/02
No. of tests	9

Additional notes:
Data not used in the analysis as the results gave negative roughness values.

Site 2 - General Site Description

Site name:	Bibury
Receiving STW:	Bibury
Operating Utility:	Thames Water

Pumping Main Characteristics

Pipe nominal diameter	0.125m
Pipe internal diameter (estimated)	0.1276m
Pipe length	1100m
Pipe material	UPVC (assumed Class C UPVC)

Pumping Station Characteristics

Wet well area	7.76m^2
No. of pumps	2
Maximum flow rate	12.09 l/s
Maximum pumping head	42.75m
Maximum static head	34.85m

Test details

Date of test	03/03/03
No. of tests	5

Additional notes:

Photo 1: Bibury - Site overview

Photo 2: Bibury - Controls

Photo 3: Bibury - Dry well

Photo 4: Bibury - Wet well

Site 3 - General Site Description

Site name:	Bishopstone
Receiving STW:	Swindon
Operating Utility:	Thames Water

Pumping Main Characteristics

Pipe nominal diameter	0.13m (unlikely to be this value)
Pipe internal diameter (estimated)	0.1312m
Pipe length	1286m
Pipe material	Cast iron (assumed Class C)

Pumping Station Characteristics

Wet well area	$3.46m^2$
No. of pumps	2
Maximum flow rate	11.68 l/s
Maximum pumping head	11.8m
Maximum static head	1.86m

Test details

Date of test	27/05/03
No. of tests	5

Additional notes:
A gate valve was located on the Bauer.

The nominal diameter as recorded on the Thames Water database was 0.13m. This does not correspond to any cast iron pipe nominal diameter in use therefore the closest diameter pipe to this value was chosen.

Photo 1: Bishopstone - Controls

Photo 2: Bishopstone - Dry Well

Photo 3: Bishopstone - Wet well

Site 4 - General Site Description

Site name:	Bourton-on-the-water
Receiving STW:	Rissington
Operating Utility:	Thames Water

Pumping Main Characteristics

Pipe nominal diameter	0.25m
Pipe internal diameter (estimated)	0.2472m
Pipe length	570m
Pipe material	Ductile iron

Pumping Station Characteristics

Wet well area	3.78m^2
No. of pumps	2
Maximum flow rate	51 l/s
Maximum pumping head	13.3m
Maximum static head	7.14m

Test details

Date of test	02/07/02
No. of tests	2

Additional notes:
We were unable to perform tests at this site due to the presence of a valve on the Bauer connection pipe, which prevented measurements of the pressure in the pumping main. Test results were however available from 2 tests by Thames Water and the measurements made during these tests have been re-analysed for this study.

Site 5 - General Site Description

Site name:	Bradfield Farm
Receiving STW:	Reading
Operating Utility:	Thames Water

Pumping Main Characteristics

Pipe nominal diameter	0.15m
Pipe internal diameter (estimated)	0.1448m
Pipe length	980m
Pipe material	Ductile iron

Pumping Station Characteristics

Wet well area	6.65m^2
No. of pumps	2
Maximum flow rate	22.4 l/s
Maximum pumping head	59.5m
Maximum static head	49.5m

Test details

Date of test	04/10/02 & 16/10/02
No. of tests	6

Additional notes:
Testing at the Bradfield Farm site was carried out over 2 days. One the first day the gasket on the Bauer connector connection ruptured due to the high static head and pumping head on the pipeline. It was not possible to replace this gasket on site and therefore a second site visit was required in order to conduct the test.

Photo 1: Bradfield Farm - Site overview

Photo 2: Bradfield Farm - Controls

Photo 3: Bradfield Farm - Wet well

Photo 3: Bradfield Farm - Bauer connector and pressure sensors

Photo 4: Bradfield Farm - Blown gasket on Bauer connection

Site 6 - General Site Description

Site name:	Cheddington South End
Receiving STW:	Aylesbury
Operating Utility:	Thames Water

Pumping Main Characteristics

Pipe nominal diameter	0.15m
Pipe internal diameter (estimated)	0.1448m
Pipe length	1700m
Pipe material	Ductile iron

Pumping Station Characteristics

Wet well area	$4.52m^2$
No. of pumps	2
Maximum flow rate	33.68 l/s
Maximum pumping head	40m
Maximum static head	1.22m

Test details

Date of test	09/07/03
No. of tests	8

Additional notes:
Site refurbished in 1993.

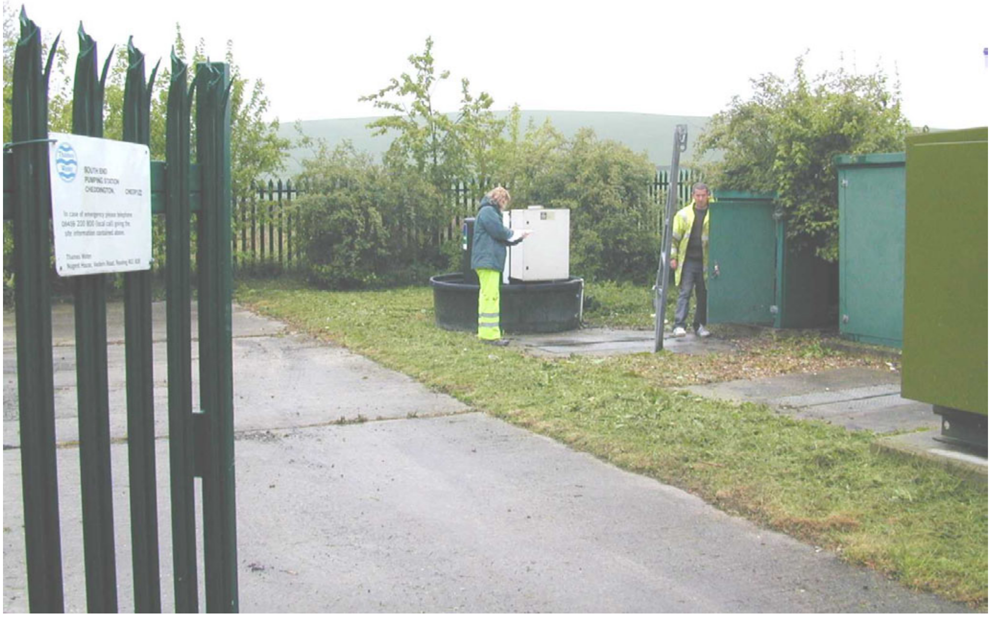

Photo 1: Cheddington - Site overview

Photo 2: Cheddington - Control system

Photo 3: Cheddington - Dry well

Photo 4: Cheddington - Wet well outflow pipes

Site 7 - General Site Description

Site name:	Church St
Receiving STW:	NA
Operating Utility:	United Utilities

Pumping Main Characteristics

Pipe nominal diameter	0.25m
Pipe internal diameter (estimated)	0.2054
Pipe length	233.28m
Pipe material	Ductile iron (cement mortar lined)

Pumping Station Characteristics

Wet well area	5.38m^2
No. of pumps	2
Maximum flow rate	4.6 l/s pump 1, 4.5 l./s pump 2
Maximum pumping head	28.8 l/s
Maximum static head	15.42m

Test details

Date of test	10/07/00
No. of tests	3

Additional notes:
Pumping main installed in 1997.

Site 8 - General Site Description

Site name:	Dene Hollow
Receiving STW:	Harwell
Operating Utility:	Thames Water

Pumping Main Characteristics

Pipe nominal diameter	0.125m
Pipe internal diameter (estimated)	0.1319m
Pipe length	2800m
Pipe material	Asbestos cement

Pumping Station Characteristics

Wet well area	2.94m^2
No. of pumps	2
Maximum flow rate	7.3 l/s
Maximum pumping head	22m
Maximum static head	12.47m

Test details

Date of test	10/10/02
No. of tests	7

Additional notes:
The Bauer was located on an upstand of pipe, located outside of the dry well.

Photo 1: Dene Hollow - Bauer connector and pressure sensors

Photo 2: Dene Hollow - Pumping main entering dry well

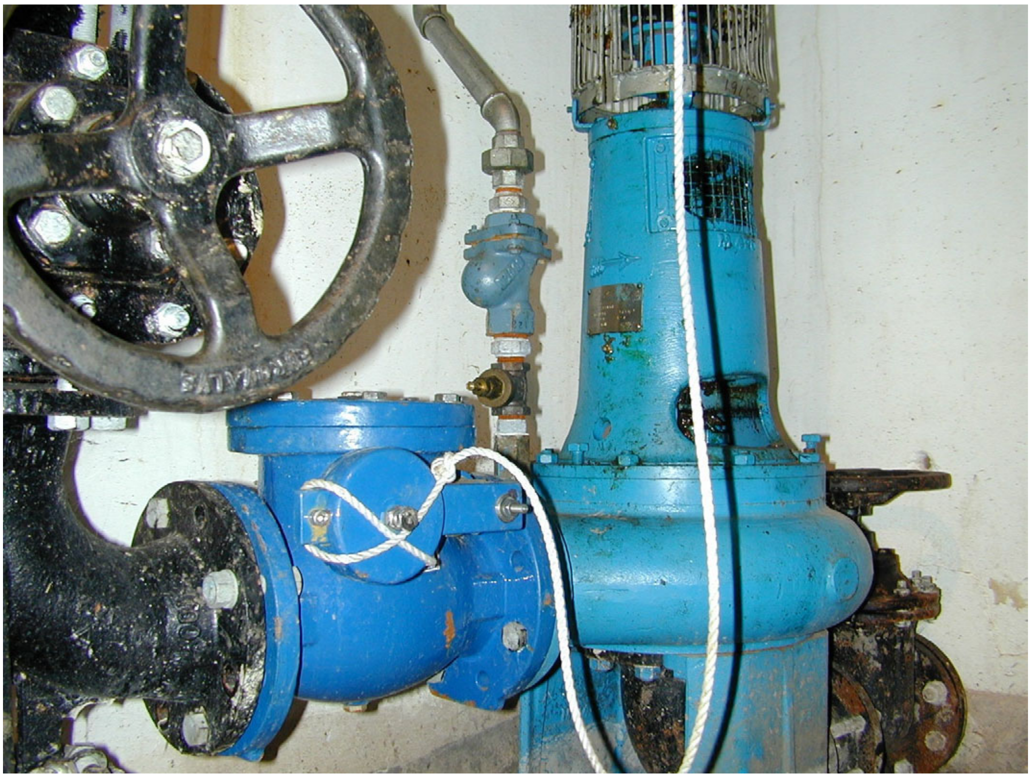

Photo 3: Dene Hollow - Pumps in dry well

Site 9 - General Site Description

Site name:	Fairmile
Receiving STW:	Cholsey
Operating Utility:	Thames Water

Pumping Main Characteristics

Pipe nominal diameter	0.15m
Pipe internal diameter (estimated)	0.1518m
Pipe length	789.7m
Pipe material	Steel (possibly with some asbestos cement sections)

Pumping Station Characteristics

Wet well area	5.94m^2
No. of pumps	2
Maximum flow rate	22 l/s
Maximum pumping head	27.3m
Maximum static head	12.54m

Test details

Date of test	30/07/02
No. of tests	4

Additional notes:

The operator on site stated that the pumping main has burst at a number of locations in the past and that section over time most of the original asbestos cement pipe had been replaced by steel pipe. It is unknown how much of each material is present.

