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Head loss increase in service lines with time – With examples from Asker municipality

Akram Yousefi
Water and environmental engineering

Foreword

The present master thesis is written alongside Science and Technology faculty of Norwegian university of life sciences (NMBU). Main supervisor for the thesis was Vegard Nilsen (NMBU).

Thesis performed in cooperation with Asker municipality, where Gjermund Deggerdal has been supervisor. Asker municipality set up office, computer and software for this thesis. The goal for the thesis has been to evaluate effect of age of pipes on head loss.

At the end, I would like to thank my supervisor and all who helped on this thesis.

Norwegian University of life science

Ås, 15 May 2019

Akram Yousefi

ABSTRACT

There are several challenges when it comes to analyze the pressure situation in service lines, such as roughness and inner diameter of pipes, water flow rate through pipe and the pressure loss at tapping sleeves.

Roughness and inner diameter of some pipes will change over time as a result of processes between the inner side of pipe walls and water flowing through pipes. Water demand for garden irrigation and expected maximum demand are the critical demands which hydraulic system is required to provide for residents. Another challenge is to analyze the pressure loss at tapping sleeves.

The goal for this thesis is to analyze the effect of these parameters on pressure loss. In this thesis consists of two main parts: theoretical part, and simulation of the hydraulic model and analyzing the results.

Reduction of inner diameter in aged iron-based pipes, such as galvanized steel or cast-iron pipe is complicated. This thesis assumed that 50 % reduction of diameter in galvanized pipes and cast-iron pipes in 50 years, could be a proper estimation. Reduction in diameter for other types of material is neglectable.

Although the effect of local pressure loss on total pressure loss was investigated, but it was not possible to clarify how the local pressure loss coefficient is defined in Aquis. Loss coefficient is presented in graphs based on the ratio of cutout diameter and main branch diameter.

By comparing result in different scenario, for iron-based pipes, it was concluded that the effect of diameter changes on pressure loss (both friction loss and local pressure loss) is considerable. For other type of material, flow rate changes are most decisive parameter causing pressure loss.

Reduction of diameter in galvanized steel pipe, which was widely used in service lines, and also in cutout hole of tapping sleeves, are mostly the result of chemical or physical process inside pipes. This thesis made a hypothesis of 50 % diameter reduction in 50 years for galvanized pipe and cast-iron pipes. More reliable estimation requires further studies. Collecting data and statistical sample of old galvanized steel pipe for “probability estimation” could be a starting point.

TABLE OF CONTENTS

Table of figure

Table of tables

1 INTRODUCTION

Hydraulic water distribution systems’ (WDS) simulation models are often used to verify pipelines and system capacity. Modell-based analysis of water distribution system is important to provide the proper pressure for consumers but not typically include service lines. Pipes roughness and inner diameter are two decisive parameters to analyze friction loss. These parameters will change with time, so when analyzing pressure loss in old pipes, effect of time in these parameters is important.

1.1 Background:

Ssummer 2018, there was a several complaints from Asker residents about low water pressure due to garden irrigation and increased water consumption. In order to provide the proper pressure at receivers like home, gardens and in general private users, it was decided to consider adding service lines to municipality’s model, which are not normally included at a typical municipality’s model. Pressure loss happens along the flow in pipes because of friction forces and also in different situation when velocity or direction of the flow may change along the pipe. This paper is an effort to predict pressure loss in different possible situations.

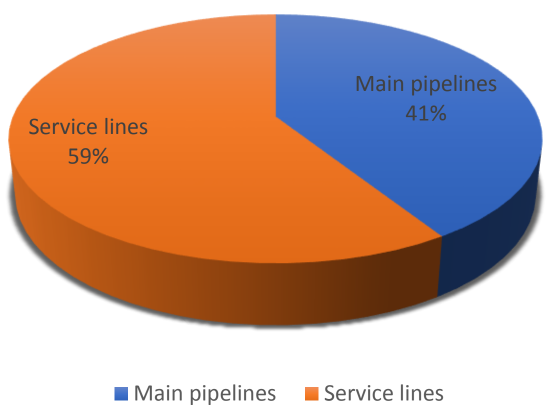
AQUIS is the water distribution system simulation model, used at Asker municipality. A hydraulic modeling tool simulates the behavior of flow directions, pressure, and thermal conditions in water distribution network. Gemini VA documents large parts of the VA network in Norway and Gemini Portal is a simplified online version of Gemini VA, which gives updated information to users. It includes service lines’ information such as their materials and size of the pipelines and also which year pipes and houses are constructed. Although Gemini Portal is a reliable source of information, there is still lack of information for some pipeline. Like material type or pipe diameters or the age of the pipes. There should be an estimation or reasonable guess for these kinds of data. This paper has presented these estimations and shows different scenarios at AQUIS.

Simulating a new model and adding service line into a hydraulic model is a time-consuming process, therefore Asker municipality decided to select an area “Askerelva pressure zone” to get analyzed in this paper.

1.2 About Asker municipality water distribution system:

Asker is a municipality in Akershus county located at southwest of Oslo. Asker and Bærum Vannverk IKS (ABV) is an intermunicipal company owned by the municipalities of Asker and Bærum and is the supplier of water to Asker and Bærum municipalities. Raw water from Holsfjorden in Buskerud is used as the main water source. ABV produces drinking water at treatment plants and distribution of water internally in the municipality to consumers is responsibility of Asker municipality. Distribution of water for 58 338 (in 2017) residents in Asker municipality is done via the municipal water pipeline network.

Water distribution pipeline has had technologically developed since 1930. There is a total of 788 km pipeline in Asker municipality and 466 km of them, nearly 59%, are private pipelines or called as service lines.



Water pressure in pipelines and quality of the pipes have direct effect on the amount of leakage. Asker municipality has a very hilly topography. As a result of topography, it is decided to have a high pressure in Asker pipeline system. Since reduction of pressure leads to the reduction of leakage amount and water loss. Asker municipality decided to adjust the water pressure by dividing Asker into several pressure zones in order to be able to deliver water with pressure between 2-9 bar. By having proper pressure from water supply and lowering pressure in the falls and increasing pressures at hills, water leakage reduces, and pipes lifetime increases.

It is required to provide enough water pressure for consumers. In 2018 Asker municipality lowered the pressure in Askerelva pressure zone about 2 bar. This pressure adjustment for Asker municipality worked well for average yearly consumption, but not sufficient for extra water consumption as garden irrigation based on some complaints from receivers.

“Askerelva” pressure zone is subjected in this paper to get analyzed in order to find the reasons for pressure loss.

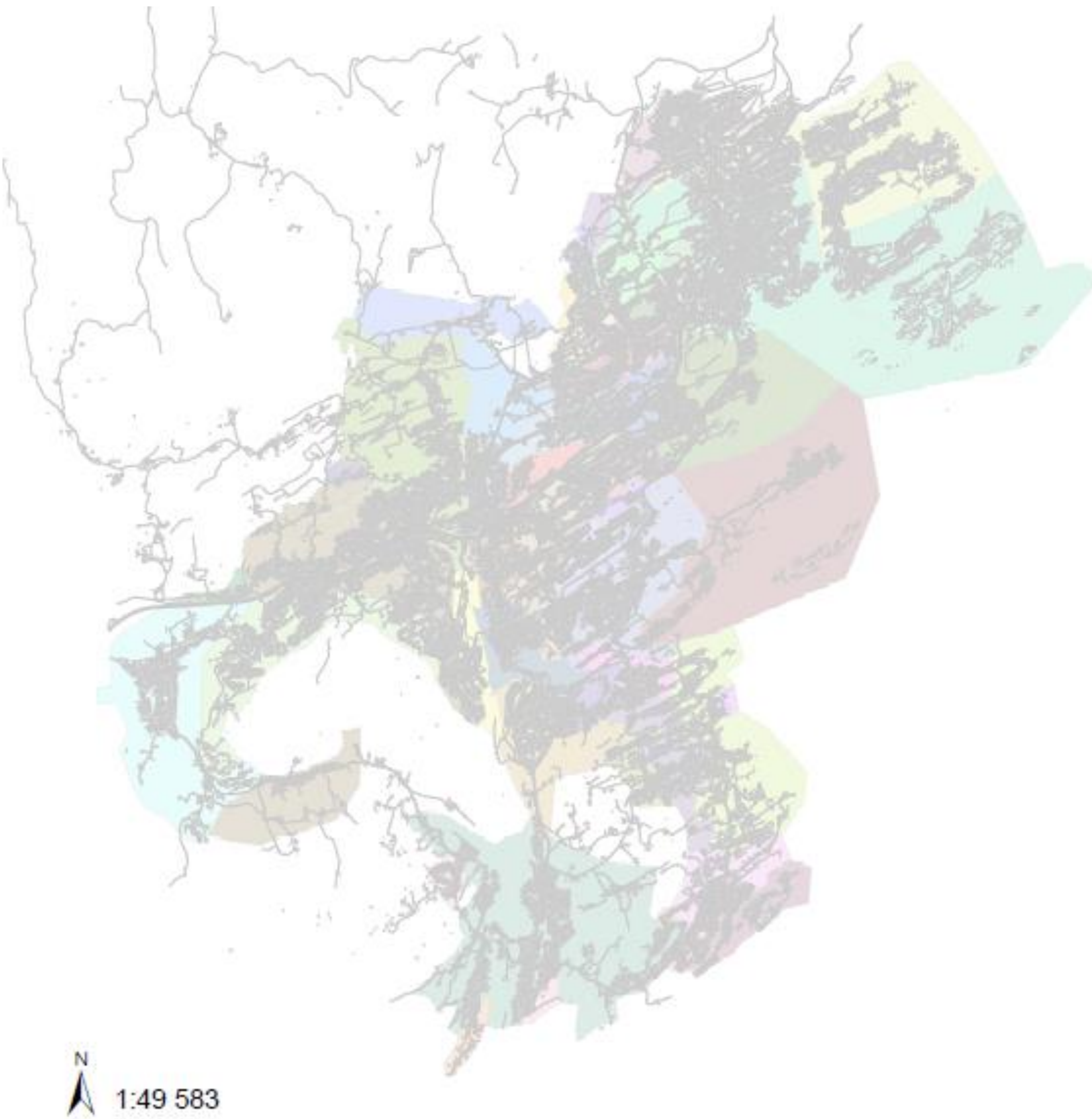


Figure 1-1: Different colors presenting pressure zone in Asker municipality.

1.3 Goals and purpose

In agreement between NMBU and Asker municipality, it is stated that this paper must prepare pipes roughness, change in capacity over time, friction loss and finally minor losses, presented in tables, figures or graphs which could be easily used by engineer to analyze the model. This paper will also simulate the result in the municipality's water distribution system model (AQUIS).

The overall objective of this paper is to assess the pressure conditions in the Askerelva pressure zone and the effect of old service lines, garden irrigation and minor head loss in service lines on the pressure conditions in the Askerelva pressure zone.

Sub-goals will be:

1. To investigate the pipes' roughness and internal dimension over time in service lines with different materials and with varying water quality.
    a. Create tables and figures that can be used in practice in Asker and Other places to insert service lines in hydraulic models with a reasonable dimension, roughness and singular loss.
    b. Create tables, figures, diagram or nomograms where pressure losses in service lines can be used for easy evaluation of the system without the use of hydraulic models.
2. Simulate the pressure conditions by AQUIS in the Askerelva pressure zone under different assumptions about the three mentioned factors. Particularly interest will be:
    a. To investigate the effect of pipes' roughness and internal dimension.
    b. To investigate the pressure of the location had complaint about low pressure in different scenarios.

Literature review has summarized the relevant scientifically efforts on how to calculate these parameters and how they may affect each other.

2 LITERATURE REVIEW

The total head loss of a pipe, tube or duct system, is the sum major losses due to friction forces along the pipes length and other losses when direction or speed of the flow changes through pipe(Çengel & Cimbala, 2006). This can be expressed as:

$$h_{\text{loss}} = \sum h_{\text{major-losses}} + \sum h_{\text{minor-losses}}$$

- h_{loss} = Total head loss in the pipe or duct system
- $h_{\text{major-losses}}$ = Major loss due to friction in the pipe
- $h_{\text{minor-losses}}$ = Minor loss due to the components in the system
- These two major losses are explained in detail in different parts.

2.1 Flow through pipes

Darcy and Weisbach developed an equation to describe the friction head loss of the flow in pipes. The dimensionless Friction factor in Darcy-Weisbach equation is the ratio of wall friction forces to inertial forces and according to Sharp and Walski (1988) it could be related to the pipe wall roughness and the Reynolds number of the flow (Çengel & Cimbala, 2006)

The loss of head resulting from the fluid through a pipeline is expressed by the Darcy Formula (Çengel & Cimbala, 2006)

$$h_{\text{major-losses}} = f_D . \frac{L}{D}\frac{V^2}{2g} \qquad \text{Eq.(1)}$$

Where:

- h_{loss}= head loss (m)
- f_D = Darcy-Weisbach friction coefficient
- L = length of duct or pipe (m)
- D = hydraulic diameter (m)
- V = flow velocity (m/s)
- g = acceleration of gravity $(m/s^{2)}$

As Darcy-Weisbach equation shows, the friction loss relates directly to the length of the pipeline, the friction factor and velocity. So, the longer the pipeline is, and the bigger friction factor is so greater the friction loss. On the opposite, the fiction factor is greater when diameter is smaller. (Michalos, 2016) side 27(7)

Friction loss:

An accurate calculation of head loss is important for performance of water pipeline. However, the calculation of friction loss is only possible when correct friction factor is applied for hydraulic calculations. (Michalos, 2016)

There have been major contributions in the development of pipe flow theories. Relative roughness was identified as an important parameter in fluid flow as early as in the nineteenth century by Darcy in 1850. Fanning proposed a correlation for the pressure drop and surface roughness. (Kandlikar et al., 2005). Reynold in 1884 worked on distinction between laminar and turbulent flow. Studying the effect of roughness on pressure drop was started by Nikuradse in 1930. He found experimental values of friction factor by experiments on sand roughness pipes.(Kandlikar et al., 2005)

Colebrook and White (1937) found the experimental values for friction factor in commercial pipes and provided a formula for relation between relative roughness, friction factor and Reynold number. The Colebrook-White formula can be applied to any fluid in any pipe operating under turbulent flow conditions. (Rahman, 2018)

$$\frac{1}{\sqrt{f}} = -2\log\left(\frac{e/D}{3.7} + \frac{2.51}{Re\sqrt{f}}\right) \qquad \text{Eq.(2)}$$

Where:

- Reynolds number (Re)
- Relative roughness of the pipe, e/D.
- Roughness, (e)
- Inner diameter of the pipe (D)

Different approaches on practical application of Colebrook equation mainly provided explicit equations to approximate the Colebrook-White equation.

Halland equation is relatively accurate, and easy to apply.(Çengel & Cimbala, 2006) Chapter8.

$$\frac{1}{\sqrt{f}} = -1.8\log\left(\frac{(\frac{e}{D})^{1.11}}{3.7} + \frac{6.9}{Re}\right) \qquad \text{Eq.(3)}$$

Swamee and Jain equation in is one of the easiest equations to apply for ($4000 < Re < 10^8$) and ($10^{-6} < \frac{e}{D} < 0.01$) and provides an accurate estimation of friction factor circular pipes. (Rahman, 2018)

$$\frac{1}{\sqrt{f}} = -1.8 \log(\frac{e/D}{3.7} + \frac{6.9}{\mathrm{Re}^{0.9}}) \qquad \text{Eq.(4)}$$

Moody Diagram

Moody presented Colebrook´s equation for both laminar and turbulent flow in a graph with Darcy friction factor on the left vertical axis, against the Reynolds number on the horizontal axis, for relative roughness (e/D) in the range of :0 - 0.05 (Michalos, 2016).

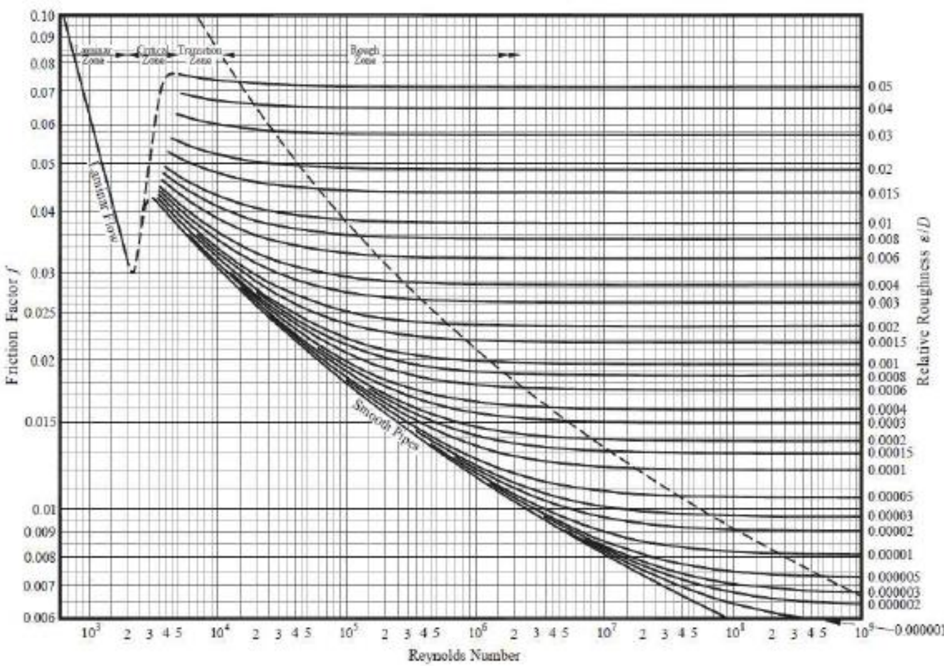


Figure 2-1: Moody diagram (Rennels & Hudson, 2012)

Reynold number:

Reynolds number is an important dimensionless quantity in fluid mechanics used to help predict flow patterns. Flow at low Reynolds numbers ($Re < 2300$) tends to be dominated by laminar flow. Laminar flow is characterized by smooth, constant fluid motion. When Reynold number increases ($2300 < Re < 4000$) flow inters a transition regime. Turbulent flow occurs at high Reynolds numbers ($Re > 4300$ 4300)(Rahman, 2018).

$$Re = \frac{VD}{\text{v}} \qquad \text{Eq.(5)}$$

$V =$ Velocity of the fluid through conduct (m/s)

$$V = \frac{Q}{A} \qquad \text{Eq.(6)}$$

- $D =$ Inner diameter of the pipes (m)
- $\text{v} =$ Kinematic viscosity of the fluid (m2/s), For water distribution systems with 5-6℃, is 1.51010^{-6}

Flow in water distribution systems are turbulent and Reynold number will vary with different flow velocities, and velocity itself is dependent on flow rate and the inside diameter of the pipes.

2.2 Water demand

Water distribution systems shall be designed to supply the demands of all customers while maintaining the minimum required pressures.

Water consumption is the quantity utilized directly by the consumers and is used in water system in terms of water demand. Water distribution system shall be dimensioned so that it functions well in all critical situation such as highest flow demands.

According to technical provision for Asker municipality (*Tekniske bestemmelser*, 2017) handbook, one of these critical values is expected total water flow, which is the maximum water demand for ordinary receivers like households using simultaneously.

$$q_{net} = q_1 + 0.015(Q - q_1) + 0.17\sqrt{Q - q_1} \qquad \text{Eq.(7)}$$

- q_{net}: Expected total water flow in service lines (l/s)
- q_1: Demand of largest consumer (l/s)
- Q: Total theoretical water flow- all fixtures summarized (l/s)

Expected total water flow in service lines are calculated by equation (7) or figure (2.2).

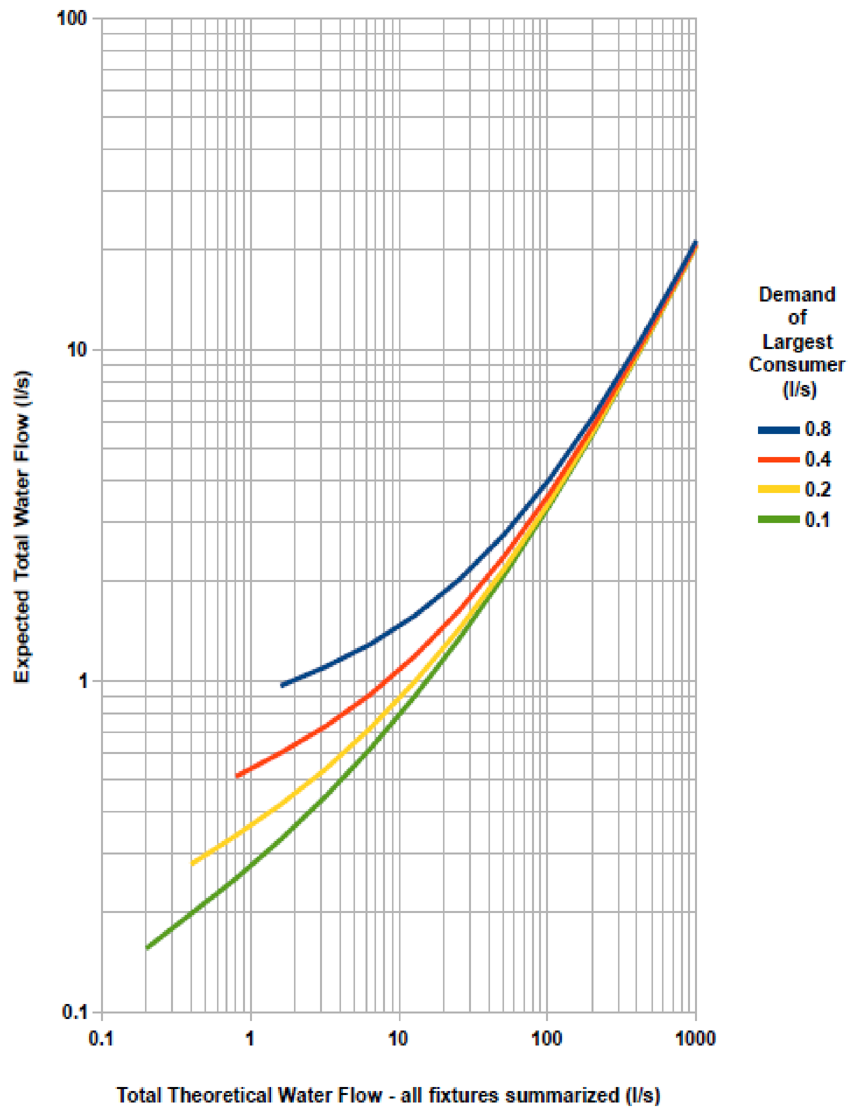


Figure (2.2) Expected total water flow in service lines (ToolBox, 2008)

Although a water distribution system should be able to provide expected total demand for household, but dimensioning water system based on expected demand will be oversizing. Since not all consumers will used the maximum value at the same time, water systems will be dimensioned for a peak hour demand.

Maximum flow rate delivered by distribution system for average daily demand which is based on consumers demand, occurs during morning hours and is called as peak hour demand. Peak hour demand is expressed as average daily demand times peak hour factor. Peak hour factor is an indicator which is used in water consumption curve in AQUIS.

$$Q_{\text{peak Hourly}} = Q_{\text{Average daily}} \left(\frac{l}{\text{day. person}}\right) \times \text{Peak hour factor} \qquad \text{Eq.(8)}$$

The third critical water demand in distribution system is garden irrigation demand which is extra water needed in summer. Problems with low water pressure may arise on some waterworks during periods of need for gardening. Moreover, when many subscribers use a lot of water at the same time, the pressure is reduced. Therefore, it is necessary to analyze the system considering irrigation consumption. Garden irrigation water each house needs should be evaluated according to the house areal, gardens and facilities related to each house.

2.3 Loss in carrying capacity

Roughness and inner diameter of the pipes are two properties that may change as pipes age. These changes can have a large effect on the capacity and head loss of a distribution system. Changes in roughness over time and its effect on pressure loss has been studied by researchers, on the other hand diameter changes have been largely ignored until more recently (Sharp & Walski, 1988). Chemical or biological processes between pipe's inside wall and water flowing through pipes leads to a combination of increased roughness and reduced pipe diameter. Increased roughness leads to increased head loss, and increased velocity as a result of reduced diameter also leads to increase head loss (Christensen, 2009).

2.3.1 Roughness in old pipes

Colebrook and White investigated the problem of changing pipe roughness with time. They formed the hypothesis that metal pipe roughness in larger diameters grows roughly linearly with time and that the pH of the water relates the rate of growth (Sharp & Walski, 1988). A slightly modified form of their equation to predict roughness is:

$$e = e_0 + at \qquad \text{Eq.(9)}$$

$$a = 10^{-(4.08+0.38\,LSI)} \text{ for } LSI < 0 \qquad \text{Eq.(10)}$$

When:

- $e =$ Absolute roughness height over time (mm) for metal pipe in contact with specific water quality
- e_0= Roughness height at time zero (mm), as an indicator for pipe material characteristics.
- a= Growth rate of roughness height (ft/year), as an indicator for water quality characteristics.
- t= Time (year)
- LSI= Langelier Saturation Index (see Water quality)

According to experimental studies of Echávez (1997) roughness value for small diameter pipes, follows a parabolic law more than a lineal law.

Example of parabolic equation, according to Echávez (1997):

$$e = e_0 + at - 0.00045\,t^2 \qquad \text{Eq.(11)}$$

Roughness heights, e_0 (mm), as an indicator for pipe material characteristics for new pipes are given in table (2.2). (Cengel, 2010)

Table 2-1: Absolute roughness for materials used in Asker municipality:

Material:	Absolute Roughness (mm)
Cast Iron- Ductile	0.25
Cast Iron- Grey	0.15
Galvanized Steel	0.15
Copper	0.0015
Plastic pipes:	0.0015

Pipe material together with water quality inside pipe are decisive factors for corrosion and sedimentation process inside the pipe which may affect the capacity of the system.

2.3.1.1 Water quality

Characteristic and chemistry of water from a treatment plant delivered to the residence is important. Besides its health effect, it may affect roughness of the pipe and carrying capacity of the pipes, together with material type of the pipe. Physical or chemical processes inside the pipes may form a layer of sediments or biofilm and cause the reduction of diameter in the cross section of the pipe.

There have been numbers of development to predict corrosivity of water, but none is able to predict the corrosivity. Experience has shown that by formation of a protective calcium carbonate film, corrosion will generally be minimized. Langelier saturation index is one of the calcium carbonate-based indices (Gebbie, 2000).

The Langelier Saturation Index (LSI) is a measure of the balance between pH and calcium carbonate. Corrosivity is a measure of how aggressive or stable water is with respect to its degree of $CaCO_3$ saturation. If a water has a negative LSI value, it is under-saturated with respect to calcium carbonate and is potentially corrosive. If a water has a positive LSI value, it is oversaturated with $CaCO_3$ and a protective layer of calcium carbonate can form. Saturated water has a LSI of zero (Gebbie, 2000).

Langelier Index can be calculated by equation (12) and (13) (Gebbie, 2000):

$$LSI = pH - pH_s \qquad \text{Eq.(12)}$$

Temperature is an important indicator for calculating pH of saturation (pH_s). So, in any given temperature:

$$pH_s = 9.3 + A + B - (C + D) \quad \text{Eq.(13)}$$

$$A = \frac{log\left[TDS\ \left(\frac{mg}{L}\right)\right] - 1}{10}$$

$$B = (-13.2 \times (log[\ (°C) + 273]) + 34.55$$

$$C = log\left[Ca^{2+}\ as\ (CaCO_3), \frac{mg}{L}\right] - 0.4$$

$$D = log\left[ALK\ as\ (CaCO_3), \frac{mg}{L}\right]$$

Where:

- pH_s= is the pH of water saturated with calcium carbonate
- A= refers to total dissolved solids (mg/L)
- °C= refers to temperature
- C= represents the calcium hardness (mg/L as calcium carbonate)
- D= is total alkalinity (mg/L as calcium carbonate)

When Langelier index is defined, growth rate will then be calculated. Growth rate varies considerably with water conditions.

2.3.1.2 Pipe Material:

Roughness value and inner diameter of the pipes and their changes over time, are important indicators for pressure loss. Both of these values relate to the type of pipe material and the quality of water flowing through pipes.

Service line materials used in Asker municipality are mostly: galvanized steel, copper, cast-iron, PVC and PE.

Cast-iron:

In the early 1860-1850 gray cast-iron pipes came to Norway. The problem with grey cast-iron pipes is that it`s very corrosive. Gray cast iron was replaced by ductile cast iron from 1965, but still has corrosion problem. Cast-iron pipes are not very common in service lines, but very few of them are used(*Vann og avløpsteknikk*, 2017)

Galvanized steel:

Galvanized steel pipes are mostly used in water pipelines between the war in 1940’s until 1960-1970’s since they are very cheap compare to other materials like copper. They are not so common at municipal distribution system but were used as private pipes in service lines. Galvanized pipes are very corrosive. Although they may look fine from outside, they may lose their flow capacity as a result of sedimentation, encrustation and other processes inside pipes’ wall.

Copper:

Copper are good quality pipes and since they are expensive, not so preferable in pipelines. Copper is a last longing pipe. copper prices have grown because of the expanding demand.

Plastic pipes:

In the early 1970s thermoplastic pipes came to Norway and have been widely used. The plastic pipes are made of polyethylene (PE), polyvinyl chloride (PVC) and polypropylene (PP). In Norway plastic piping has been used in service line because of the price, but also because PE pipes is easy to work with(*Vann og avløpsteknikk*, 2017).

PVC:

PVC pipes have many advantages. They are lightweight, easy to handle, smooth with low hydraulic roughness and is resistant to erosion from soil and rocks (*Vann og avløpsteknikk*, 2017)

PE:

Polyethylene can be found in different categories based on their material type: PEL, PEH, PE50, PE80, PE100

2.3.2 Changes in Diameter over time

Reduction in flow capacity increases the pressure loss by affecting velocity of flow through pipes, but this reduction in pipe's diameter has often been neglected. Exact estimation of diameter reduction is very complicated (Boxall et al., 2004).

There are mostly two approaches in the case of diameter changes: First is neglecting reduction of pipes' diameter. This assumption is mostly popular for simulation of hydraulic models (Aquis). It is assumed that for estimating the increase in roughness, diameter reduction is already considered in the concept, since the roughness height is estimated while the effect of pipes' material and quality of water are considered (Kaur et al., 2018).