At the pumping station there were two values. A non-return valve was located upstream of the pump, while another non-return valve was located on the pumping main itself.

Photo 1: Fairmile - Site overview

Photo 2: Fairmile - Controls

Photo 3: Fairmile - Dry well with bauer connector

Photo 4: Fairmile - Wet well

Site 10 - General Site Description

Site name:	Freckleton
Receiving STW:	Clifton Marsh
Operating Utility:	United Utilities

Pumping Main Characteristics

Pipe nominal diameter	0.6m
Pipe internal diameter (estimated)	0.5818m
Pipe length	2450m
Pipe material	PE 100 SDR-26

Pumping Station Characteristics

No. of pumps	5
Maximum flow rate	320 l/s
Maximum pumping head	16m
Maximum static head	11.3m

Test details

Date of test	16/07/03
No. of tests	7

Additional notes:

Because of the size of the station an overpumping facility using a Bauer connector was not available. The pressure sensors were instead connected to existing pressure tapping points close to each of the pumps. The level sensor could not be set at the wet well and therefore level readings in the well were recorded from the meter readings within the station.

The static level could not be measured directly during the tests and was estimated from as-built drawings. The discharge location at the Clifton Marsh treatment works was visited to check that the pipe was full to the mouth of the discharge pipe when the pumps were not operating.

An electromagnetic flow meter was located on the pumping main in the valve chamber just outside the building. Readings from the flow meter were shown on the display in the pumping station.

Only the fixed speed pumps were tested. There were also 2 variable speed pumps in the station. They were designated as storm flow pumps.

The Freckleton station had recently been refurbished and the pumping main replaced. Twin pumping mains had been replaced by a single pumping main to the Clifton Marsh treatment works.

Photo 1: Freckleton - View of the pumps

Site 11 - General Site Description

Site name:	Garsington
Receiving STW:	Oxford
Operating Utility:	Thames Water

Pumping Main Characteristics

Pipe nominal diameter	0.1m
Pipe internal diameter (estimated)	0.1032m
Pipe length	950m
Pipe material	UPVC (assumed PN8)

Pumping Station Characteristics

Wet well area	$3.14m^2$
No. of pumps	2
Maximum flow rate	6.8 l/s
Maximum pumping head	30.75m
Maximum static head	24.2m

Test details

Date of test	12/11/02
No. of tests	4

Additional notes:

For the first test pump 2 was run but it did not seem to be operating correctly so pump 1 was also started. This may have been due to blockages/ragging of pump 2. For the remainder of the tests both pumps were operating correctly.

Photo 1: Garsington - Pumping main with Bauer connector

Photo 2: Garsington - Dry well

Photo 3: Garsington - Wet well

Site 12 - General Site Description

Site name:	Great Coxwell
Receiving STW:	Great Coxwell
Operating Utility:	Thames Water

Pumping Main Characteristics

Pipe nominal diameter	0.125m
Pipe internal diameter (estimated)	0.1276m
Pipe length	1445m
Pipe material	UPVC (assumed Class C UPVC)

Pumping Station Characteristics

Wet well area	2.54m^2
No. of pumps	2
Maximum flow rate	15.6 l/s
Maximum pumping head	48.5m
Maximum static head	19.3m

Test details

Date of test	18/03/03
No. of tests	6

Additional notes:

Photo 1: Great Coxwell - Site overview

Photo 2: Great Coxwell - Controls

Photo 3: Great Coxwell - Dry well

Photo 4: Great Coxwell - Wet well

Site 13 - General Site Description

Site name:	Hebden Green
Receiving STW:	NA
Operating Utility:	United Utilities

Pumping Main Characteristics

Pipe nominal diameter	0.15m
Pipe internal diameter (estimated)	0.1605m
Pipe length	382
Pipe material	Cast iron (assumed Class B)

Pumping Station Characteristics

Wet well area	$2.25m^2$
No. of pumps	2
Maximum flow rate	34 l/s pump 1, 26 l/s pump 2
Maximum pumping head	NA
Maximum static head	1.22m

Test details

Date of test	10/07/00
No. of tests	6

Additional notes:
Pumping main installed in 1982.

Site 14 - General Site Description

Site name:	Heskin Lane
Receiving STW:	Burscough STW
Operating Utility:	United Utilities

Pumping Main Characteristics

Pipe nominal diameter	0.15m
Pipe internal diameter (estimated)	NA
Pipe length	215m
Pipe material	Cast iron

Pumping Station Characteristics

Wet well area	NA
No. of pumps	2
Maximum flow rate	90 l/s (total), 45 l/s per pump
Maximum pumping head	17m
Maximum static head	6.4m

Test details

Date of test	07/11/02
No. of tests	NA

Additional notes:
There are two pumping mains at this station. It appears from the test results than one of the mains may be blocked.

Site 15 - General Site Description

Site name:	Highway Lane
Receiving STW:	NA
Operating Utility:	United Utilities

Pumping Main Characteristics

Pipe nominal diameter	0.1m
Pipe internal diameter (estimated)	NA
Pipe length	600m
Pipe material	Cast iron

Pumping Station Characteristics

Wet well area	7.69m^2
No. of pumps	2
Maximum flow rate	13.2 l/s pump 1, 12.3 l/s pump 2
Maximum pumping head	24.8m
Maximum static head	14.65m

Test details

Date of test	28/08/01
No. of tests	9

Additional notes:
There is uncertainty over the diameter of the pumping main. The records give a value of 100mm but it is suspected that the pipe diameter is more likely 125mm or 150mm.

Site 16 - General Site Description

Site name:	Hithercroft
Receiving STW:	Cholsey
Operating Utility:	Thames Water Utilities

Pumping Main Characteristics

Pipe nominal diameter	0.1m
Pipe internal diameter (estimated)	0.1075m
Pipe length	10m
Pipe material	UPVC

Pumping Station Characteristics

Wet well area	5.11m^2
No. of pumps	2
Maximum flow rate	14.3 l/s
Maximum pumping head	12.6m
Maximum static head	Unknown, estimated to be 11.5m

Test details

Date of test	11/07/02
No. of tests on site	4

Additional notes:

From the information available on the database it appeared that the Hithercroft PS pumped the flow a distance of approximately 100-200m to the St Johns PS in Wallingford. However, on site it was discovered that the Hithercroft station only pumped the flow a short distance to the centre of the adjacent roadway from where it gravity feed to the St John PS. The static head level could not be measured on site and therefore was estimated from the test results.

Due to the uncertainty in the static head measurements it was decided not to include these tests results in the analysis.

Photo 1: Hithercroft - Controls

Photo 2: Hithercroft - Dry well

Photo 3: Hithercroft - Wet well

Site 17 - General Site Description

Site name:	Lea Gate
Receiving STW:	Clifton Marsh
Operating Utility:	United Utilities

Pumping Main Characteristics

Pipe nominal diameter	1.0m
Pipe internal diameter (estimated)	0.999m
Pipe length	3.6km
Pipe material	Cement mortar lined ductile iron

Pumping Station Characteristics

Wet well area	NA
No. of pumps	4
Maximum flow rate	NA
Maximum pumping head	NA
Maximum static head	NA

Test details

Date of test	NA
No. of tests	NA

Additional notes:
This test was performed for UU prior to the present project. Insufficient information was available to check the tests and calculated k_s values.

Site 18 - General Site Description

Site name:	Lea Gate
Receiving STW:	Clifton Marsh
Operating Utility:	United Utilities

Pumping Main Characteristics

Pipe nominal diameter	1.0m
Pipe internal diameter (estimated)	1.01m
Pipe length	3600m
Pipe material	Ductile iron (cement lined)

Pumping Station Characteristics

No. of pumps	5
Maximum flow rate	738 l/s
Maximum pumping head	10m
Maximum static head	6.198m

Test details

Date of test	16/07/03
No. of tests	8

Additional notes:

Because of the size of the station an overpumping facility using a Bauer connector was not available. The pressure sensors were instead connected to existing pressure tapping points close to each of the pumps. The level sensor could not be set at the wet well and therefore level readings in the well were recorded from the meter readings within the station.

The static level could not be measured directly during the tests and was estimated from as-built drawings. The discharge location at the Clifton Marsh treatment works was visited to check that the pipe was full to the mouth of the discharge pipe when the pumps were not operating.

It was possible to close the inlet to the pumping station while doing the pump down tests. There was however a problem estimating the volume of the wet well as the inlet was below the pump down levels and remained full of water during the tests. The additional volume of flow in the inflow pipe therefore had to be estimated.

Photo 1: Lea Gate - View of the pumps

Photo 2: Lea Gate - Wet well

Photo 3: Lea Gate - Outflow from Lea gate at Clifton Marsh

Photo 4: Lea Gate - Controls

Site 19 - General Site Description

Site name:	Nether Winchendon
Receiving STW:	Aylesbury
Operating Utility:	Thames Water

Pumping Main Characteristics

Pipe nominal diameter	0.1m
Pipe internal diameter (estimated)	0.101m
Pipe length	904m
Pipe material	MDPE (assumed SDR11)

Pumping Station Characteristics

Wet well area	$2.54m^2$
No. of pumps	2
Maximum flow rate	8.9 l/s
Maximum pumping head	22.55m
Maximum static head	4.5m

Test details

Date of test	09/05/03
No. of tests	5

Additional notes:

Photo 1: Nether Winchendon - Site overview

Photo 2: Nether Winchendon - Controls

Photo 3: Nether Winchendon - Dry well

Photo 4: Nether Winchendon - Wet well

Site 20 - General Site Description

Site name:	St John's New
Receiving STW:	Cholsey
Operating Utility:	Thames Water

Pumping Main Characteristics

Pipe nominal diameter	0.15m
Pipe internal diameter (estimated)	0.1434m
Pipe length	520m
Pipe material	Cast iron

Pumping Station Characteristics

Wet well area	2.75m^2
No. of pumps	2
Maximum flow rate	19.8 l/s
Maximum pumping head	16.1m
Maximum static head	Unknown, estimated to be approximately 6m

Test details

Date of test	23/07/02
No. of tests	6

Additional notes:
No static head measurement was possible on site. Due to this it was decided not to include these test results in the analysis.