Secondly, is to predict the loss in flow capacity by estimating roughness and diameter separately and calculate the pressure loss as a result of both. In this assumption, increase in pipes' roughness and decrease in pipe's diameter should be calculated separately although they may affect each other (Kaur et al., 2018).

Kandlikar et al. (2005) considered the effect of flow constriction due to roughness elements and proposed that the constricted flow area should be taken in the velocity calculations.

$$D_{\text{Constricted Flow}} = D_{\text{pipe-inner}} - 2e \qquad \text{Eq.(14)}$$

- $D_{\text{Constricted Flow}}$: The constricted flow diameter, (mm)
- $D_{\text{pipe-inner}}$: Pipes inner diameter, (mm)
- e: Surface roughness (mm)

Pipe material, water quality and how material will react when it is in contact with water have direct effect on reduction of diameter. This reduction is a result of chemical and physical processes inside pipes. Processes like sedimentation, encrustation, and fouling, known as corrosion (Shahzad & James, 2002)

2.3.2.1 Chemical or biological processes within the service water:

There are many problems connected to water chemistry in distribution system due to deterioration, but corrosion, encrustation and biofouling are responsible for decreasing of the pipe cross section.

Corrosion

The corrosion process is very complex and depends on the pipeline materials, the distributed water characteristics and also on the operating conditions (Shahzad & James, 2002).

Corrosion may be the result of direct oxidation or electrolytic action, both fostered by aggressive water forming electrochemical couples on the pipe wall (Association, 2001).

Encrustation and Tubercles

Encrustation is a by-product of corrosion and mineral deposits, such as iron, manganese, and carbonates. Corrosion inside a pipe can lead to formation of ferric hydroxide deposits on the walls. Pressure or velocity changes along the pipe system may disturb the equilibrium of the water and result in the deposition of insoluble iron and manganese hydroxides which may occupy relatively large volumes. over time, they ultimately harden into scale deposits (Shahzad & James, 2002).

Indicators of encrusting water include (Shahzad & James, 2002):

- pH above 7.5
- If the carbonate hardness of the groundwater exceeds 300 ppm, encrustation due to deposition of calcium carbonate is likely
- If the iron content of the water exceeds 2 ppm, encrustation due to precipitation of iron is likely
- If the manganese content of the water exceeds 1 ppm, coupled with high pH, encrustation is extremely likely if oxygen is present

Mielcarzewicz and Pelka demonstrated a correlation between thickness of encrustation and pipe diameter with respect to time (Shahzad & James, 2002):

$$S_t = 0.0169 \times t^{0.439} \times {d_0}^{0.841} \qquad \text{Eq.(15)}$$

When:

- S_t: thickness of encrustation (mm)
- d_0: initial diameter of pipe (mm)
- t: age of pipe (year)

Biofouling:

Fouling is usually caused by natural biological activity in any type of pipe material and results in buildup of an organic deposit on the interior of the pipe and decrease the effective diameter of pipes. The thickness of the biofilm deposits is an important parameter but is difficult to determine but experimental studies shows that the maximum thickness of biofilm is l00mm(Shahzad & James, 2002).

2.3.2.2 Experiments on diameter changes

Exact effect of each processes on decreasing diameter of the cross section is unclear. Each material has its own reaction towards these processes. Galvanized steel and cast-iron are the most corrosive pipes.

On an experimental research on Wslkerton, Ontario, Shahzad and James (2002) concluded that although loss in the carrying capacity of water pipes has been reported, but encrustation, tuberculation, biofouling, corrosion and biofilms in a pipe network cannot be modeled simply, because of its dependence on the unstable quality of water supplied and inter-relation of some processes like biofilm formation and corrosion in water distribution system. They also reported that the pipe diameter decreases more rapidly in early years.

On an investigation of the increase in roughness of cast-iron walls in 1981, Lamont reported that tuberculation can reduce the capacity of cast-iron mains between 15% to 70%, after 30 years. This capacity reduction depends on the pipes corrosion rate and diameter. Encrustation does not continue to grow indefinitely until it clogs the pipes of larger diameter but remains stationary after reaching 25-49 mm in thickness (Shahzad & James, 2002).

Kaur et al. (2018) reported that inspections in water system in Norway and Estonia have shown that nominal diameter of old rough pipes can be reduced up to 50%. As discussed before, when pipes are new the roughness increases rapidly and then become steady.

2.4 Local head loss in pipes

When water flows through various fittings, valves, bends, elbows, tees, inlets, exits and enlargements, the smooth flow of the fluid get interrupted. This leads to additional losses, which is called as minor head loss because they are generally minor compared to the friction head loss in the pipes or the major losses. In some cases, the minor losses may be greater than the major losses. (Çengel & Cimbala, 2006). Minor head loss (H_s) is calculated by:

$$H_s = k_s \frac{V^2}{2g} \qquad \text{Eq.(16)}$$

While:

- $k_s =$ Minor loss coefficient
- $V =$ velocity of the water flowing at the service lines.

This thesis is focused on the losses in T-junctions, tapping sleeves and bends.

Head loss in Branches from water mains:

When it is needed to tap a pipe that is already in service, one possibility is to shut down the water line and install a T-junction (T-fitting). It is also possible to tap into the line under pressure using a tapping sleeve. Since there is no need to shut down the main line to be tapped, it is preferable (Walski et al., 2002)

This is up to municipality who will decide which of these two methods will be used to make a branch from a main water line.

T-Junctions:

T-junction is a very common component in pipe networks. They are mainly used to distribute the flow from main pipe to several branching pipes or used to collect the flow from several branches to a main pipe. Direction inflow and outflow through junctions are very important.

According to Idel'chik (1966), loss coefficient in T-junctions is dependent on the area and flow in branches and main pipes. He has presented loss coefficient in different scenarios, when there is a branch from a main pipe and flow is divided in T-junction.

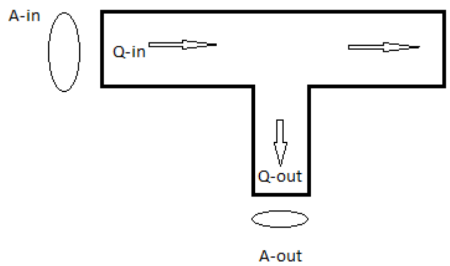


Figure 2-2: Flow is divided in T-junction

Table 2-2: Loss coefficient in T-junction (Idel'chik, 1966)

A_{out}/A_{in}	Q_{out}/Q_{in}									
	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
	k_s									
0.09	2.80	4.50	6.00	7.88	9.40	11.1	13.0	15.8	20.0	24.7
0.19	1.41	2.00	2.50	3.20	3.97	4.95	6.50	8.45	10.8	13.3
0.27	1.37	1.81	2.30	2.83	3.40	4.07	4.80	6.00	7.18	8.90
0.35	1.10	1.54	1.90	2.35	2.73	3.22	3.80	4.32	5.28	6.53
0.44	1.22	1.45	1.67	1.89	2.11	2.38	2.58	3.04	3.84	4.75
0.55	1.09	1.20	1.40	1.59	1.65	1.77	1.94	2.20	2.68	3.30
1.00	0.90	1.00	1.13	1.20	1.40	1.50	1.50	1.80	2.06	2.30

The exact calculation of how flow will be divided after the junction, is very complicated, but hydraulic models are able to provide these values according to consumers' demand. Idel'chik table is illustrated in figure (2-3) to give a better understanding.

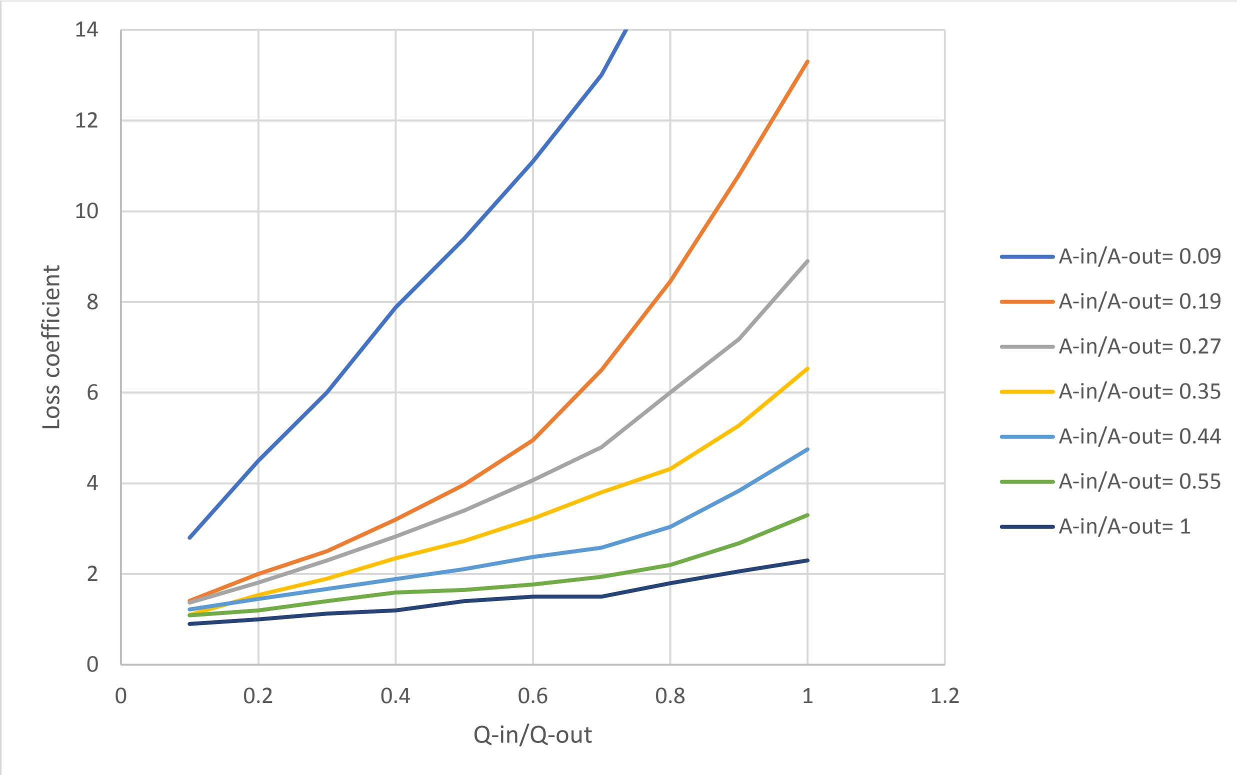


Figure 2-3: Loss coefficient values in T-junctions(Idel'chik, 1966)

As a typical average value for loss coefficients in T-junctions when area of the main pipe (inflow) and the branch pipe (outflow) are equal is given as k_s= 1.8 or 2 (Çengel & Cimbala, 2006).

Tapping sleeves:

Tapping into a main pipe is very common since there is no need to shut down the system. The problem with a tapping machine is that the cutout hole, should not be the same size as the pipe, since it would drastically weaken the main. Therefore, the cutout hole should be at least one size smaller than the main pipe. That is why a standard T-junction loss coefficient is not very accurate (Walski et al., 2002).

The head loss through the tap is usually greater than loss in T-fitting because the tap hole is smaller than the internal pipe diameter and the tap is not as smooth as a T-fitting. As the velocity of the water flowing through the branch increases, the head loss increases and the difference in minor loss coefficient may become significant (Walski et al., 2002)

As loss coefficient is needed for finding the minor head loss, and it is an important factor. An experimental research by Walski et al. (2002) shows that the key factor in installing a tap was the size of a cutout in the pipe being tapped. The head loss was highly dependent on the hole size and ratio of opening size to pipe diameter (d/D).

$$k = 1.28\,\exp\ (6.92\left[1 - \frac{d}{D}\right]) \qquad \text{Eq.(17)}$$

Which is almost equal to:

$$k = 1.97\ (\frac{d}{D})^{-4} \qquad \text{Eq.(18)}$$

Where for both equation:

- k= loss coefficient
- d= the diameter of the cutout hole
- D= the diameter of main branch

Bends and Valves

Loss coefficients for different situation in table(2-3) and (2-4) according to Çengel and Cimbala (2006) are:

Table 2-3: loss coefficient for valves

Valve:		
Globe valve:	fully open	Ks=10
Angle valve:	fully open	Ks=5
Ball valve:	fully open	Ks=0.05
Swing check valve:		Ks=2
Gate valve:	fully open	Ks=0.2
	1/4 closed	Ks=0.3
	1/2 closed	Ks=2.1
	3/4 closed	Ks=17

Table 2-4: loss coefficent for bends

Bends:	
90 smooth bend	
Falnged:	Ks=0.3
Threaded	Ks=0.9
90 miter bend	
Without vanes:	Ks=1.1
with vanes:	Ks=0.2

3 METHODOLOGY

Since the main goal of this paper is to find the effect of changes in roughness, inner diameter and minor head loss on total head loss for old pipes used in service lines, it is essential to construct a proper process to find all the required data. This paper divides these processes into two main parts: theoretical part, and hydraulic simulation model. Data used in theoretical calculation is preferred to be specified for the Asker municipality. Result found by theoretical calculation is used in the hydraulic simulation model for Asker municipality-Askerelva pressure zone. Results from hydraulic simulation model will be analyzed.

3.1.1 Assumptions:

This thesis is based on two main assumptions:

- Water from a treatment plant flowing through pipes has had the same quality along the pipeline system over years.
- Receivers' water demand or the consumption will be the connected pipe's flow rate of the pipe

3.1.2 Procedure:

In order to find pressure loss in the water distribution system using Darcy-Weisbach equation (1), there is a need to find proper friction factor.

Colebrook-White equation (2) is required to find friction loss. There are some unknown data which are required to be found or calculated. Challenge in water distribution system is that these unknown parameters may be constant, or they would vary in time. Different type of material with different size are used in service lines used in in Asker municipality's water distribution system, which may have installed and used from a different era. But it is still possible to analyze different scenarios.

Overall processes:

1. Choose the best investigation method for each parameter mentioned in literature review based on the data specified for Asker municipality.
2. The next step will then be to categorize the data. Results will be presented by tables, figures or diagram.
3. Simulate the pressure conditions by AQUIS in the Askerelva pressure zone and analyze the results.

Steps needed to categorize available data:

1. Parameters like material of the pipes, quality of the water distributed from treatment plants, different water demands, won't change over years or will be considered as constant parameters in this paper. Diameter and roughness are parameters which change over years

and are tightly connected to each other. Reynolds number, friction factor and head loss depend on roughness and diameter.

2. Diameter changes and growth in roughness and their effect on each other are complicated subjects. In most theoretical research, friction loss is mostly affected by pipes roughness and its changes not reduction of diameter. In practice, reduction of diameter in cross section area is as important as roughness, since it a decisive parameter for amount of water flowing through pipes. In this paper both diameter and roughness are considered.
3. In simulation the hydraulic model, two scenarios are considered. One when reduction in diameter is neglected and second when both diameter and roughness are included and their effect on friction loss will be analyzed.
4. Absolute roughness in each pipe are functions of material, age and water quality. Material type of pipes are available at GEMINI portal and absolute roughness is measured for each type of material. The quality of water distributed from a treatment plant are available on laboratory of ABV. Decisive parameters can be calculated, and roughness value will then be a function of pipe's age.
5. Relative roughness to use in Colebrook-White or similar equations will be the ratio of roughness specified for old pipes divided in original inner diameter.
6. For calculating Reynolds number, we need to know velocity of water through pipe, which both velocity and cross section area is unknown. Velocity will change through pipe very often. Using flow rate or water demand in area of the cross section of the pipe would be reasonable to limit the unknown parameters. Inner cross section area of pipes are also needed, which relates to inner diameter of the pipe. As explained, the right side of equation (19) can be a proper substitute whenever velocity is needed.

$$V = \frac{Q}{A} = \frac{4Q}{\pi D^2} \qquad \text{Eq.(19)}$$

7. Since Reynold number depends on velocity of the flow through pipes, water distribution system will be analyzed based on 3 value of flow rate, for the most critical situations which may occur.
   - Expected total water flow in service lines (q_{net})
   - Peak hour demand
   - Extra garden irrigation water demand

   Each of these water demands are based on the different needs of residents in Asker municipality and its standards.