Photo 1: St Johns New - Controls

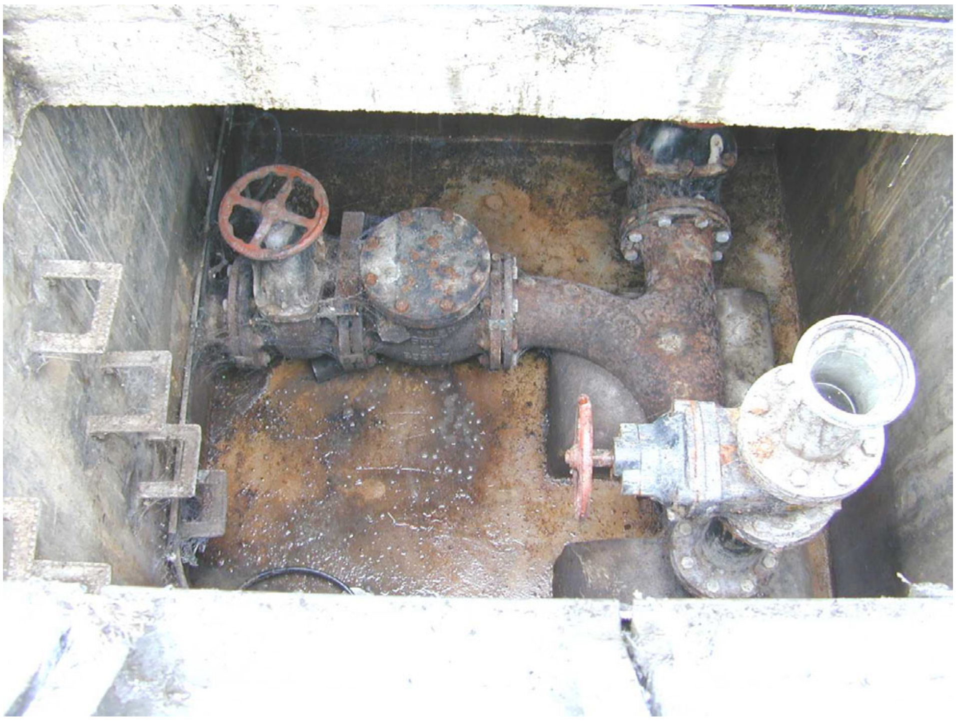

Photo 2: St Johns New - Dry Well

Photo 3: St Johns New - Wet well

Site 21 - General Site Description

Site name:	Stadhampton
Receiving STW:	Stadhampton
Operating Utility:	Thames Water

Pumping Main Characteristics

Pipe nominal diameter	0.1m
Pipe internal diameter (estimated)	0.102m
Pipe length	780m
Pipe material	Cast iron

Pumping Station Characteristics

Wet well area	2.54m^2
No. of pumps	2
Maximum flow rate	6.1 l/s
Maximum pumping head	13.75m
Maximum static head	3.35m

Test details

Date of test	25/03/03
No. of tests	7

Additional notes:

Photo 1: Stadhampton - Site overview

Photo 2: Stadhampton - Controls

Photo 3: Stadhampton - Dry well with Bauer connector

Photo 4: Stadhampton - Wet well with level sensors

Site 22 - General Site Description

Site name:	The Dell
Receiving STW:	NA
Operating Utility:	United Utilities

Pumping Main Characteristics

Pipe nominal diameter	0.075m
Pipe internal diameter (estimated)	0.08077m
Pipe length	233m
Pipe material	Cast iron (assumed Class B)

Pumping Station Characteristics

Wet well area	2.6m^2
No. of pumps	2
Maximum flow rate	4.6 l/s
Maximum pumping head	23.6m
Maximum static head	17.24m

Test details

Date of test	01/11/02
No. of tests	9

Additional notes:
Pumping main installed in 1971.

Site 23 - General Site Description

Site name:	Whitchurch Hill
Receiving STW:	Whitchurch Hill
Operating Utility:	Thames Water

Pumping Main Characteristics

Pipe nominal diameter	0.1m
Pipe internal diameter (estimated)	0.1071m
Pipe length	1440
Pipe material	Steel

Pumping Station Characteristics

Wet well area	3.65m^2
No. of pumps	2
Maximum flow rate	6.2 l/s
Maximum pumping head	24m
Maximum static head	12.35m

Test details

Date of test	15/08/02
No. of tests	6

Additional notes:

Photo 1: Whitchurch Hill - Controls

Photo 2: Whitchurch Hill - Dry well

Photo 3: Whitchurch Hill - Wet well

Appendix B Field test results

Summary of Pumping Test Results

Bibury SPS

	units	pump 2	pump 1	pump 2	pump 1	pump 2
Static Head	m	34.98	34.98	34.98	34.98	34.98
Inflow Rate - dy/dt		0.000245	0.000269	0.000185	0.000203	0.000181
ave		0.000245	0.000269	0.000185	0.000203	0.000181
Pump Down Rate - dy/dt		0.001208	0.001253	0.001302	0.001355	0.001272
ave		0.001208	0.001253	0.001302	0.001355	0.001272
$\Delta p/\Delta t$		0.0011	0.0007	0.0009	0.0003	0.0006
		0.0011	0.0006	0.0008	0.0005	0.0008
		0.001	0.0006	0.0008	0.0007	0.0009
ave		0.00107	0.00063	0.00083	0.00050	0.00077
Max Head	m					
	m	42.8	42.6	42.75	42.6	42.7

Wet Dimensions	m	2	2	2	2	2
Area	m^2	7.76	7.76	7.76	7.76	7.76
Q_{in}	m^3/s	0.00190	0.00209	0.00144	0.00158	0.00141
Q_p	m^3/s	0.01127	0.01181	0.01154	0.01209	0.01128
V_p	m/s	0.882	0.924	0.903	0.946	0.882
K_{losses}		9.0	9.0	9.0	9.0	9.0
Head Losses	m	0.357	0.391	0.374	0.410	0.357
Pipe Area	m^2	0.01279	0.01279	0.01279	0.01279	0.01279
Pipe Diameter	m	0.1276	0.1276	0.1276	0.1276	0.1276
Pipe Length	m	1100	1100	1100	1100	1100
ΔH	m	7.47	7.23	7.40	7.21	7.37
$\Delta H/L$		0.00679	0.00657	0.00673	0.00656	0.00670
Average Temp T	°C	14.0	14.0	14.0	14.0	14.0
Kinematic Viscosity		1.460E-06	1.460E-06	1.460E-06	1.460E-06	1.460E-06

Re		7.706E+04	8.072E+04	7.888E+04	8.265E+04	7.709E+04
Friction Factor, λ		0.021860875	0.01929394	0.02067263	0.01835703	0.02154951
K_s	m	9.227E-05	1.304E-05	5.288E-05	-	8.085E-05
K_s	mm	0.092	0.013	0.053	-	0.081
pipe material	upvc, OD=140.2, WT=6.3 Class C					

More Detailed Minor Loss Calculations

Loss Calculations	*K*	*no.*		*$V^2/2g$*	*losses*
globe valve (fully open)	10				
angle valve (fully open)	5				
swing check valve (fully ope	2.5				
gate valve (fully open)	0.19				
close return bend	2.2				
standard tee	1.8				
standard elbow	0.9	2	1.8	0.04	0.071
medium sweep elbow	0.75	8	6	0.04	0.238
long sweep elbow	0.6	2	1.2	0.04	0.048
valve (non return)	1.7	0	0	0.04	0.000
			9	0.357	

An additonal head of one pipe diameter has been added to the static head measurement to account for level changes at the discharge location

Summary of Pumping Test Results

Bishopstone SPS

	units	1	2	1	2	1&2
Static Head	m	2.00	1.97	1.95	1.86	1.87
Inflow Rate - dy/dt		0.0003249	0.0004264	0.0003534	0.0002765	0.0001891
		0.0004264	0.0003534	0.00003	0.00019	
ave		0.00037565	0.0003899	0.00019	0.0002328	0.0001891
Pump Down Rate - dy/dt		0.0027046	0.0021	0.0026	0.0030	0.0032
						0.0031
ave		0.0027046	0.0021	0.0026	0.0030	0.0032
Δp/Δt	min	9.83	10.4	9.77	10.2	11.56
	max	10.5	10.66	10.39	10.51	11.98
ave		10.2	10.53	10.08	10.36	11.77
Max Head	m					
	m	10.23	10.6	10.2	10.4	11.8

Wet Dimensions	m	2.1	2.1	2.1	2.1	2.1
Area (circular)	m^2	3.46	3.46	3.46	3.46	3.46
Q_{in}	m^3/s	0.00130	0.00135	0.00066	0.00081	0.00065
Q_p	m^3/s	0.01067	0.00850	0.00973	0.01103	0.01163
V_p	m/s	0.789	0.629	0.720	0.816	0.860
K_{losses}		6.390	6.390	6.390	6.390	6.390
Head Losses	m	0.203	0.129	0.169	0.217	0.241
Pipe Area	m^2	0.01352	0.01352	0.01352	0.01352	0.01352
Pipe Diameter	m	0.1312	0.1312	0.1312	0.1312	0.1312
Pipe Length	m	1286	1286	1286	1286	1286
ΔH	m	8.03	8.50	8.08	8.32	9.69
ΔH/L		0.00625	0.00661	0.00629	0.00647	0.00753
Average Temp T	°C	15.6	15.3	16.3	17.2	18.1
Kinematic Viscosity		1.416E-06	1.424E-06	1.398E-06	1.376E-06	1.354E-06

Re		7.311E+04	5.795E+04	6.756E+04	7.778E+04	8.333E+04
Friction Factor, λ		0.025815085	0.04299776	0.031221	0.0250424	0.02620733
K_s	m	2.721E-04	1.786E-03	6.180E-04	2.378E-04	3.064E-04
K_s	mm	0.272	1.786	0.618	0.238	0.306
pipe material	cast iron, Class C					

More Detailed Minor Loss Calculations

Loss Calculations	*K*	*no.*		*$V^2/2g$*	*losses*
globe valve (fully open)	10				
angle valve (fully open)	5				
swing check valve (fully op	2.5				
gate valve (fully open)	0.19	1	0.19		
close return bend	2.2				
standard tee	1.8				
standard elbow	0.9	1	0.9	0.03	0.029
medium sweep elbow	0.75	4	3	0.03	0.095
long sweep elbow	0.6	1	0.6	0.03	0.019
valve (non return)	1.7	1	1.7	0.03	0.054
			6.39		0.143

An additonal 1 pipe diameter of head has been added to the static head measurements to account for water level changes at the discharge location

Summary of Pumping Test Results

Rissington Rd SPS, Bourton-on-the-Water

	units	pump 1	pump 2
Static Head	m	7.14	7.14
Inflow Rate - dy/dt	l/s	31.5	23.62
		27	23.62
		22.23	22.23
ave		26.91	23.16
Pump Down Rate - dy/dt		55.0000	38.6200
		52.2000	47.24
		47.4300	47.43
ave		51.5433	44.4300
Max Head			
	m	13.3	12
Wet Dimensions	m		
Area	m^2	3.78	3.78
Q_{in}	m^3/s	0.02691	0.02316
Q_p	m^3/s	0.05154	0.04443
V_p	m/s	1.07	0.93
K_{losses}		9.8	9.8
Head Losses	m	0.47616	0.35381
Pipe Area	m^2	0.04799	0.04799
Pipe Diameter	m	0.2472	0.2472
Pipe Length	m	570	570
ΔH	m	5.69	4.51
$\Delta H/L$		0.00998	0.00791
Average Temp T	°C	15.0	15.0
Kinematic Viscosity		1.432E-06	1.432E-06
Re		1.854E+05	1.598E+05
Friction Factor, λ		0.042	0.045
K_s	m	3.263E-03	3.911E-03
K_s	mm	3.26	3.91
Pipe material	ductile iron, OD=274mm, WT=13.6mm		

More detailed minor loss calculations

Detailed Local Losses - Pump 1				
Loss Calculations	*K*	*no.*	*$V^2/2g$*	*losses*
globe valve (fully open)	10			
angle valve (fully open)	5			
swing check valve (fully open)	2.5			
gate valve (fully open)	0.19			
close return bend	2.2			
standard tee	1.8			
standard elbow	0.9	2	0.06	0.106
medium sweep elbow	0.75	6	0.06	0.265
long sweep elbow	0.6	3	0.06	0.106
valve (non return)	1.7	1	0.06	0.100
				0.476

Detailed Local Losses - Pump 2				
Loss Calculations	*K*	*no.*	*$V^2/2g$*	*losses*
globe valve (fully open)	10			
angle valve (fully open)	5			
swing check valve (fully open)	2.5			
gate valve (fully open)	0.19			
close return bend	2.2			
standard tee	1.8			
standard elbow	0.9	2	0.04	0.079
medium sweep elbow	0.75	6	0.04	0.197
long sweep elbow	0.6	3	0.04	0.079
valve (non return)	1.7	1	0.04	0.074
				0.354

Summary of Pumping Test Results

Bradfield Farm, Bradfield

	units	pump 1	pump 1	pump 2	pump 1	pump 2	pump 2
Static Head	m	49.29	49.67	49.60	49.59	49.43	49.57
Inflow Rate - dy/dt		0.000147	0.00064851	0.00064267	0.00068807	0.00057737	0.00030395
		0.000648508	0.00064267	0.00068807	0.00057737	0.00030395	
ave		0.000397754	0.00064559	0.00066537	0.00063272	0.00044066	0.00030395
Pump Down Rate - dy/dt		0.0018863	0.00160256	0.00272727	0.00215517	0.00260417	0.00131004
ave		0.0018863	0.00160256	0.00272727	0.00215517	0.00260417	0.00131004
$\Delta p/\Delta t$		0.0013	0.001	0.0021	0.0018	0.0026	0.0016
		0.0012	0.0009	0.0013	0.0017	0.0026	0.0016
		0.001	0.001	0.0016	0.0012	0.0025	0.0018
ave		0.00117	0.00097	0.00167	0.00157	0.00257	0.00167
	m						
Pumping Head	m	57	56.75	59.5	56.85	59.4	59.5

Wet Dimensions	m						
Area	m^2	6.65	6.65	6.65	6.65	6.65	6.65
Q_{in}	m^3/s	0.00265	0.00429	0.00442	0.00421	0.00293	0.00202
Q_p	m^3/s	0.01519	0.01495	0.02256	0.01854	0.02025	0.01073
V_p	m/s	0.92	0.91	1.37	1.13	1.23	0.65
K_{losses}		4.8500	4.8500	4.8500	4.8500	4.8500	4.8500
Head Losses	m	0.21030	0.20374	0.46399	0.31332	0.37373	0.10501
Pipe Area	m^2	0.01647	0.01647	0.01647	0.01647	0.01647	0.01647
Pipe Diameter	m	0.1448	0.1448	0.1448	0.1448	0.1448	0.1448
Pipe Length	m	980	980	980	980	980	980
ΔH	m	7.50	6.88	9.43	6.94	9.59	9.83
$\Delta H/L$		0.00766	0.00702	0.00962	0.00708	0.00979	0.01003
Average Temp T	°C	10.5	10.5	10.5	10.5	10.5	10.5
Kinematic Viscosity		1.567E-06	1.567E-06	1.567E-06	1.567E-06	1.567E-06	1.567E-06

Re		8.522E+04	8.388E+04	1.266E+05	1.040E+05	1.136E+05	6.022E+04
Friction Factor, λ		0.025571442	0.02419481	0.01456762	0.01587847	0.01839226	0.06704845
K_s	m	3.023E-04	2.245E-04	-	-	2.30E-05	6.211E-03
K_s	mm	0.30	0.22	-	-	0.02	6.21
Pipe material	ductile iron, OD=170mm, WT=12.6mmm						

More Detailed Minor Loss Calculations

Loss Calculations	*K*	*no.*		1 *$V^2/2g$*	*losses*
globe valve (fully open)	10				
angle valve (fully open)	5				
swing check valve (fully op	2.5				
gate valve (fully open)	0.19				
close return bend	2.2				
standard tee	1.8				
standard elbow	0.9	1	0.9	0.04	0.039
medium sweep elbow	0.75	3	2.25	0.04	0.098
long sweep elbow	0.6	0	0	0.04	0.000
valve (non return)	1.7	1	1.7	0.04	0.074
			4.85		0.210

Additonal head of 1 pipe diameter added to static level to account for changes in level at the discharge location

Summary of Pumping Test Results

Cheddington SPS

	units	2	2	2	2	1	1	1	1
Static Head	m	1.34	1.34	1.34	1.36	1.34	1.21	1.07	1.20
Inflow Rate - dy/dt		0.001538	0.001048	0.000778	0.000678	0.000924	0.000750	0.000614	0.000649
		0.001048	0.000778	0.000678	0.000924	0.000750	0.000614	0.000649	
ave		0.001293	0.000913	0.000728	0.000801	0.000837	0.000682	0.000631	0.000649
Pump Down Rate - dy/dt		0.005618	0.0062	0.0067	0.0067	0.0050	0.0067	0.0065	0.0054
ave		0.0056	0.0062	0.0067	0.0067	0.0050	0.0067	0.0065	0.0054
$\Delta p/\Delta t$									
ave									
Max Head	m								
	m	43.6	44	44	44.2	42	41	41	41

Wet Dimensions	m	2.4	2.4	2.4	2.4	2.4	2.4	2.4	2.4
Area (circular)	m^2	4.52	4.52	4.52	4.52	4.52	4.52	4.52	4.52
Q_{in}	m^3/s	0.00585	0.00413	0.00329	0.00362	0.00379	0.00309	0.00286	0.00293
Q_p	m^3/s	0.03127	0.03206	0.03345	0.03378	0.02641	0.03324	0.03223	0.02752
V_p	m/s	1.899	1.947	2.031	2.051	1.604	2.019	1.957	1.671
K_{losses}		8.450	8.450	8.450	8.450	8.450	8.450	8.450	8.450
Head Losses	m	1.553	1.632	1.777	1.813	1.107	1.755	1.650	1.203
Pipe Area	m^2	0.01647	0.01647	0.01647	0.01647	0.01647	0.01647	0.01647	0.01647
Pipe Diameter	m	0.1448	0.1448	0.1448	0.1448	0.1448	0.1448	0.1448	0.1448
Pipe Length	m	1700	1700	1700	1700	1700	1700	1700	1700
ΔH	m	40.70	41.02	40.88	41.02	39.55	38.03	38.28	38.59
$\Delta H/L$		0.02394	0.02413	0.02405	0.02413	0.02326	0.02237	0.02251	0.02270
Average Temp T	°C	19.5	16.0	16.0	16.0	16.0	16.0	16.0	16.0
Kinematic Viscosity		1.323E-06	1.406E-06	1.406E-06	1.406E-06	1.406E-06	1.406E-06	1.406E-06	1.406E-06

Re		2.078E+05	2.005E+05	2.092E+05	2.113E+05	1.652E+05	2.079E+05	2.016E+05	1.721E+05
Friction Factor, λ		0.018868995	0.01809283	0.01655787	0.0162899	0.02570414	0.01559423	0.0166959	0.0230926
K_s	m	7.585E-05	5.303E-05	1.981E-05	1.496E-05	3.578E-04	1.307E-06	2.077E-05	2.238E-04
K_s	mm	0.076	0.053	0.020	0.015	0.358	0.001	0.021	0.224
pipe material	150mm ductile iron, OD=170mm, WT=12.6								

More Detailed Minor Loss Calculations

Loss Calculations	*K*	*no.*		$V^2/2g$	*losses*
globe valve (fully open)	10				
angle valve (fully open)	5				
swing check valve (fully ope	2.5				
gate valve (fully open)	0.19				
close return bend	2.2				
standard tee	1.8				
standard elbow	0.9	1	0.9	0.18	0.165
medium sweep elbow	0.75	3	2.25	0.18	0.413
long sweep elbow	0.6	6	3.6	0.18	0.661
valve (non return)	1.7	1	1.7	0.18	0.312
			8.45		1.240

An additional one pipe diameter added to the static head to account for level changes at the discharge location

Summary of Pumping Test Results
Church St SPS

	units	1	1	1
Static Head	m	15.42	15.42	15.42
Fill time	s	109	228	202
ave		109	228	202
Pump down time	s	69	45	49
ave		69	45	49
Pump down rate		0.0234	0.0359	0.0329
ave		0.02339	0.03587	0.03294
Discharge head	m			
	m	19.7	20.7	21
Wet Dimensions	m	NA	NA	NA
Area	m^2	5.38	5.38	5.38
Test Volume		1.61	1.61	1.61
Q_{in}	m^3/s	0.01481	0.00708	0.00799
Q_p	m^3/s	0.0382	0.0429	0.0409
V_p	m/s	1.153	1.296	1.235
K_{losses}		10.850	10.850	10.850
Head Losses	m	0.735	0.929	0.844
Pipe Area	m^2	0.03314	0.03314	0.03314
Pipe Diameter	m	0.2054	0.2054	0.2054
Pipe Length	m	620	620	620
ΔH	m	3.55	4.35	4.74
$\Delta H/L$		0.00572	0.00702	0.00764
Average Temp T	^oC	17.0	17.0	17.0
Kinematic Viscosity		1.381E-06	1.381E-06	1.381E-06
Re		1.715E+05	1.928E+05	1.838E+05
Friction Factor, λ		0.017338774	0.016836309	0.020177398
K_s	m	3.687E-05	3.035E-05	1.569E-04
K_s	mm	0.037	0.030	0.157
pipe material		Ductile iron	Ductile iron	Ductile iron
Built	1997			