8. Since flow in water distribution systems are turbulent, Swamee and Jain equation (4), which is easier to apply than Colebrook-White equation and applicable in ($4000 < Re < 10^8$), could be used to calculate friction factor.
9. Flow in smooth pipes depends on Reynolds number. Smooth pipes, such as plastic pipes or even copper, has absolute roughness equal or almost equal to zero. In general, flow in distribution system is turbulent.
10. Head loss per length of pipe is dimensionless and depends on friction factor, inner diameter and water flow rate. This is a proper way to show how friction effects the pressure loss through pipes.

$$\frac{h_{major-losses}}{L} = f_D . \frac{8\,Q^2}{2g.\,D^5\pi^2} \qquad \text{Eq.(20)}$$

11. Results will be presented by table and figures.

3.2 Theoretic analysis

In this part best investigation method for each parameter will be selected. The next step will then be to categorize the data.

3.2.1 Water demand

Peak hour demand:

Required average daily flow for private consumers has estimated the water demand of 160 (l/day), including leakage, for each person. Maximum flow rate delivered by distribution system which is based on consumers demand, occurs during morning hours and is called as peak hour demand. Peak hour demand is expressed as average daily flow times peak hour factor divided by 24 hours. Peak hour factor in Aquis is an indicator defined in water demand curve as a multiplier for average daily flow for each house according to the number of people living there. Peak hour factor in Asker municipality is equal to 2.5.

$$\text{peak hour demand} = \text{Average daily flow } \times \text{Peak hour factor} \qquad \text{Eq.(21)}$$

$$Q_{\text{peak- hourly}} = 400 \left(\frac{l}{\text{day. person}}\right)$$

$$Q_{\text{peak- hourly}} = 0.00463 \left(\frac{l}{s.\text{ person}}\right) \qquad \text{Eq.(22)}$$

Expected total water flow in service lines ($\mathbf{q_{net}}$)

Expected total water flow is a big value since it considers maximum simultaneously water consumption from a house. It does not happen very often, neither is realistic that all the houses in a neighborhood consume this big amount of water simultaneously, therefore distribution system will be analyzed by setting this amount of consumption for one house at a time and analyze pressure for that. Service lines are dimensioned based on this consumption which occurs at full utilization over short time intervals in second and minute scale, not hourly scale.

Demand for different consumers according to technical provision for Asker municipality (*Tekniske bestemmelser*, 2017) handbook, are listed in the table (3-1).

Table 3-1: Demand of each consumer, q_1 (l/s)

Outlet Points:	Flow Demand: (l/s)	
	Cold Water:	Warm Water:
Dish washing machine	0.2	0.2
Kitchen sink	0.1	0.1
Washing machine	0.2	0.2
Bathroom sink	0.1	0.1
Toilet	0.1	-
Bidet	0.1	0.1
Bath	0.3	0.3
Shower	0.2	0.2
Hose/ Drain valve (indoors)	0.2	0.2
Hose/ Drain valve (outdoors)	0.2	0.2
Garden faucet	0.4	-

Total theoretical water flow (all fixtures summarized) for a normal house in Norway is 8 (l/s). Demand of largest consumer or the required demand for garden irrigation is $0.4\ (\frac{l}{s})$)

Using the figure (2.2) or formula (7) gives the expected total water flow in service lines equal to:

$$q_{net} = 0.8\ (\frac{l}{s})$$

Extra garden irrigation water demand

Water consumption at Askerelva pressure zone is shown in figure (**Error! Reference source not found.**), which shows that water consumption increases in week 10 in May and continues until week 39 in September as a result of garden irrigation in summer.

Figure 3-1: Askerelva pressure zone (*Water consumption*, 2017)

For daily household water consumption, it is usual to multiply average daily consumption for each person to the number of people living in a house. On the other hand, garden irrigation should be estimated according to the areal of the house and gardens which need to be irrigated. Since it is difficult to estimate the proper consumption for each house, a middle value will be considered as a water demand for irrigation used in each house.

Figure (**Error! Reference source not found.**) shows water consumption ($\frac{l}{\text{day}}$) for each person in Askerelva pressure zone during a year. Middle consumption in summer is: 370 ($\frac{l}{\text{day.person}}$) and in other periods of the year is 140 ($\frac{l}{\text{day.person}}$). Middle extra consumption used for garden irrigation in summer time is then: 230 ($\frac{l}{\text{day.person}}$).

The middle summer consumption for Askerelva pressure zone with the population of 3598 in total is:

$$230\ \left(\frac{\mathrm{l}}{\mathrm{day.\,person}}\right) \times 3598 = 827540\ (\frac{\mathrm{l}}{\mathrm{day}})$$

There are 91 houses located in Askerelva pressure zone. Middle irrigation consumption for each house is:

$$\text{Middle irrigation water consumtion in each house} = \frac{\text{Total middle irrigation consumtion}}{\text{number of houses}}$$

$$Q_{\mathrm{irrigation-demand}} = \frac{827540\ \left(\frac{\mathrm{l}}{\mathrm{day}}\right)}{91\ (\mathrm{hus})} = 9093.8\ \left(\frac{\mathrm{l}}{\mathrm{day.\,hus}}\right)$$

If garden irrigation is assumed to be done during 8 hours in a day time.

$$Q_{irrigation-demand} = \frac{9093.8\ \left(\frac{l}{day.\,hus}\right)}{8 \times 60 \times 60\ (\frac{day}{s})}$$

$$Q_{irrigation-demand} = 0.315\ \left(\frac{l}{s}\right) for\ each\ house$$

3.2.2 Pipe material

Information about material, size and installation, can be found from Gemini. Materials used in Asker municipality are galvanized steel, copper, cast-iron, polyvinyl chloride (PVC) and (polyethylene) PE. Usually information in Gemini shows outer diameter of galvanized, copper and plastic pipes and inner diameter of cast-iron ductile and gray pipes. There is no information available for some old pipes, and in some case the specific type of old metal pipes is not specified. Material and size of these pipes should be estimated or guessed according to the year the neighborhood or connecting houses are constructed or what type of material was used in a that period and area.

In order that each pipe will be noticed in Aquis, it should be specified with a code or name to differentiate by its material, in its age and diameter.

3.2.2.1 Pipe specification and classification:

Pipes are dimensioned in different categories. Pipes specification are technical documents to address additional information for specific pipes. Commercial pipes are available in standard sizes: in American system, Nominal Pipe Size (NPS) are presented in inches and in the European equivalent, nominal diameter (DN) are presented in mm. Outside diameters for metric and imperial standards are indicated in the table below.

Pipe's classification:

Each type of pipe is classified by different indicator: SDR, Sch, K or class. Pipes may also be classified by safety factor and allowed pressure PN.

Most common sizes for different materials

- Copper:

Copper pipes are measured by their outside diameter in millimeters. Common sizes are DN15 mm, DN18 mm, DN22 mm, DN28 mm, DN35 mm, DN42 mm, DN54 mm, DN66.7 mm and DN76.1 mm outside diameters.

Table 3-2: Copper pipes Outer & Inner diameter (Uhlen, 1996)

Nominal Diameter		Nominal Pipe Size – NPS		
DN	Inner diameter (mm)	NPS	Outer diameter (mm)	Inner diameter (mm)
DN 12	9.6	1/2	12.7	9.5
DN 15	12.6	3/4	19.1	15.9
DN 18	15.6	1	25.4	22.2
DN 22	19	1-1/4	31.8	27.8
DN 28	25	1-1/2	38.1	34.1
DN 35	31	1-3/4	44.5	40.5
DN 42	38	2	50.8	46.8
DN 54	50	2-1/4	57.1	52.1

- Galvanized steel:

Galvanized pipes are also named after their outside diameter. Common sizes are ¼", ½", ¾", 1", 1 ¼", 1 ½", 2". Common Schedules numbers presenting wall thicknesses are 5, 10, 40, and 80.

It is important to consider that old pipes used in service lines specially galvanized steel pipes were generally thicker than the newly made pipes. Schedules numbers (Sch40) (*Galvanized Standard Steel Pipe*, 2008)

Table 3-3: Galvanized pipe (Uhlen, 1996)

Nominal Pipe Size	Outer diameter (mm)	Inner diameter (mm)
1/4	13.5	8.9
1/2	21.3	16.1
3/4	26.9	21.3
1	33.7	27.3
1-1/4	42.4	36
1-1/2	48.3	41.9
2	60.3	53.1

- Cast iron are classified by K9-K10

Table 3-4: SJK & SJG pipes, classified by K9-K10 (*Kravspesifikasjon for duktile støpejernsrør*, 2012)

Pipe Code in Aquis	Outer diameter (mm)	Outer diameter (mm)	Pipe Code in Aquis	Inner diameter (mm)
SJK K-9 40	56	40	SJG-K9-32	32
SJK K-9 50	66	50	SJG-K9-40	40
SJK K-9 65	82	65		

- PVC are classified based on SDR, PN & C-factor:

Among so many commercially available PVC pipes, those with maximum operating pressure of 10 bar and SDR of 21, and C-factor of 2.5 are most suitable and meet the requirements of designing service pipelines (Pipelife.no)

Table 3-5: PVC pipes (Uhlen, 1996)

Material	SDR	Design factor	Maximum allowed pressure	Outer diameter (mm)	Inner diameter (mm)	Code in AQUIS
PVC	SDR 21	2.5	PN10	20	16.2	PVC-SDR21-20
				25	20.4	PVC-SDR21-25
				32	26.2	PVC-SDR21-32
				40	33	PVC-SDR21-40
				50	41.4	PVC-SDR21-50
				63	57	PVC-SDR21-63
				75	67.8	PVC-SDR21-75

- PE are also classified based on SDR, PN:

Among so many commercially available PE pipes, those with maximum operating pressure of 10-12.5 bar and SDR of 11-17, are most suitable and meet the requirements of designing service pipelines. PVC, PE are classified based on SDR, PN & C-factor: (Pipelife.no)

Table 3-6: PE100 classifications (HALLINGPLAST, 2009)

Material	SDR	Design factor	Maximum allowed pressure	Outer diameter (mm)	Inner diameter (mm)	Code in AQUIS
PE100	SDR17	1.25	PN10	40	35.2	PE100-SDR17-40
		1.25	PN10	50	44	PE100-SDR17-50
		1.25	PN10	63	55.4	PE100-SDR17-63
		1.25	PN10	75	66	PE100-SDR17-75
	SDR11	1.6	PN12.5	25	20.2	PE100-SDR11-25
		1.6	PN12.5	32	26	PE100-SDR11-32
		1.6	PN12.5	40	32	PE100-SDR11-40
		1.6	PN12.5	50	40	PE100-SDR11-50
		1.6	PN12.5	63	50	PE100-SDR11-63
		1.6	PN12.5	75	63	PE100-SDR11-75

Table 3-7: PE50 size (HALLINGPLAST, 2009)

Material	SDR	Design factor	Maximum allowed pressure	Outer diameter	Inner diameter	Code in AQUIS
PE50	SDR11	1.6	PN10	20	16	PE-SDR11-20
		1.6	PN10	25	20.4	PE-SDR11-25
		1.6	PN10	32	26.2	PE-SDR11-32
		1.6	PN10	40	32.8	PE-SDR11-40
		1.6	PN10	50	41	PE-SDR11-50
		1.6	PN10	63	51.4	PE-SDR11-63
		1.6	PN10	75	61.4	PE-SDR11-75

Table 3-8: PE80 size (HALLINGPLAST, 2009)

Material	SDR	Design factor	Maximum allowed pressure	Inner diameter	Inner diameter	Code in AQUIS
PE80	SDR11	1.6	PN10	20	16	PE80-SDR11-20
		1.6	PN10	25	20.4	PE80-SDR11-25
		1.6	PN10	32	26.2	PE80-SDR11-32
		1.6	PN10	40	32.6	PE80-SDR11-40
		1.6	PN10	50	40.8	PE80-SDR11-50
		1.6	PN10	63	51.4	PE80-SDR11-63
		1.6	PN10	75	61.4	PE80-SDR11-75

In general: most of the pipes are categorized based on outer diameter and it is inner diameter which is used in velocity, Reynold number and friction loss equations. Cast-iron pipes are categorized by their inner diameter.

3.2.3 Water quality in Asker municipality

Drinking water from a treatment plant delivered to residence in Asker municipality has a good quality. When analyzing an aged pipe system, quality of water and its history is needed to predict the probable effect it had on pipe system over years. As explained before, water chemistry together with type of material may affect roughness changes and decrease of fluid capacity of the pipe. Corrosion effect is what is called as water characteristics and Langelier Saturation Index as an indicator for water chemistry.

pH of saturation is a temperature dependence factor and will be calculated by equation (13). There are some factors consider when using measured data from the laboratory into equation (13) for calculating Langelier Sauration Index:

- The concentration of various constituents in a water can be expressed in one of two ways: as the ion "as is" or as calcium carbonate "as $CaCO_3$". To convert from ion form of Calcium to the equivalent as $CaCO_3$, it should multiply by the conversion factors of 2.5 (Gebbie, 2000).
- Alkalinity is typically reported as milliEquivalents per Liter ($\frac{mmol}{L}$) "as $CaCO_3$" in Asker municipality treatment plant (ABVann). It should be converted to mg/L as "as $CaCO_3$", by multiplying by 50 (the approximate molar mass of $\frac{CaCO_3}{2}$ (Gebbie, 2000).
- TDS and Conductivity:

  Laboratory in ABVann provides data on conductivity. It needs to be converted to TDS. There is not a relationship between conductivity and TDS that is very repeatable across different locations and different dissolved material (Carlson, 2005). There is still a rough estimation of TDS from conductivity by:

$$TDS\ \left(\frac{mg}{L}\right) = SC\ \left(\frac{uS}{cm}\right) \times 0.65 \qquad \text{Eq.(23)}$$

where:

TDS = Total Dissolved Solids in mg/L

SC = Specific Conductance (temperature corrected) in $\frac{uS}{cm}$. ($1\frac{uS}{cm} = 0.1\frac{mS}{m}$)

$$TDS\ \left(\frac{mg}{L}\right) = SC\ \left(\frac{mS}{m}\right) \times 65$$

In the table (3-9) related water quality for Asker municipality from ABVann (2018) are converted to the units required in equation (13).

Table 3-9: Data from ABVann (2018), and converting value, Result to be used

Parameter	Data from ABV	Units	Required Units	Convert Units	Results
pH	7.2 ∓ 0.06	-	-	-	7.2 ∓ 0.06
Calcium	5.8 ∓ 0.80	“as ion”	“as $CaCO_3$”	$\times 2.5$	5.8 ∓ 2
Temperature	6	℃	℃	-	6
Alkalinity	0.259 ∓ 0.030	mmol/L	mg/L	$\times 50$	12.95 ∓ 1.5
Conductivity	4.9 ∓ 0.02	mS/m	mg/L	$\times 65$	318.5 ∓ 1.3
Hardness	0.99	dH	mg/L	German unit	7.4

By using equation (13) and the result from table (3-9), pH_s will be:

$$pH_s \approx 10.04$$

By using equation (12), the value of langelier saturation index will be:

$$LSI \approx -2.7$$

Since water has a negative LSI value, it is under-saturated with respect to calcium carbonate and is potentially corrosive (Gebbie, 2000).

Equation (10), will give the roughness growth rate in “ft/year”

$a\left(\frac{ft}{year}\right) = 10^{-(4.08+0.38\,LSI)}$

It is important to notice that the growth rate calculated by equation (10) are in “ft/year” and should be converted to “mm/year”

$$a \approx 0.26\left(\frac{mm}{year}\right) \qquad \text{Eq.(24)}$$

3.2.4 Loss in Carrying Capacity

This thesis will simulate the water system in both situations when diameter reduction is analyzed and also when is neglected, in order to evaluate the effect of diameter changes on pressure loss.

Exact effect of each processes on decreasing diameter of the cross section is unclear. Each material has its own reaction towards these processes. This paper will present estimation of diameter reduction for each material which includes any applicable results internationally, nationally or locally.

3.2.4.1 Roughness and inner diameter changes over time

Predicting exact reduction of diameter in pipe is very complicated, since many different factors with different impression may affect this event.

Predicting roughness in old metal pipes in this paper, is based on current characteristics of the water flowing through pipes. According to equation (9) and (24), roughness for iron based metal pipes are:

$$e = e_0 + 0.26\,t \qquad \text{Eq.(25)}$$

As mentioned before roughness value for galvanized pipes with diameter smaller than 50 mm. follows a parabolic law more than a lineal law, equation (11)

$$e = e_0 + 0.042\,t - 0.00045\,t^2$$

Which 0.042 is roughness growth rate and relates to quality of water.

In order to make the best hypothesis for relevant parabolic equation, for iron-based pipes with diameter smaller than 50 mm which relates more to growth rate of water in Asker municipality, there is a need to find x value in equation bellow:

$$e = e_0 + 0.26\,t - \mathrm{x}\,t^2 \qquad \text{Eq.(26)}$$

Differentiation of equation (11) showing the slope of the will be:

$$\frac{\partial e}{\partial t} = 0.042 - 0.00090t$$

Differentiation of equation (26) showing the slope of the will be:

$$\frac{\partial e}{\partial t} = 0.26 - 2xt$$

Assuming these two differentiations are the same:

$$x = 0.0028$$

Final equation for iron-based pipes with diameter smaller than 50 mm, suitable for quality of water in Asker municipality distribution system will be:

$$e = e_0 + 0.26\,t - 0.0028\,t^2 \qquad \text{Eq.(27)}$$

Reduction of effective diameter in aged **galvanized steel** pipes is complicated, since it may vary from one situation to another. Experiments shows that galvanized pipes in Asker municipality may be clogged after 15 years, or some old pipes are still in use. But in general, according to Kaur et al. (2018), 50% reduction of galvanized pipes in 50 years, could be a proper estimation.

But it is important to notice that rate of changes in pipes roughness and diameter as a result of the quality of water are higher at 15, 25, and 30 years old pipes. (Kaur et al., 2018) and (Shahzad & James, 2002)

Figure (3-2) and (3-3) shows changes in pipes roughness and diameter in respect to time in iron-based pipes.

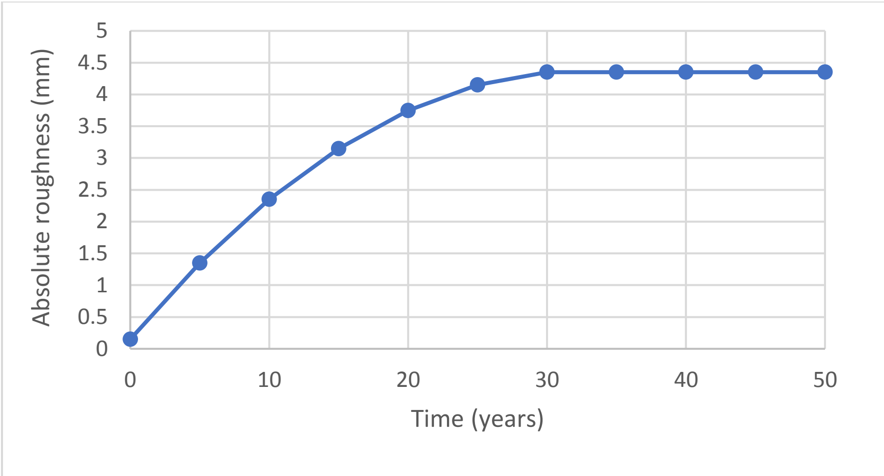


Figure 3-2: Roughness change over time

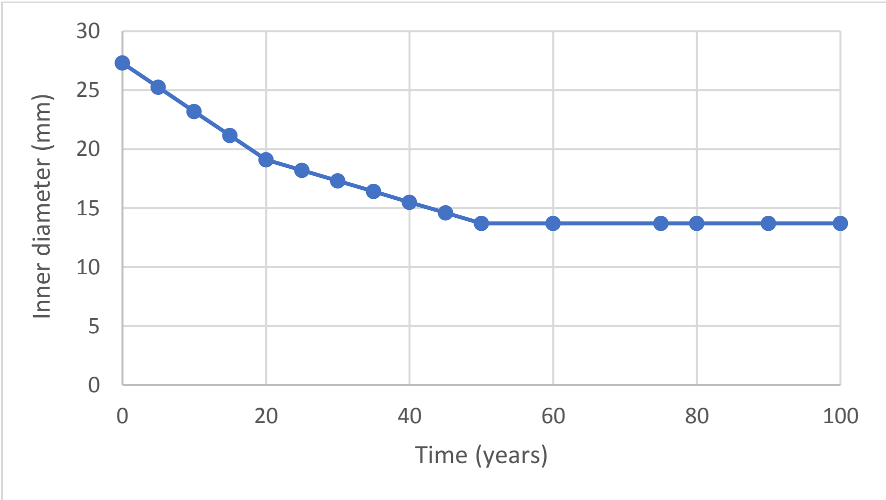


Figure 3-3: Diameter changes over time

For **galvanized steel** pipes with diameter smaller than 50 mm:

According to Kaur et al. (2018), inspections in water system in Norway and Estonia have shown that nominal pipe diameter can be reduced up to 50%. As discussed before, when pipes are new the roughness increases rapidly and then become steady.

For **Cast iron-** ductile pipes with diameter smaller than 50 mm:

Cast Iron- ductile is a very rough pipe. Roughness and inner diameter for aged pipes are calculated as the same method for galvanized steel pipes. It is assumed to reduce its diameter by 50% in 50 years.

Cast-iron ductile and gray inner diameter is mentioned in Gemini Portal while other types of pipe are usually mentioned as their outer diameter size.

For **Copper** pipes with diameter smaller than 50 mm:

Although copper pipes are metal but does not follow equation (9). Copper pipes are not corrosive, and roughness is as small as plastic pipes.

Flow in copper pipes are smooth and roughness is and according to Echávez (1997) Copper corrode but the change in diameter for 30 years old copper pipes is so very thin layer which can be removed easily.

PVC and PE (low or high density) pipes are all smooth pipes with zero or very small diameter and roughness changes.

3.3 Tapping Sleeves

As explained, loss coefficient is required for calculating minor head loss (Local pressure drop) in tapping sleeves. In old pipelines, diameter of the hole where main branch and main pipe are connected is unknown except there is a documentation for that and has probably changes as a result of galvanic corrosion where galvanized steel and copper are joint together.

- M: Main pipe
  (municipality's pipe)
- B: main Branch
  (service line, tapped into main pipe)
- S: Service line
  (other branches)

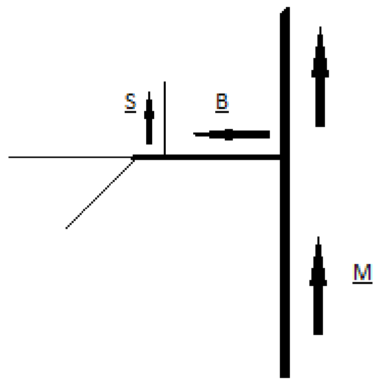


Figure 3-4: main pipe, main branch

According to technical provision for Asker municipality (*Tekniske bestemmelser*, 2017):

- Main pipes DN 125-300, it is allowed to connect a main branch with 38-mm hole and main branch up to DN 54 diameter.
- Main pipes DN 100, it is allowed to connect to main branch DN 35 diameter, with 32 mm hole diameter will be used.
- T-junctions will always be used for main branch bigger than DN 63.

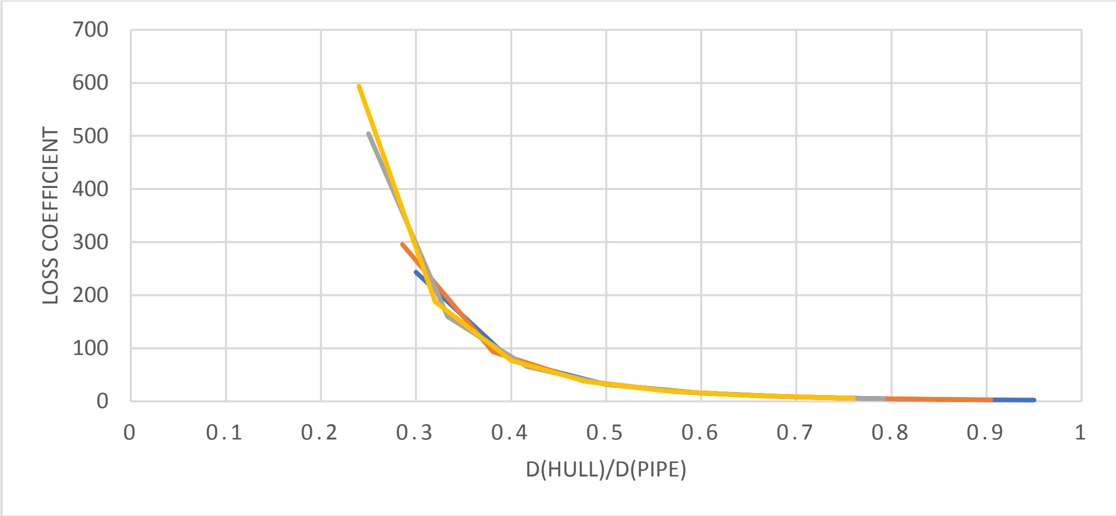


Figure 3-5: Loss coefficient in Tapping sleeves

When analyzing water distribution system considering old service pipes, there could be a lack of information in the case of diameter of the cutout hole inside main line connecting branch pipes. Therefor this information can be used when designing new systems but not sufficient in the case of systems which already exist or missing enough information.

Since the ratio of diameter in hull and service line vary from 0 to 1, the value of 0.6 could be a proper estimation as an average ratio. Loss coefficient according to equation (18) is: 15.

This is an assumption of average ratio between main branch diameter and the diameter of the cutout hole for all size of main branch. But many of the main branches found to have even smaller hole. The ratio of 0.33 will be assumed for these small cutout hole.

There have been seen several tapping sleeves at Asker municipality which their cutout hole was 10 mm while the pipe was 30mm. as a statistical sample, the loss coefficient of 200 will also be chosen to analyze the loss.

Minor head loss for each service line should calculated separately base on water velocity in main branch from main pipe.

3.4 AQUIS and GEMINI Portal

Like any similar simulation program, Aquis follows the principles of mass and energy balance and hydraulics rules. It computes head loss between two junctions by calculating elevation difference, friction loss and minor head loss between two junctions. (Aquis, 2012)

As (Aquis, 2012) claims, users are able to:

- Import network data with consumer information from external data such as Geographic Information System (GIS).
- Create and edit network information.
- Perform hydraulic simulations for design studies.
- Display simulation results as thematic views, profiles, and time series.
- Generate reports.
- Export data for external analysis.

A typical model consists of several objects such as nodes, pipes and valves. Reservoir are in node category, Valve and pumps are in pipe' category.

The ensuing figure shows a simple model of a network with nodes, pipes, pump, valve and a reservoir.

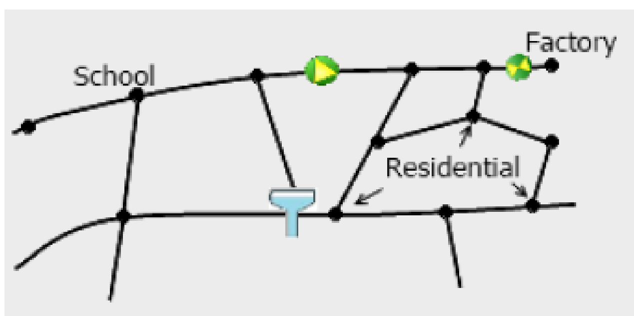


Figure 3-6:Aquis typical model with nodes, pipes (Aquis, 2012)

Units: All parameters should be defined in SI units.

Nodes: For inserting nodes, the elevation is necessary. Elevation information is taken from Gemini Portal.

Pipes: For inserting pipes in the model, the pipes' type, roughness and inner diameter is needed. Pipes' types are specified in Gemini Portal presents pipes' type which includes material, diameter and the year pipe was established which gives the age of the pipe. Diameter presented by Gemini are the outer diameter for galvanized pipe, PE, PVC and Copper. Gemini presents inner diameter of cast-iron ductile and gray.

To help Aquis distinguish between each pipe among many types, pipes should be specified by a name in which it presents pipes material, size, age and other characteristics if available.

Consumers:

Each consumer is connected to one and the closest pipe in the network, but each node may be connected to several consumers. Consumer type and flow needs to be defined for consumers. Consumer type is presented in time series table in a fraction of flow demand based.

Peak hourly flow demand for water distribution system is 160 (l/s) per person. This will be multiplied by the number of people living in each house and is required during morning from 8-10 am.

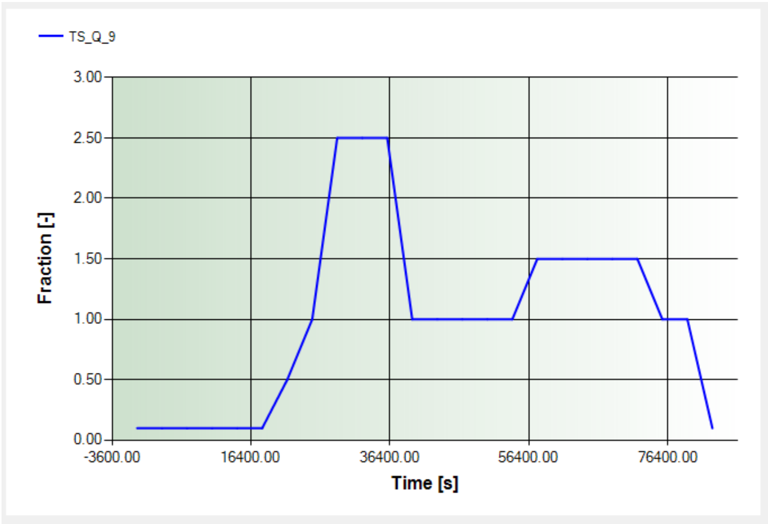


Figure 3-7: time serie for Peak hour demand (Aquis)

Net maximum simultaneously demand for each house is 0.8 (l/s)) and supersedes other type of consumers in a very short time interval of some seconds or minutes.