More Detailed Minor Loss Calculations

Loss Calculations	*K*	*no.*		*$V^2/2g$*	*losses*
globe valve (fully open)	10		0	0.07	0.000
angle valve (fully open)	5		0	0.07	0.000
swing check valve (fully ope	2.5		0	0.07	0.000
gate valve (fully open)	0.19	0	0	0.07	0.000
close return bend	2.2		0	0.07	0.000
standard tee	1.8		0	0.07	0.000
standard elbow	0.9	2	1.8	0.07	0.122
medium sweep elbow	0.75	5	3.75	0.07	0.254
long sweep elbow	0.6	6	3.6	0.07	0.244
valve (non return)	1.7	1	1.7	0.07	0.115
			10.85		0.620

Summary of Pumping Test Results

Dene Hollow SPS

	units	pump 1	pump 2	pump 1	pump 2	pump 1	pump 2	pump 1
Static Head	m	12.60	12.60	12.60	12.60	12.60	12.60	12.60
Inflow Rate - dy/dt		0.0004	0.00043	0.00046	0.00048	0.00036	0.00037	0.00031
		0.00043	0.00046	0.00048	0.00036	0.00037	0.00031	
ave		0.00041692	0.00045	0.00047	0.00042	0.00036	0.00034	0.00031
Pump Down Rate - dy/dt		0.0018	0.0023	0.0020	0.0022	0.0020	0.0025	0.0022
ave		0.0018	0.0023	0.0020	0.0022	0.0020	0.0025	0.0022
$\Delta p/\Delta t$								
ave								
Max Head	m							
	m	22	22	20.4	22	20.4	22	20.4

Wet Dimensions	m							
Area	m^2	2.94	2.94	2.94	2.94	2.94	2.94	2.94
depth of pumping	m	0.5	0.4	0.4	0.4	0.4	0.4	0.4
time to pump	s	220	176	204	178	196	160	178
Q_{in}	m^3/s	0.00122	0.00132	0.00139	0.00124	0.00107	0.00100	0.00093
Q_p	m^3/s	0.00668	0.00668	0.00576	0.00660	0.00599	0.00734	0.00660
V_p	m/s	0.49	0.49	0.42	0.48	0.44	0.54	0.48
K_{losses}		7.2500	7.2500	7.2500	7.2500	7.2500	7.2500	7.2500
Head Losses	m	0.0882	0.0882	0.0657	0.0862	0.0711	0.1067	0.0862
Pipe Area	m^2	0.01366	0.01366	0.01366	0.01366	0.01366	0.01366	0.01366
Pipe Diameter	m	0.1319	0.1319	0.1319	0.1319	0.1319	0.1319	0.1319
Pipe Length	m	2800	2800	2800	2800	2800	2800	2800
ΔH	m	9.31	9.31	7.73	9.31	7.73	9.29	7.71
$\Delta H/L$		0.00332	0.00332	0.00276	0.00333	0.00276	0.00332	0.00275
Average Temp T	°C	16.0	16.0	16.0	16.0	16.0	16.0	16.0
Kinematic Viscosity		1.406E-06	1.406E-06	1.406E-06	1.406E-06	1.406E-06	1.406E-06	1.406E-06

Re		4.584E+04	4.584E+04	3.955E+04	4.533E+04	4.116E+04	5.043E+04	4.533E+04
Friction Factor, λ		0.036	0.036	0.040	0.037	0.037	0.030	0.031
K_s	m	9.965E-04	9.965E-04	1.417E-03	1.078E-03	1.086E-03	4.750E-04	5.187E-04
K_s	mm	1.00	1.00	1.42	1.08	1.09	0.47	0.52
Pipe material	asbestos cement - OD = 149.9, WT = 9mm							

More Detailed Minor Loss Calculations

Loss Calculations	*K*	*no.*		*$V^2/2g$*	*losses*
globe valve (fully open)	10				
angle valve (fully open)	5				
swing check valve (fully o	2.5				
gate valve (fully open)	0.19				
close return bend	2.2				
standard tee	1.8				
standard elbow	0.9	0	0	0.01	0.000
medium sweep elbow	0.75	5	3.75	0.01	0.046
long sweep elbow	0.6	3	1.8	0.01	0.022
valve (non return)	1.7	1	1.7	0.01	0.021
			7.25		0.068

An additonal one pipe diameter has been added to the static head to account for changes to the levels at the discharge location

Summary of Pumping Test Results

Fairmile SPS, Cholsey

	units	pump 1	pump 2	pump 1	pump 2	both
Static Head	m	12.69	12.69	12.69	12.69	12.69
Inflow Rate - dy/dt		0.000512	0.000464	0.0006034	0.0006468	0.0004976
		0.000464	0.0006034	0.0006468	0.0004976	
ave		0.00049	0.00053	0.00063	0.00057	0.00025
Pump Down Rate - dy/dt		0.0029	0.0032	0.0032	0.0031	0.0036
ave		0.0029	0.0032	0.0032	0.0031	0.0036
Δp/Δt		0.0025	0.0039	0.0028	0.0032	0.0048
		0.0025	0.0039	0.0025	0.003	0.0044
ave		0.0025	0.0039	0.00265	0.0031	0.0046
Ave Head	m					
	m	26.8	26.8	26.9	26.9	29.8
length - well bottom to transducer		3.1	3.1			
Wet Well Diameter	m	2.75	2.75	2.75	2.75	2.75
Area	m^2	5.94	5.94	5.94	5.94	5.94
Q_{in}	m^3/s	0.00290	0.00317	0.00371	0.00340	0.00148
Q_p	m^3/s	0.01991	0.02237	0.02258	0.02184	0.02261
V_p	m/s	1.10	1.24	1.25	1.21	1.25
K_{losses}		4.3	4.3	4.3	4.3	4.3
Head Losses	m	0.26529	0.33490	0.34126	0.31917	0.34196
Pipe Area	m^2	0.01810	0.01810	0.01810	0.01810	0.01810
Pipe Diameter	m	0.1518	0.1518	0.1518	0.1518	0.1518
Pipe Length	m	789.7	789.7	789.7	789.7	789.7
ΔH	m	13.84	13.77	13.87	13.89	16.77
ΔH/L		0.01753	0.01744	0.01756	0.01759	0.02123
Average Temp T	°C	22.7	22.7	22.7	22.7	22.7
Kinematic Viscosity		1.258E-06	1.258E-06	1.258E-06	1.258E-06	1.258E-06

Re		1.328E+05	1.492E+05	1.506E+05	1.456E+05	1.507E+05
Friction Factor, λ		0.043130114	0.03399414	0.03358735	0.0359688	0.04052661
K_s	m	0.00215202	1.042E-03	1.002E-03	1.250E-03	1.802E-03
K_s	mm	2.152	1.042	1.002	1.250	1.802
Pipe Material	Steel, OD=159, WT=3.6					

More Detailed Minor Loss Calculations

Loss Calculations	*K*	*no.*		$V^2/2g$	*losses*
globe valve (fully open)	10				
angle valve (fully open)	5				
swing check valve (fully ope	2.5				
gate valve (fully open)	0.19				
close return bend	2.2				
standard tee	1.8				
standard elbow	0.9	1	0.9	0.06	0.056
medium sweep elbow	0.75	0	0	0.06	0.000
long sweep elbow	0.6	0	0	0.06	0.000
valve (non return)	1.7	2	3.4	0.06	0.210
			4.3		0.056

Additional head of one pipe diameter added to static level to account for changes in level at the discharge location

Summary of Pumping Test Results

Freckleton SPS

	units	SW3	SW3	SW2	SW2	SW1	SW1	DWF1
Static Head	m	11.3	11.3	11.3	11.3	11.3	11.3	11.3
Inflow Rate - dy/dt		0.00067	0.00067	0.00042	0.00060	0.00059	0.00056	0.00084
		0.00067	0.00042	0.00060	0.00059	0.00056	0.00084	
ave		0.00067	0.00054	0.00051	0.00060	0.00058	0.00070	0.00084
Pump Down Rate - dy/dt		0.00078	0.0009	0.0011	0.0011	0.0010	0.0023	0.0025
ave		0.00078	0.0009	0.0011	0.0011	0.0010	0.0023	0.0025
$\Delta p/\Delta t$								
ave								
Max Head	m							
	m	15	14.5	14.5	15.5	16	15.8	16

Wet Dimensions	m	67	58	56	62	65	44	39
Area (rectangular)	m^2	168	158	133	155	188	97	91
Q_{in}	m^3/s	0.11182	0.08599	0.06786	0.09238	0.10826	0.06775	0.07621
Q_p	m^3/s	0.24166	0.22196	0.21968	0.26384	0.30168	0.29544	0.30146
V_p	m/s	0.909	0.835	0.826	0.992	1.135	1.111	1.134
K_{losses}		14.3	14.3	14.3	14.3	14.3	14.3	14.3
Head Losses	m	0.601	0.507	0.497	0.716	0.937	0.898	0.935
Pipe Area	m^2	0.26585	0.26585	0.26585	0.26585	0.26585	0.26585	0.26585
Pipe Diameter	m	0.5818	0.5818	0.5818	0.5818	0.5818	0.5818	0.5818
Pipe Length	m	2450	2450	2450	2450	2450	2450	2450
ΔH	m	3.10	2.69	2.70	3.48	3.76	3.60	3.76
$\Delta H/L$		0.00126	0.00110	0.00110	0.00142	0.00154	0.00147	0.00154
Average Temp T	°C	20.0	16.0	16.0	16.0	16.0	16.0	16.0
Kinematic Viscosity		1.312E-06	1.406E-06	1.406E-06	1.406E-06	1.406E-06	1.406E-06	1.406E-06

Re		4.031E+05	3.455E+05	3.420E+05	4.107E+05	4.696E+05	4.599E+05	4.693E+05
Friction Factor, λ		0.017474029	0.018000154	0.0184456	0.01647979	0.01361718	0.01358756	0.0136413
K_s	m	2.545E-04	2.881E-04	3.328E-04	1.722E-04	1.318E-05	9.789E-06	1.418E-05
K_s	mm	0.255	0.288	0.333	0.172	0.013	0.010	0.014
pipe material	PE100 SDR-26							