Garden irrigation water demand is 0.31 (l/s) will be added to peak hour demand in summer.

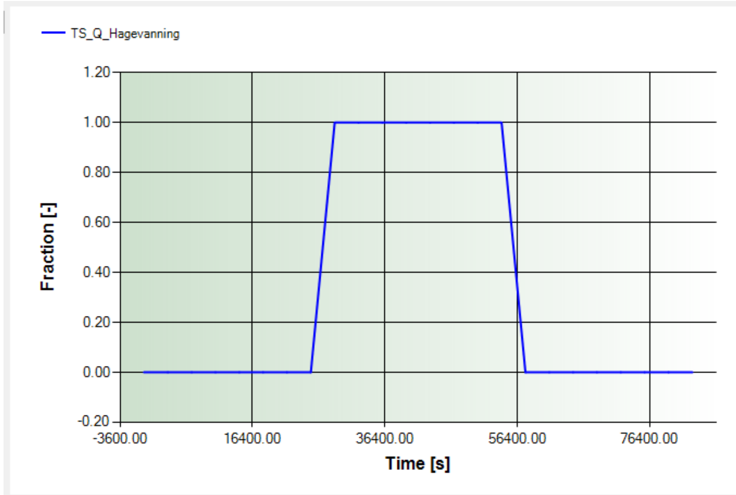


Figure 3-8: time serie for extra garden irrigation demand (Aquis)

Without any service pipe in the system, consumers demand will get affiliate as water demand to the closest junction in municipality's pipeline. Total water demand may be the addition of different demand types.

figure (3-9) shows consumers with average daily water demand linked (affiliated) to nearest node of municipality's pipeline by green lines. Brown points are consumption points calculated by equation (22) and number of people registered at each house (PE):

$$Q_{\text{peak- hourly}} = 0.00463\ \left(\frac{l}{s}\right) \times \text{PE}$$

Figure (3-10) shows consumers with garden irrigation water demand added to average daily water demand, inked (affiliated) to nearest node of municipality's pipeline by green lines. Brown points are consumption points calculated by equation (22).

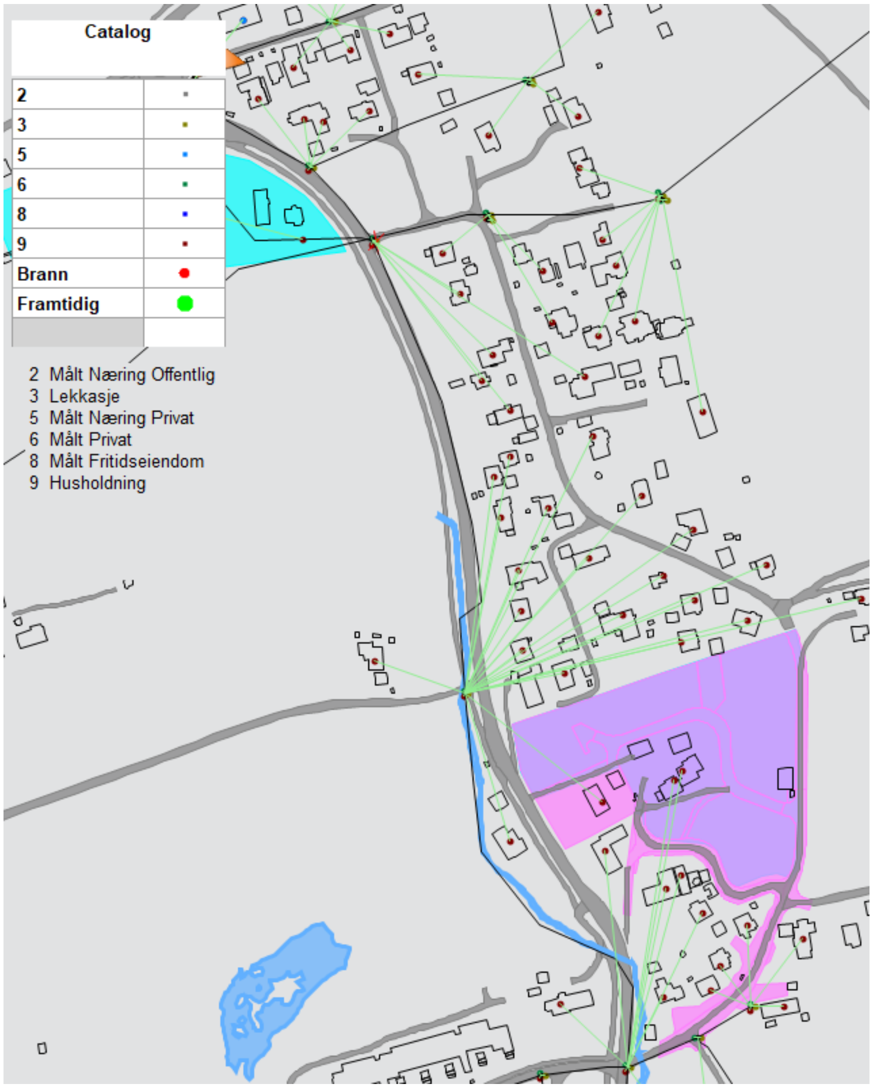


Figure 3-9: Average daily demand affiliated to the nearest node with no service lines designed

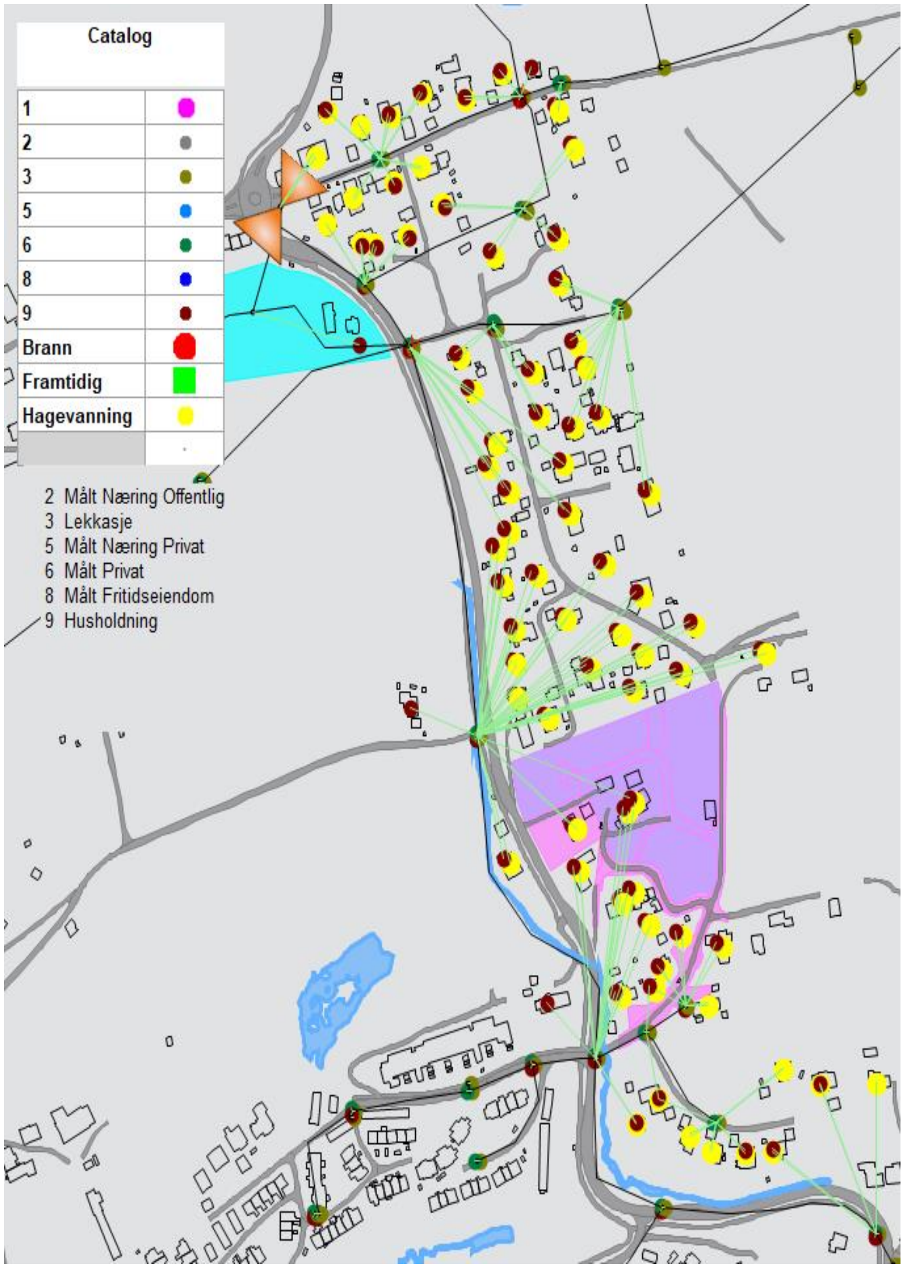


Figure 3-10: irrigation demand, affiliated to the nearest junction, when service lines are not designed.

Pipelines' material

As explained before, there are some pipelines which finds no information for them, there are also some other pipes which are known to be metal pipes but not specified which type. In the figure (3-11) pipes in red color are totally unknown, pipes in yellow are unspecified metal pipes Blue pipes are PE. These unknown pipes are mostly galvanized steel or copper pipes.

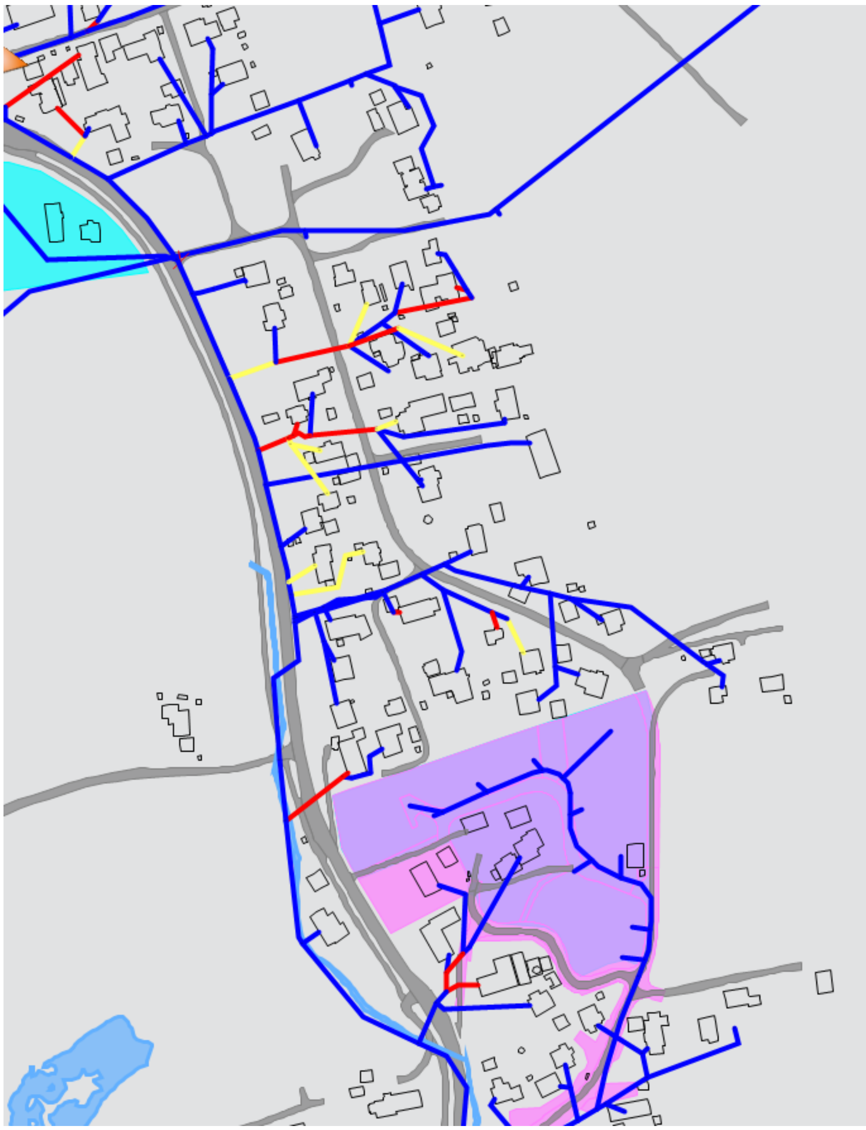


Figure 3-11: Pipes type base on Gemini Portal.

Those metal pipes with the diameter of 48mm, are most probably galvanized steel. Since 48mm copper pipes was and are not a common standard dimension. Metal pipes with diameter of 33 mm are probably galvanized steel, copper pipes of 1 ¼ , has a diameter of 31.8 mm which is very close to 33 mm, but the probability of being a galvanized steel pipe is higher.

Galvanized steel pipe and copper pipe both have standard dimension of 42mm, so the challenge will be to guess the pipe type by looking at neighboring houses or pipes, which year they are establishes and so on.

Unknown pipe close to copper pipes are assumed to be a copper.

When analyzing each pipe to estimate the type, the year of construction may be important. In the year between 1940 and until 1960-1970 the economy was bad and the use of cheap pipes and other building materials where more common. Galvanized steel pipes were mostly used since they are cheap. If they are metal pipe and constructed after 1970's they are most probably to be the copper pipe. Copper pipes were used in most pipelines until plastic pipes become the most popular pipes, which has good quality and are cheap.

Considering unspecified or unknown pipes as galvanized pipe leads to a safer simulation. Galvanized pipe has bigger roughness value and the reduction in cross section area may happen more due to corrosion, encrustation, sedimentation or other processes. Therefore, if the system works fine when galvanized pipe is established, then it will work well if they were copper pipes.

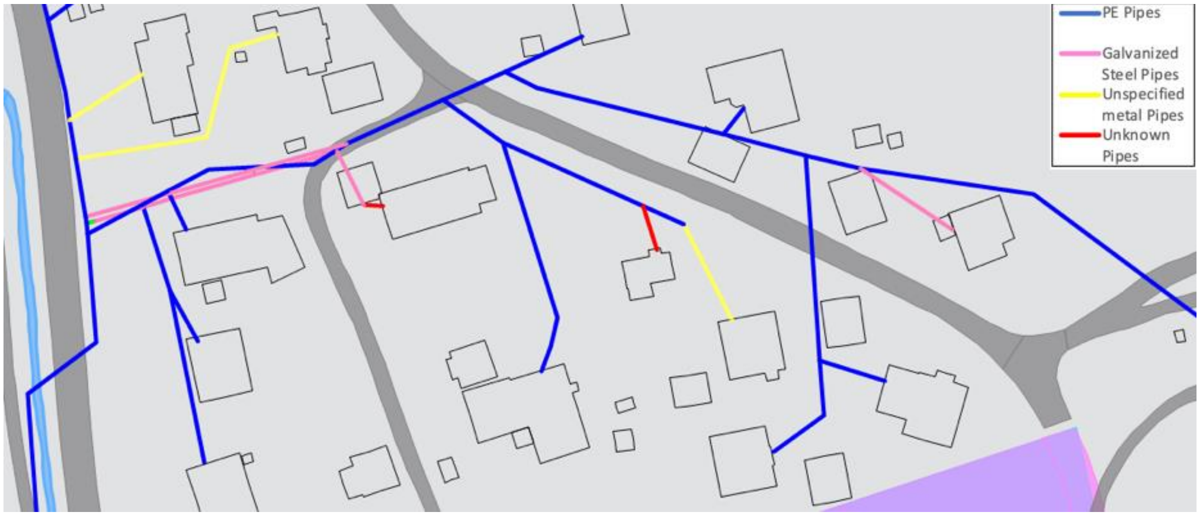


Figure 3-12: Predicting pipes' material-1

Since this area are mostly plastic type and galvanized pipe, all unknown pipes are assumed to be as galvanized pipes.

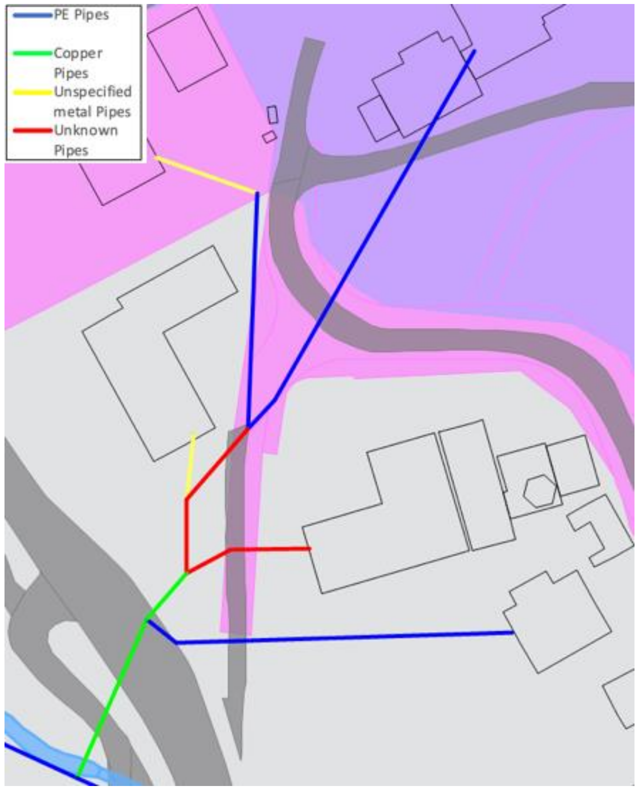


Figure 3-13: predicting pipes' material-2

These pipes are most probably copper and assumed to be as copper pipes.

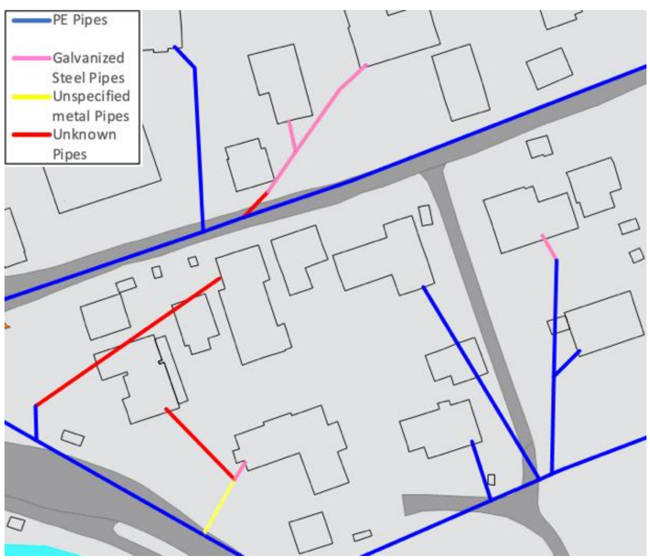


Figure 3-14: Predicting pipes' material-3

Red and yellow pipes are assumed to be galvanized steel pipe.

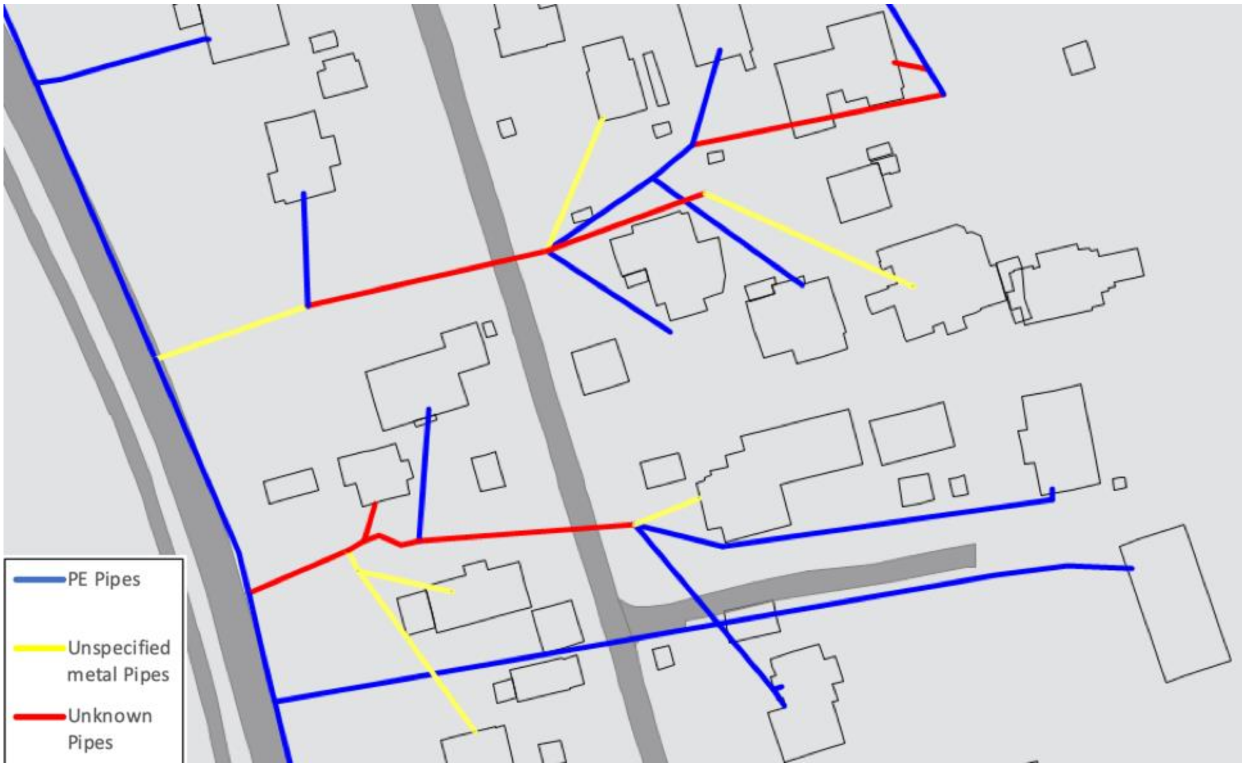


Figure 3-15: Predicting pipes' material-4

To make an assumption for material type of the pipes, yellow pipes with 48 mm diameter are taken as galvanized pipes, 33 mm are most probably galvanized pipes and 42 mm pipes are also assumed as galvanized pipe.

The total pipeline with respect to pipes' type will be:

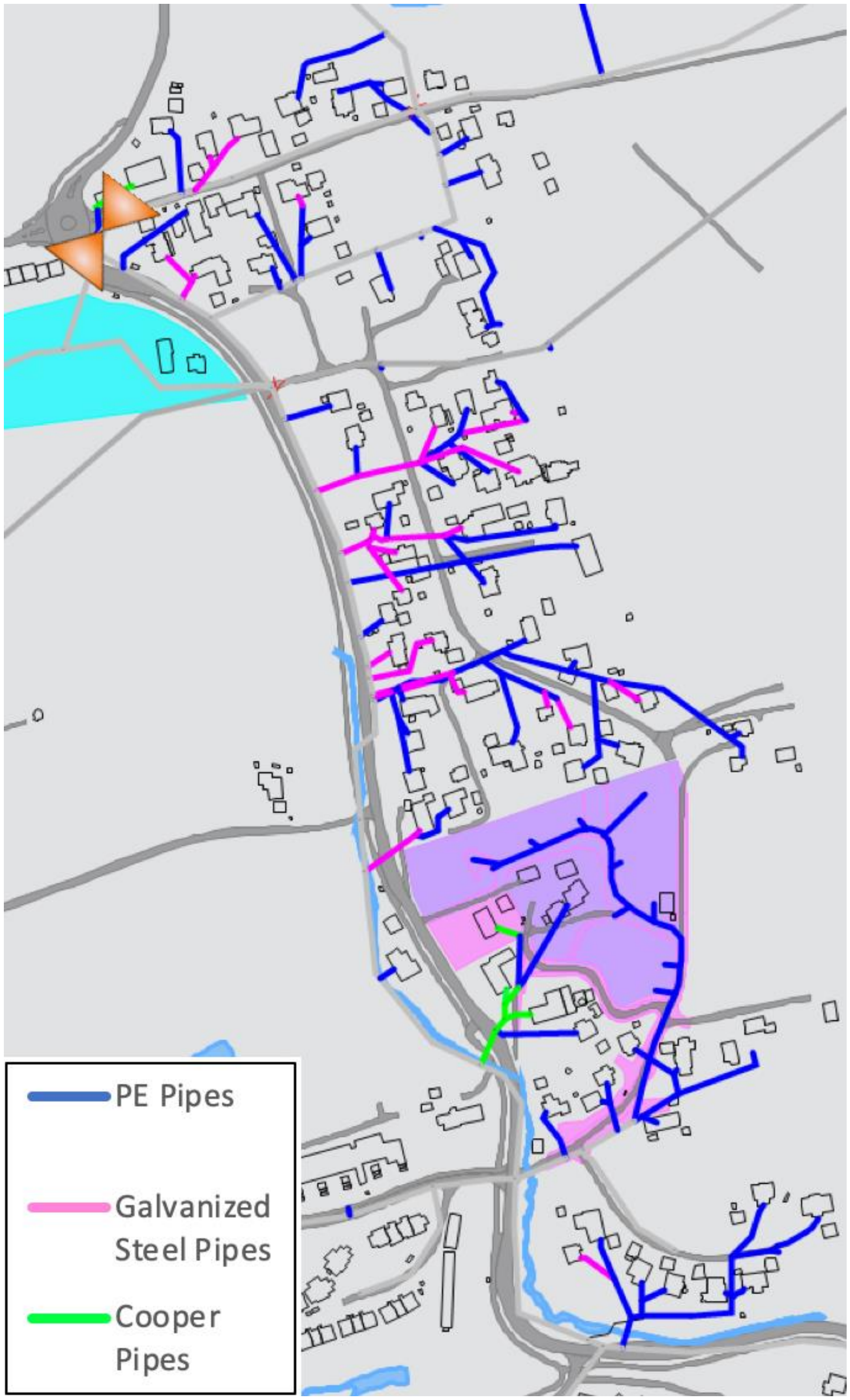


Figure 3-16: Pink pipes are galvanized steel and green pipes are copper pipes.

Minor head loss in Aquis:

How Aquis calculates minor head loss is not clear. Aquis calculated total pressure drop base on Colebrook and White's formula and Darcy-Weisbach fromula, which according to "Aquis help" allows by local pressure drop in pipe section, to add pressure drop coefficient in elbows, and T-junctions into the system.

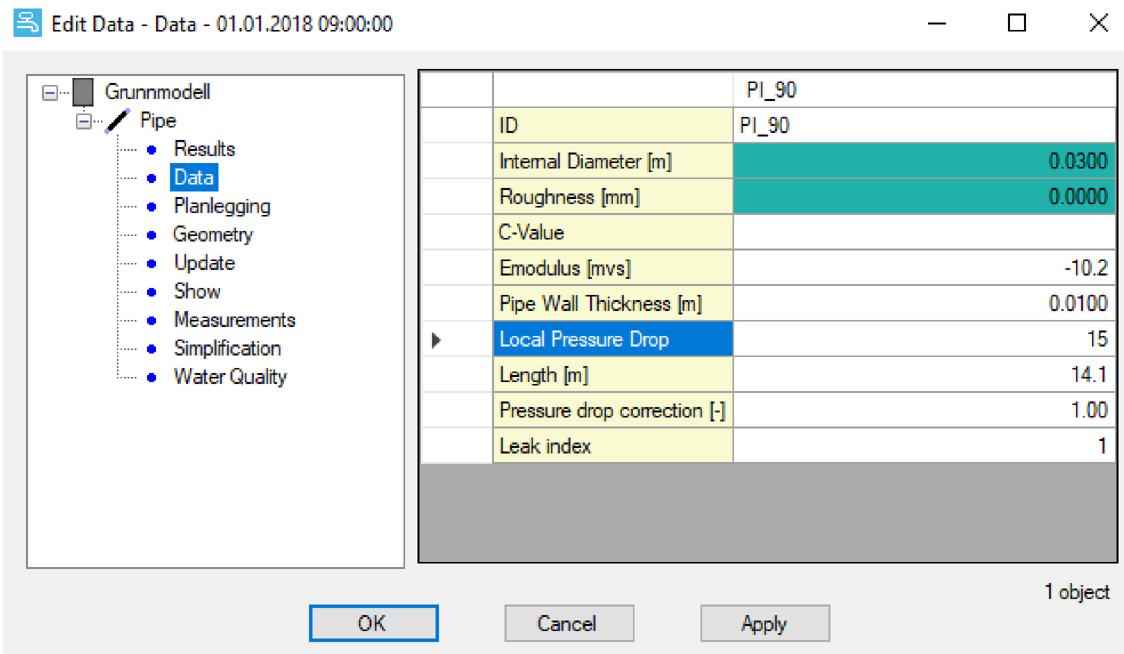


Figure 3-17: Loss coefficient in Aquis

When examined so, by loss coefficient of 15, the pressure drop was significant, reducing pressure from 49.1 mvs to -2260 mvs which according to theoretical formula (16), the pressure drop was supposed to be 0.12 m.

For testing if local pressure drops are assumed in Aquis or not, with no roughness, simulation resulted in no drop.