More Detailed Minor Loss Calculations

Loss Calculations	*K*	*no.*		$V^2/2g$	*losses*
globe valve (fully open)	10				
angle valve (fully open)	5				
swing check valve (fully ope	2.5				
gate valve (fully open)	0.19	3	0.57		
close return bend	2.2				
standard tee	1.8				
standard elbow	0.9	6	5.4	0.04	0.227
medium sweep elbow	0.75	4	3	0.04	0.126
long sweep elbow	0.6	6	3.6	0.04	0.152
valve (non return)	1.7	1	1.7	0.04	0.072
			14.27		0.505

Summary of Pumping Test Results

South End SPS, Garsington

	units	both	pump 2	pump 1	pump 2
Static Head	m	23.55	23.99	24.78	24.14
Inflow Rate - dy/dt		0.00069	0.00055	0.000537	0.00052
		0.00055	0.000537	0.00052	
ave		0.00062	0.0005435	0.0005285	0.00052
Pump Down Rate - dy/dt		0.00135	0.00158	0.0016	0.00165
ave		0.00135	0.00158	0.0016	0.00165
Δp/Δt		0.0009	0.0018	0.0014	0.0019
		0.001	0.0022	0.0014	0.0015
		0.001	0.002	0.0012	0.0019
ave		0.00097	0.00200	0.00133	0.00177
Max Head	m	30.75	30.75	31.5	31.2

Wet Dimensions	m	2	2	2	2
Area	m^2	3.14	3.14	3.14	3.14
Q_{in}	m^3/s	0.00195	0.00171	0.00166	0.00163
Q_p	m^3/s	0.00619	0.00667	0.00669	0.00682
V_p	m/s	0.740	0.798	0.799	0.815
K_{losses}		4.100	4.100	4.100	4.100
Head Losses - bends	m	0.114	0.133	0.134	0.139
Pipe Area	m^2	0.00836	0.00836	0.00836	0.00836
Pipe Diameter	m	0.1032	0.1032	0.1032	0.1032
Pipe Length	m	950	950	950	950
ΔH	m	7.08	6.63	6.58	6.92
ΔH/L		0.00746	0.00698	0.00693	0.00729
Average Temp T	°C	14.0	14.0	14.0	14.0
Kinematic Viscosity		1.460E-06	1.460E-06	1.460E-06	1.460E-06

Re		5.230E+04	5.638E+04	5.651E+04	5.761E+04
Friction Factor, λ		0.027574143	0.0222121	0.02195569	0.02221409
K_s	m	2.626E-04	5.474E-05	4.691E-05	5.726E-05
K_s	mm	0.263	0.055	0.047	0.057
pipe material	upvc - metric PN8 (assume OD = 110mm, WT=3.4)				

More Detailed Minor Loss Calculations

Loss Calculations	*K*	*no.*		$V^2/2g$	*losses*
globe valve (fully open)	10				
angle valve (fully open)	5				
swing check valve (fully ope	2.5				
gate valve (fully open)	0.19				
close return bend	2.2				
standard tee	1.8				
standard elbow	0.9	1	0.9	0.03	0.025
medium sweep elbow	0.75	2	1.5	0.03	0.042
long sweep elbow	0.6	0	0	0.03	0.000
valve (non return)	1.7	1	1.7	0.03	0.047
			4.1		0.114

An additonal one pipe diameter of head added to the static head value to account for level changes at the discharge location

Summary of Pumping Test Results

Great Coxwell SPS

	units	1	2	1	2	1	2
Static Head	m	19.43	19.38	19.32	19.26	19.29	19.25
Inflow Rate - dy/dt		0.0003	0.00023	0.00019	0.00018	0.00025	0.00025
		0.00023	0.00019	0.00018	0.00025	0.00025	
ave		0.000265	0.00021	0.000185	0.000215	0.00025	0.00025
Pump Down Rate - dy/dt		0.005	0.0057	0.0060	0.0057	0.0060	0.0057
ave		0.005	0.0057	0.0060	0.0057	0.0060	0.0057
Δp/Δt		0.0049			0.0136		0.0108
		0.0014			0.0253		0.0038
		0.0038					0.0307
ave		0.00337			0.01945		0.01510
Max Head	m						
	m	48.5	47.7	48.5	47.75	48.3	48

Wet Dimensions	m	1.8	1.8	1.8	1.8	1.8	1.8
Area (circular)	m^2	2.54	2.54	2.54	2.54	2.54	2.54
Q_{in}	m^3/s	0.00067	0.00053	0.00047	0.00055	0.00064	0.00064
Q_p	m^3/s	0.01340	0.01499	0.01562	0.01501	0.01578	0.01509
V_p	m/s	1.048	1.172	1.221	1.173	1.234	1.180
K_{losses}		3.150	3.150	3.150	3.150	3.150	3.150
Head Losses	m	0.176	0.221	0.239	0.221	0.245	0.224
Pipe Area	m^2	0.01279	0.01279	0.01279	0.01279	0.01279	0.01279
Pipe Diameter	m	0.1276	0.1276	0.1276	0.1276	0.1276	0.1276
Pipe Length	m	1445	1445	1445	1445	1445	1445
ΔH	m	28.89	28.10	28.94	28.27	28.77	28.53
ΔH/L		0.01999	0.01944	0.02003	0.01956	0.01991	0.01974
Average Temp T	°C	16.0	16.0	16.0	16.0	16.0	16.0
Kinematic Viscosity		1.406E-06	1.406E-06	1.406E-06	1.406E-06	1.406E-06	1.406E-06

Re		9.510E+04	1.064E+05	1.109E+05	1.065E+05	1.120E+05	1.071E+05
Friction Factor, λ		0.045597417	0.03541206	0.03361791	0.03557175	0.03271784	0.03547323
K_s	m	2.098E-03	9.835E-04	8.292E-04	9.981E-04	7.560E-04	9.894E-04
K_s	mm	2.098	0.983	0.829	0.998	0.756	0.989
pipe material	upvc, OD=140.2, WT=6.3*2, Class C						

More Detailed Minor Loss Calculations

Loss Calculations	*K*	*no.*		*$V^2/2g$*	*losses*
globe valve (fully open)	10				
angle valve (fully open)	5				
swing check valve (fully op	2.5				
gate valve (fully open)	0.19				
close return bend	2.2				
standard tee	1.8				
standard elbow	0.9	1	0.9	0.06	0.050
medium sweep elbow	0.75	3	2.25	0.06	0.126
long sweep elbow	0.6	0	0	0.06	0.000
valve (non return)	1.7	0	0	0.06	0.000
			3.15		0.176

An additional head of 1 pipe diameter has been added to the static level to account for changes in level at the discharge location

Summary of Pumping Test Results

Hebden Green SPS

	units	1	1	1	2	2	2
Static Head	m	1.22	1.22	1.22	1.22	1.22	1.22
Fill time	s						
ave							
Pump down time	s	27	28	27	75	71	74
ave		27	28	27	75	71	74
Pump down rate		0.0250	0.0241	0.0250	0.0090	0.0095	0.0091
ave		0.02496	0.02407	0.02496	0.00899	0.00949	0.00911
Discharge head	m						
	m	9	9	9	4.5	4.5	4.5

Wet Dimensions	m	NA	NA	NA	NA	NA	NA
Area (circular)	m^2	2.25	2.25	2.25	2.25	2.25	2.25
Test Volume		0.67	0.67	0.67	0.67	0.67	0.67
Q_{in}	m^3/s						
Q_p	m^3/s	0.02496	0.02407	0.02496	0.00899	0.00949	0.00911
V_p	m/s	1.234	1.190	1.234	0.444	0.469	0.450
K_{losses}		6.690	6.690	6.690	6.690	6.690	6.690
Head Losses	m	0.519	0.483	0.519	0.067	0.075	0.069
Pipe Area	m^2	0.02023	0.02023	0.02023	0.02023	0.02023	0.02023
Pipe Diameter	m	0.1605	0.1605	0.1605	0.1605	0.1605	0.1605
Pipe Length	m	382	382	382	382	382	382
ΔH	m	7.26	7.30	7.26	3.21	3.20	3.21
$\Delta H/L$		0.01901	0.01910	0.01901	0.00841	0.00839	0.00841
Average Temp T	°C	17.0	18.0	19.0	16.2	16.8	14.5
Kinematic Viscosity		1.381E-06	1.357E-06	1.334E-06	1.401E-06	1.386E-06	1.446E-06

Re		1.434E+05	1.408E+05	1.485E+05	5.090E+04	5.435E+04	4.997E+04
Friction Factor, λ		0.039317836	0.042496269	0.039317836	0.1342354	0.12000696	0.1306052
K_s	m	1.739E-03	2.184E-03	1.741E-03	2.563E-02	2.137E-02	2.454E-02
K_s	mm	1.739	2.184	1.741	25.633	21.375	24.539
pipe material		cast iron	cast iron	cast iron	cast iron	cast iron	cast iron
Built	circa 1982						

More Detailed Minor Loss Calculations

Loss Calculations	*K*	*no.*				*$V^2/2g$*	*losses*
globe valve (fully open)	10				0	0.08	0.000
angle valve (fully open)	5				0	0.08	0.000
swing check valve (fully op	2.5				0	0.08	0.000
gate valve (fully open)	0.19	1			0.19	0.08	0.015
close return bend	2.2				0	0.08	0.000
standard tee	1.8				0	0.08	0.000
standard elbow	0.9	3			2.7	0.08	0.209
medium sweep elbow	0.75	2			1.5	0.08	0.116
long sweep elbow	0.6	1			0.6	0.08	0.047
valve (non return)	1.7	1			1.7	0.08	0.132
					6.69		0.387

Summary of Pumping Test Results

Heskin Lane SPS

	units	1	2
Static Head	m	6.4	6.4
Fill time	s		
ave			
Pump down time	s		
ave			
Pump down rate			
ave			
Discharge head	m		
	m	16.1	16.8
Wet Dimensions	m		
Area (circular)	m^2		
Test Volume			
Q_{in}	m^3/s		
Q_p	m^3/s	0.0449	0.0474
V_p	m/s	2.228	2.352
K_{losses}		4.140	4.140
Head Losses	m	1.047	1.167
Pipe Area	m^2	0.02016	0.02016
Pipe Diameter	m	0.1602	0.1602
Pipe Length	m	215	215
ΔH	m	8.65	9.23
$\Delta H/L$		0.04025	0.04294
Average Temp T	°C	17.0	18.0
Kinematic Viscosity		1.381E-06	1.357E-06
Re		2.585E+05	2.777E+05
Friction Factor, λ		0.025493224	0.024408686
K_s	m	4.029E-04	3.403E-04
K_s	mm	0.403	0.340
pipe material		cast iron	cast iron
Built	1960s		

More Detailed Minor Loss Calculations

Loss Calculations	*K*	*no.*			*$V^2/2g$*	*losses*
globe valve (fully open)	10			0	0.25	0.000
angle valve (fully open)	5			0	0.25	0.000
swing check valve (fully ope	2.5			0	0.25	0.000
gate valve (fully open)	0.19	1		0.19	0.25	0.048
close return bend	2.2			0	0.25	0.000
standard tee	1.8			0	0.25	0.000
standard elbow	0.9	1		0.9	0.25	0.228
medium sweep elbow	0.75	1		0.75	0.25	0.190
long sweep elbow	0.6	1		0.6	0.25	0.152
valve (non return)	1.7	1		1.7	0.25	0.430
				4.14		0.617

Summary of Pumping Test Results

Highway Lane SPS

	units	1	1	1	2
Static Head	m	14.65	14.65	14.65	14.65
Fill time	s	1713	1743	1738	1779
ave		1713	1743	1738	1779
Pump down time	s	255	246	250	222
ave		255	246	250	222
Pump down rate		0.0090	0.0094	0.0092	0.0104
ave		0.00905	0.00938	0.00923	0.01039
Discharge head	m				
	m	23.4	23.4	23.4	22.3
Wet Dimensions	m	NA	NA	NA	3.1
Area (circular)	m^2	7.69	7.69	7.69	7.69
Test Volume		2.31	2.31	2.31	2.31
Q_{in}	m^3/s	0.00135	0.00132	0.00133	0.00130
Q_p	m^3/s	0.0104	0.0107	0.0106	0.0117
V_p	m/s	1.047	1.079	1.064	1.178
K_{losses}		4.990	4.990	4.990	4.990
Head Losses	m	0.279	0.296	0.288	0.353
Pipe Area	m^2	0.00992	0.00992	0.00992	0.00992
Pipe Diameter	m	0.1124	0.1124	0.1124	0.1124
Pipe Length	m	620	620	620	620
ΔH	m	8.47	8.45	8.46	7.30
$\Delta H/L$		0.01366	0.01364	0.01365	0.01177
Average Temp T	°C	17.0	17.0	17.0	17.0
Kinematic Viscosity		1.381E-06	1.381E-06	1.381E-06	1.381E-06
Re		8.528E+04	8.780E+04	8.661E+04	9.590E+04
Friction Factor, λ		0.0274599	0.025851714	0.026598249	0.01870405
K_s	m	3.266E-04	2.497E-04	2.843E-04	1.228E-05
K_s	mm	0.327	0.250	0.284	0.012
pipe material		cast iron	cast iron	cast iron	cast iron
Built	circa 1959				

More Detailed Minor Loss Calculations

Loss Calculations	*K*	*no.*			$V^2/2g$	*losses*
globe valve (fully open)	10				0.06	0.000
angle valve (fully open)	5				0.06	0.000
swing check valve (fully ope	2.5				0.06	0.000
gate valve (fully open)	0.19	1			0.06	0.011
close return bend	2.2				0.06	0.000
standard tee	1.8				0.06	0.000
standard elbow	0.9	3			0.06	0.151
medium sweep elbow	0.75	2			0.06	0.084
long sweep elbow	0.6	1			0.06	0.034
valve (non return)	1.7	0			0.06	0.000
						0.279

Summary of Pumping Test Results

Lea Gate SPS

	units	DWF1	DWF1	DWF2	DWF2	DWF3	DWF3	DWF4	DWF4
Static Head	m	6.198	6.198	6.198	6.198	6.198	6.198	6.198	6.198
Inflow Rate - dy/dt		0	0	0	0	0	0	0	0
ave		0	0	0	0	0	0	0	0
Pump Down Rate - dy/dt		0.0070	0.0074	0.0075	0.0078	0.0074	0.0081	0.0067	0.0072
ave		0.0070	0.0074	0.0075	0.0078	0.0074	0.0081	0.0067	0.0072
$\Delta p/\Delta t$									
ave		#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Max Head	m								
	m	10	10	10	10	10	10	10	10

Wet Dimensions	m	11.27	11.13	11.1	10.9	11.25	10.8	11.4	11.25
Area (approx equiv circular)	m^2	99.76	97.29	96.77	93.31	99.40	91.61	102.07	99.40
Q_{in}	m^3/s	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Q_p	m^3/s	0.70250	0.71539	0.72759	0.72901	0.73090	0.73878	0.68047	0.71512
V_p	m/s	0.876	0.892	0.907	0.909	0.911	0.921	0.848	0.892
K_{bend}		14.470	14.470	14.470	14.470	14.470	14.470	14.470	14.470
Head Losses - bends	m	0.566	0.587	0.607	0.609	0.612	0.626	0.531	0.586
Pipe Area	m^2	0.80214	0.80214	0.80214	0.80214	0.80214	0.80214	0.80214	0.80214
Pipe Diameter	m	1.0106	1.0106	1.0106	1.0106	1.0106	1.0106	1.0106	1.0106
Pipe Length	m	3600	3600	3600	3600	3600	3600	3600	3600
ΔH	m	3.24	3.22	3.20	3.19	3.19	3.18	3.27	3.22
$\Delta H/L$		0.00090	0.00089	0.00089	0.00089	0.00089	0.00088	0.00091	0.00089
Average Temp T	°C	20.0	20.0	20.0	20.0	20.0	20.0	20.0	20.0
Kinematic Viscosity		1.312E-06	1.312E-06	1.312E-06	1.312E-06	1.312E-06	1.312E-06	1.312E-06	1.312E-06

Re		6.746E+05	6.870E+05	6.987E+05	7.001E+05	7.019E+05	7.094E+05	6.534E+05	6.867E+05
Friction Factor, λ		0.023239424	0.022265	0.02138963	0.02129035	0.02115956	0.0206241	0.0250363	0.02228455
K_s	m	1.877E-03	1.580E-03	1.337E-03	1.311E-03	1.278E-03	1.145E-03	2.503E-03	1.585E-03
K_s	mm	1.877	1.580	1.337	1.311	1.278	1.145	2.503	1.585
pipe material	cement mortor lined Ductile Iron, OD=1048mm								

More Detailed Minor Loss Calculations

Loss Calculations	*K*	*no.*		*$V^2/2g$*	*losses*
globe valve (fully open)	10				
angle valve (fully open)	5				
swing check valve (fully open	2.5				
gate valve (fully open)	0.19	8	1.52		
close return bend	2.2				
standard tee	1.8				
standard elbow	0.9	6	5.4	0.04	0.211
medium sweep elbow	0.75	3	2.25	0.04	0.088
long sweep elbow	0.6	6	3.6	0.04	0.141
valve (non return)	1.7	1	1.7	0.04	0.066
			14.47		0.440

Summary of Pumping Test Results

Nether Winchendon SPS

	units	2	1	2	1	both
Static Head	m	2.681	3.05	2.96	3.316	4.171
Inflow Rate - dy/dt		0.00020	0.00021	0.00014	0.00018	0.00015
		0.00021	0.00014	0.00018	0.00015	
ave		0.00020	0.00017	0.00016	0.00016	0.00015
Pump Down Rate - dy/dt		0.00320	0.00330	0.00334	0.00333	0.00344
		0.00319	0.00333			
ave		0.0032	0.0033	0.0033	0.0033	0.0034
Δp/Δt		0.004	0.0039	0.0045	0.0055	0.0043
		0.003	0.004	0.0044	0.0071	0.0006
		0.0022	0.0042	0.0036		0.0013
ave		0.00307	0.00403	0.00417	0.00630	0.00207
Max Head	m					
	m	21.5	21.8	21.5	21.6	22.55

Wet Dimensions	m	1.8	1.8	1.8	1.8	1.8
Area (circular)	m^2	2.54	2.54	2.54	2.54	2.54
Q_{in}	m^3/s	0.00051	0.00044	0.00040	0.00042	0.00039
Q_p	m^3/s	0.00864	0.00887	0.00890	0.00889	0.00916
V_p	m/s	1.078	1.108	1.111	1.110	1.143
K_{losses}		8.250	8.250	8.250	8.250	8.250
Head Losses	m	0.489	0.516	0.519	0.518	0.549
Pipe Area	m^2	0.00801	0.00801	0.00801	0.00801	0.00801
Pipe Diameter	m	0.101	0.101	0.101	0.101	0.101
Pipe Length	m	904	904	904	904	904
ΔH	m	18.33	18.24	18.03	17.77	17.83
ΔH/L		0.02028	0.02017	0.01994	0.01965	0.01972
Average Temp T	°C	17.5	16.2	16.8	14.5	13.0
Kinematic Viscosity		1.368E-06	1.401E-06	1.386E-06	1.446E-06	1.489E-06

Re		7.959E+04	7.987E+04	8.096E+04	7.755E+04	7.752E+04
Friction Factor, λ		0.034553559	0.03257759	0.03203235	0.0315987	0.02992689
K_s	m	7.018E-04	5.708E-04	5.377E-04	5.084E-04	4.123E-04
K_s	mm	0.702	0.571	0.538	0.508	0.412
pipe material	MDPE, 125mm SDR11					

More Detailed Minor Loss Calculations

Loss Calculations	*K*	*no.*		*$V^2/2g$*	*losses*
globe valve (fully open)	10				
angle valve (fully open)	5				
swing check valve (fully ope	2.5				
gate valve (fully open)	0.19				
close return bend	2.2				
standard tee	1.8				
standard elbow	0.9	1	0.9	0.06	0.053
medium sweep elbow	0.75	5	3.75	0.06	0.222
long sweep elbow	0.6	6	3.6	0.06	0.213
valve (non return)	1.7	0	0	0.06	0.000
			8.25		0.489

for the static head calculation an additonal head of 1 pipe diameter has been added to account for changes in level at the discharge point

Summary of Pumping Test Results

Stadhampton SPS

	units	1	1	1	1	1	1 & 2	2
Static Head	m	2.93	2.59	1.79	1.20	0.69	1.13	1.00
Inflow Rate - dy/dt		0.0007	0.0009	0.0011	0.0011	0.0010	0.0011	0.0011
		0.0009	0.0011	0.0011	0.0010	0.0011	0.0011	
ave		0.0008	0.0010	0.0011	0.0011	0.0011	0.0011	0.0011
Pump Down Rate - dy/dt		0.0014	0.0014	0.0013	0.0013	0.0013	0.0012	0.0013
		0.0015	0.0014	0.0013	0.0013	0.0013	0.0012	0.0013
ave		0.0014	0.0014	0.0013	0.0013	0.0013	0.0012	0.0013
$\Delta p/\Delta t$		0.0006	0.0007	0.0011	0.0008	0.001	0.001	0.0007
		0.0007	0.0007	0.0011	0.0009	0.001	0.0009	0.0007
		0.0006	0.0007	0.001	0.0008	0.001	0.0009	0.0007
ave		0.00063	0.00070	0.00107	0.00083	0.00100	0.00093	0.00070
Average Head	m							
	m	12.5	12.6	12.55	12.5	12.56	13.75	12.7

Wet Dimensions	m	1.8	1.8	1.8	1.8	1.8	1.8	1.8
Area (circular)	m^2	2.54	2.54	2.54	2.54	2.54	2.54	2.54
Q_{in}	m^3/s	0.00203	0.00251	0.00277	0.00269	0.00274	0.00281	0.00273
Q_p	m^3/s	0.00568	0.00610	0.00613	0.00596	0.00595	0.00588	0.00607
V_p	m/s	0.696	0.747	0.751	0.730	0.729	0.720	0.743
K_{losses}		5.100	5.100	5.100	5.100	5.100	5.100	5.100
Head Losses	m	0.126	0.145	0.147	0.139	0.138	0.135	0.144
Pipe Area	m^2	0.00817	0.00817	0.00817	0.00817	0.00817	0.00817	0.00817
Pipe Diameter	m	0.102	0.102	0.102	0.102	0.102	0.102	0.102
Pipe Length	m	780	780	780	780	780	780	780
ΔH	m	9.44	9.86	10.62	11.16	11.73	12.49	11.56
$\Delta H/L$		0.01211	0.01265	0.01361	0.01431	0.01503	0.01601	0.01482
Average Temp T	°C	10.9	10.9	10.9	10.9	10.9	10.9	10.9
Kinematic Viscosity		1.554E-06	1.553E-06	1.553E-06	1.553E-06	1.553E-06	1.553E-06	1.553E-06

Re		4.566E+04	4.903E+04	4.930E+04	4.794E+04	4.785E+04	4.726E+04	4.882E+04
Friction Factor, λ		0.0501	0.0454	0.0483	0.0537	0.0567	0.0619	0.0537
K_s	m	2.111E-03	1.613E-03	1.924E-03	2.551E-03	2.919E-03	3.615E-03	2.545E-03
K_s	mm	2.111	1.613	1.924	2.551	2.919	3.615	2.545
pipe material	cast iron, OD=122mm, WT=15.2							

More Detailed Minor Loss Calculations

Loss Calculations	*K*	*no.*		$V^2/2g$	*losses*
globe valve (fully open)	10				
angle valve (fully open)	5				
swing check valve (fully open)	2.5				
gate valve (fully open)	0.19				
close return bend	2.2				
standard tee	1.8				
standard elbow	0.9	2	1.8	0.02	0.044
medium sweep elbow	0.75	2	1.5	0.02	0.037
long sweep elbow	0.6	3	1.8	0.02	0.044
valve (non return)	1.7	0	0	0.02	0.000
			5.1		0.126

An additional head of 1 pipe diameter has been added to the static head to acccount for changes to the water level at the discharge location

Summary of Pumping Test Results

Dell SPS

	units	1	1	1	2	2	2	2&1	2&1	2&1
Static Head	m	17.24	17.24	17.24	17.24	17.24	17.24	17.24	17.24	17.24
Fill time	s	843	802	751	798	852	831	691	740	782
ave		843	802	751	798	852	831	691	740	782
Pump down time	s	210	215	217	229	214	213	105	108	110
ave		210	215	217	229	214	213	105	108	110
Pump down rate		0.0037	0.0036	0.0036	0.0034	0.0036	0.0037	0.0074	0.0072	0.0071
ave		0.00371	0.00363	0.00359	0.00341	0.00364	0.00366	0.00743	0.00722	0.00709
Discharge head	m									
	m	23.6	23.6	23.6	23.3	23.6	23.6	29.3	29.3	29.3

Wet Dimensions	m	600x450	600x451	600x452	600x453	600x454	600x455	600x456	600x457	600x458
Area (circular)	m^2	2.60	2.60	2.60	2.60	2.60	2.60	2.60	2.60	2.60
Test Volume		0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78	0.78
Q_{in}	m^3/s	0.00093	0.00097	0.00104	0.00098	0.00092	0.00094	0.00113	0.00105	0.00100
Q_p	m^3/s	0.00464	0.00460	0.00463	0.00438	0.00456	0.00460	0.00856	0.00828	0.00809
V_p	m/s	0.905	0.898	0.904	0.856	0.890	0.898	1.670	1.615	1.579
K_{losses}		5.970	5.970	5.970	5.970	5.970	5.970	5.970	5.970	5.970
Head Losses	m	0.249	0.245	0.249	0.223	0.241	0.245	0.849	0.794	0.758
Pipe Area	m^2	0.00512	0.00512	0.00512	0.00512	0.00512	0.00512	0.00512	0.00512	0.00512
Pipe Diameter	m	0.08077	0.08077	0.08077	0.08077	0.08077	0.08077	0.08077	0.08077	0.08077
Pipe Length	m	233	233	233	233	233	233	233	233	233
ΔH	m	6.11	6.11	6.11	5.84	6.12	6.11	11.21	11.27	11.30
$\Delta H/L$		0.02623	0.02624	0.02623	0.02505	0.02626	0.02624	0.04812	0.04835	0.04851
Average Temp T	°C	17.0	18.0	19.0	16.2	16.8	14.5	14.5	14.5	14.5
Kinematic Viscosity		1.381E-06	1.357E-06	1.334E-06	1.401E-06	1.386E-06	1.446E-06	1.446E-06	1.446E-06	1.446E-06

Re		5.297E+04	5.346E+04	5.476E+04	4.933E+04	5.188E+04	5.016E+04	9.329E+04	9.023E+04	8.818E+04
Friction Factor, λ		0.050687251	0.051587304	0.050834642	0.05424139	0.05253562	0.0515844	0.02733675	0.02936817	0.03084599
K_s	m	1.739E-03	1.823E-03	1.755E-03	2.071E-03	1.910E-03	1.818E-03	2.347E-04	3.136E-04	3.778E-04
K_s	mm	1.739	1.823	1.755	2.071	1.910	1.818	0.235	0.314	0.378
pipe material		cast iron	cast iron	cast iron	cast iron	cast iron	cast iron	cast iron	cast iron	cast iron
Built	circa 1971									

More Detailed Minor Loss Calculations

Loss Calculations	*K*	*no.*				$V^2/2g$	*losses*
globe valve (fully open)	10				0	0.04	0.000
angle valve (fully open)	5				0	0.04	0.000
swing check valve (fully ope	2.5				0	0.04	0.000
gate valve (fully open)	0.19	3			0.57	0.04	0.024
close return bend	2.2				0	0.04	0.000
standard tee	1.8				0	0.04	0.000
standard elbow	0.9	3			2.7	0.04	0.113
medium sweep elbow	0.75	2			1.5	0.04	0.063
long sweep elbow	0.6	2			1.2	0.04	0.050
valve (non return)	1.7	0			0	0.04	0.000
					5.97		0.249

Summary of Pumping Test Results

Whitchurch Hill SPS, Whitchurch Hill

	units	1	2	1	2	1	2	1
Static Head	m	12.66	12.66	12.65	12.65	12.65	12.66	12.42
Inflow Rate - dy/dt		0.00044	0.00040	0.00037	0.00048	0.00040	0.00032	0.00027
		0.00040	0.00037	0.00048	0.00040	0.00032	0.00027	
ave		0.0004	0.0004	0.0004	0.0004	0.0004	0.0003	0.0003
Pump Down Rate - dy/dt		0.0012						
		0.0013						
ave		0.00125	0.0011	0.0011908	0.0012303	0.0011423	0.0012846	0.0013048
$\Delta p/\Delta t$		0.002						
		0.0023						
ave		0.00215	0.002	0.0017	0.00135	0.0013	0.0023	0.0021
Max Head	m	24.75						
	m	24	23.75	22.75	22.75	22.5	22.9	23

Wet Dimensions	m							
Area	m^2	3.65	3.65	3.65	3.65	3.65	3.65	3.65
Q_{in}	m^3/s	0.00153	0.00141	0.00136	0.00160	0.00131	0.00107	0.00098
Q_p	m^3/s	0.00610	0.00542	0.00570	0.00609	0.00548	0.00576	0.00574
V_p	m/s	0.68	0.60	0.63	0.68	0.61	0.64	0.64
K_{losses}		9.800	9.800	9.800	9.800	9.800	9.800	9.800
Head Losses	m	0.229	0.181	0.200	0.228	0.185	0.204	0.203
Pipe Area	m^2	0.00901	0.00901	0.00901	0.00901	0.00901	0.00901	0.00901
Pipe Diameter	m	0.1071	0.1071	0.1071	0.1071	0.1071	0.1071	0.1071
Pipe Length	m	1440	1440	1440	1440	1440	1440	1440
ΔH	m	11.11	10.91	9.90	9.87	9.67	10.04	10.38
$\Delta H/L$		0.00772	0.00758	0.00688	0.00686	0.00671	0.00697	0.00721
Average Temp T	°C	17.0	22.7	22.7	22.7	22.7	22.7	22.7
Kinematic Viscosity		1.382E-06	1.258E-06	1.258E-06	1.258E-06	1.258E-06	1.258E-06	1.258E-06

Re		5.247E+04	5.125E+04	5.389E+04	5.756E+04	5.181E+04	5.442E+04	5.423E+04
Friction Factor, λ		0.035396624	0.04394196	0.03607273	0.03152265	0.03809971	0.03585719	0.03732188
K_s	m	7.731E-04	1.544E-03	8.285E-04	5.091E-04	9.918E-04	8.125E-04	9.305E-04
K_s	mm	0.773	1.544	0.829	0.509	0.992	0.812	0.931
Pipe Material	assume steel, ND = 100mm, OD=114.3, WT = 3.6mm							

More Detailed Minor Loss Calculations

Loss Calculations	*K*	*no.*		*$V^2/2g$*	*losses*
globe valve (fully open)	10				
angle valve (fully open)	5				
swing check valve (fully op	2.5				
gate valve (fully open)	0.19				
close return bend	2.2				
standard tee	1.8				
standard elbow	0.9	1	0.9	0.02	0.021
medium sweep elbow	0.75	4	3	0.02	0.070
long sweep elbow	0.6	7	4.2	0.02	0.098
valve (non return)	1.7	1	1.7	0.02	0.040
			9.8		0.189

Additional head of 1 pipe diameter added to account for changing head levels at the discharge location.