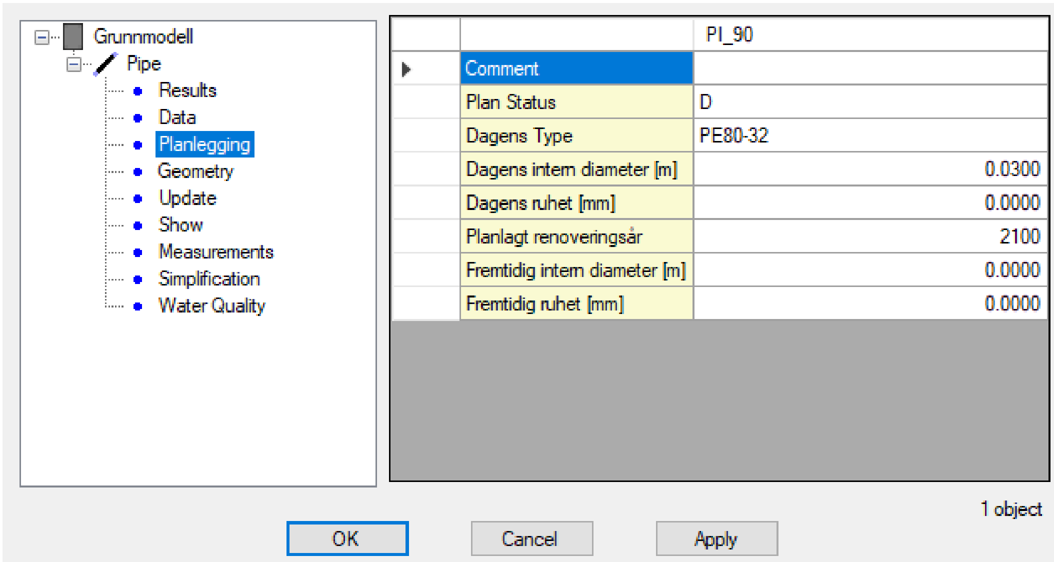


Figure 3-18: Checking if minor head loss are calculated automatically in Aquis

This paper will simulate results, assuming that local pressure drops are neglected in hydraulic model, therefore actual pressure loss are greater than what Aquis calculates (until a proper method is found to insert the loss coefficient into the program). Therefore, actual pressure of nodes is the pressure stands in Aquis minus minor head loss calculated by equation (16).

$$P_{Actual} = P_{Aquis} - H_{minor-loss} \qquad \text{Eq.(28)}$$

All the nodes connected to the main branch of the main pipe, lose pressure at the point main branch is connected to main pipe. In a typical service lines in Asker, minor head loss consists of losses in connecting point and 2 bends.

Two values of d/D is assumed. One, when $\frac{d}{D} = 0.6$ and another when $\frac{d}{D} = 0.33$:

$$H_{minor-loss} = \left[15\left((\frac{d}{D} = 0.6, tapped\ sleeve\right) + 2(90°\ Bend)\right]\frac{v^2}{2g}$$

$$H_{minor-loss-1} = 15.6 \times \frac{V^2}{2g} \qquad \text{Eq.(29)}$$

$$H_{minor-loss} = \left[15\left(\frac{d}{D} = 0.33, tapped\ sleeve\right) + 2(90°\ Bend)\right]\frac{v^2}{2g}$$

$$H_{minor-loss-2} = 200 \times \frac{V^2}{2g} \qquad \text{Eq.(30)}$$

- V: Velocity is the velocity of flow through the first branch from main pipe.

Picture (3-17) shows municipality pipeline introduced as main pipe and several branches. Yellow lines represent municipality's pipeline (main pipe) and black circles shows where in the pipelines are branches tapped to the main pipeline. The first branch from a main pipe (municipality pipeline) is called main branch since as figure shows there are also several branches afterwards, in service lines. But these pipelines are connected to each other by T-junctions. Although several local pressure losses may happen from municipality's pipeline to end point (receivers), they are all ignored in this thesis since they are pretty small values. The only considerable minor loss is at the tapped point between main pipe and the main branch.

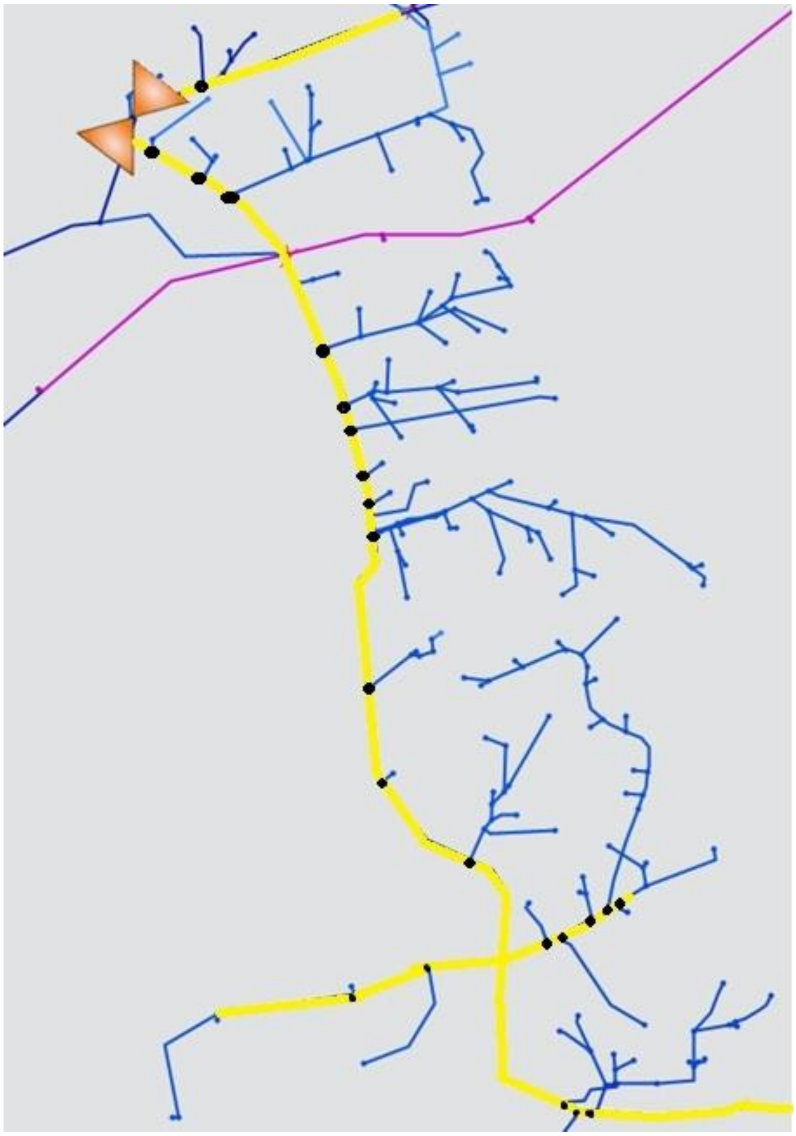


Figure 3-19: Branches from main pipeline

4 RESULTS

Different scenarios are presented here to show results in hydraulic model. Figure (4-1) shows a selected area inside Askerelva pressure zone which service line will be designed to.

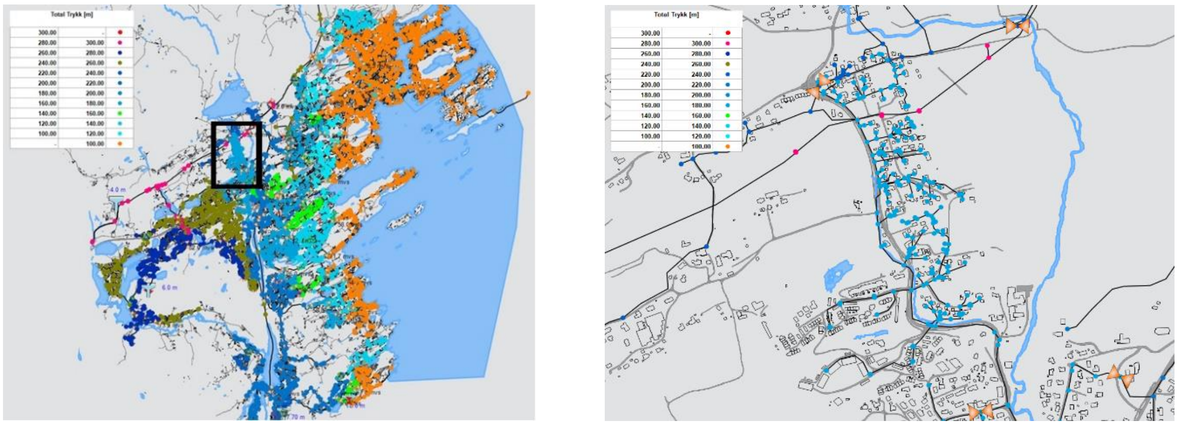


Figure 4-1:selected area in right figure, which is supposed to be analyzed

Calculated parameters and assumed data will be categorized and used in order to find the head loss. Results will be presented in tables (appendix) and illustrated by graphs.

Result should be compared in different scenarios:

- The first scenario is to analyze pressure loss for worst diameter reduction selection. To compare the results of using galvanized steel pipes which lose their flow capacity with time and cause more pressure loss in the system to the result of using plastic or copper pipe which do not lose their capacity with time.
- Second scenario is to analyze pressure loss for biggest value of water flow. To compare result for peak hour demand, garden irrigation and expected total water.

4.1 Pressure loss presented in graph

In this part, prediction of pressure loss for roughness growth in time, and diameter reduction in old pipes, are illustrated in graphs. Tables in appendix, presents exact values of roughness growth and diameter changes, for further usage and to see closely how different parameters react to one another.

Pressure loss of different material types are predicted based on two main scenarios of neglecting diameter changes and scenario of considering is major. Among the pipes used in service lines, iron-based pipes like galvanized and cast iron are the most corrosive. Diameter of these pipes will decrease with time. Each pipe is named and specified by its material, outer diameter (mm), age of the pipe

Figure (4-2) shows the difference in roughness changes with time for iron-based material pipes. And presents that the roughness in small pipe does not grow linearly. And that the rate of roughness growth is faster in first 25 years. It will continue about 50 years and after 50 years there will not be drastically growth in roughness.

Figure 4-2: Roughness change with time for iron based pipes

Figure (4-3) represents diameter reduction of the same material type of pipe. It is assumed as 50% reduction in 50 years, regardless of size of the pipe.

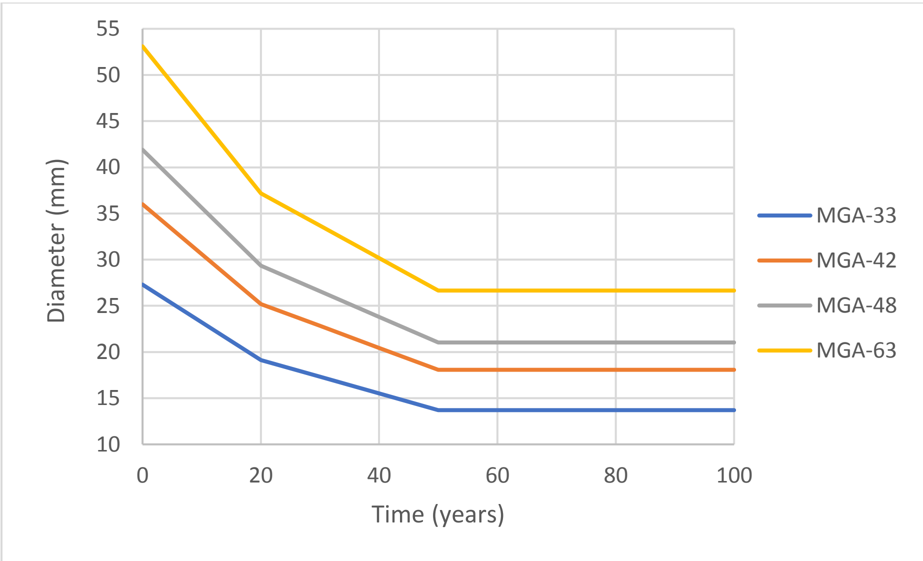


Figure 4-3: Diameter changes for different size of galvanized pipe

Figure (4-4) compares head loss for different size of the same material type of the pipe when same flow rate. As expected, the pipe with smallest diameter, has biggest head loss. Pressure loss for the same material pipe with different diameter, is very helpful to understand the effect of diameter on pressure loss.

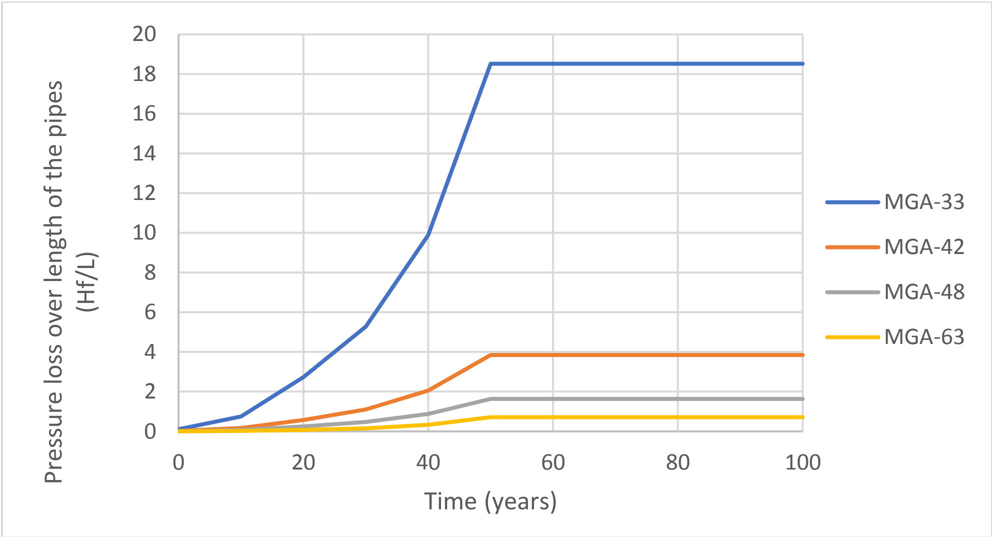


Figure 4-4: Pressure loss of different size pipes by expected total water demand in service lines

Figure (4-5) shows the same situation, when the flow rate is changed to irrigation demand. Pressure loss follows the same pattern as previous figure.

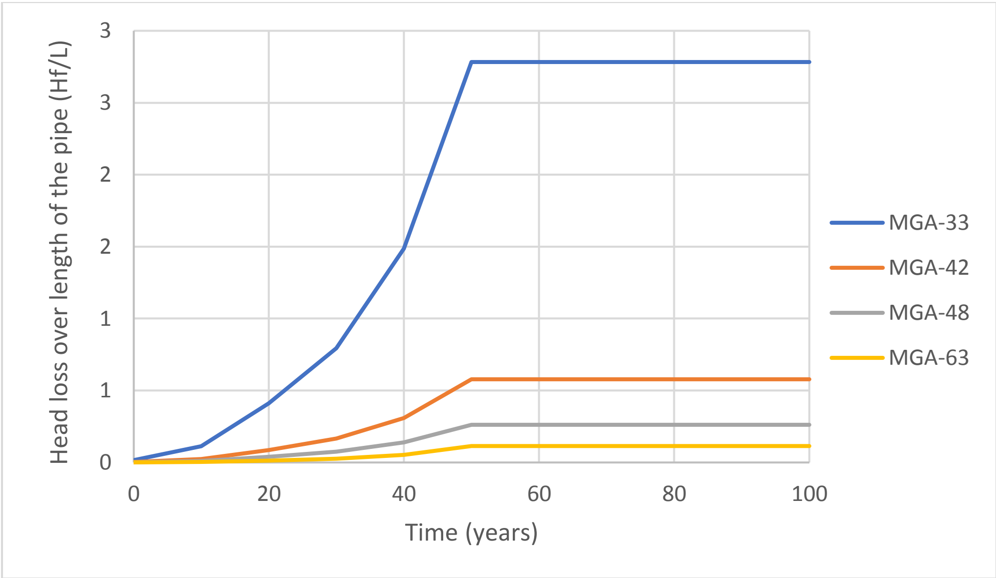


Figure 4-5: Pressure loss of different size pipes by irrigation demand

Figure (4-6) compares pressure loss of galvanized steel pipe with diameter of 33 (mm) for two different water flow rate.

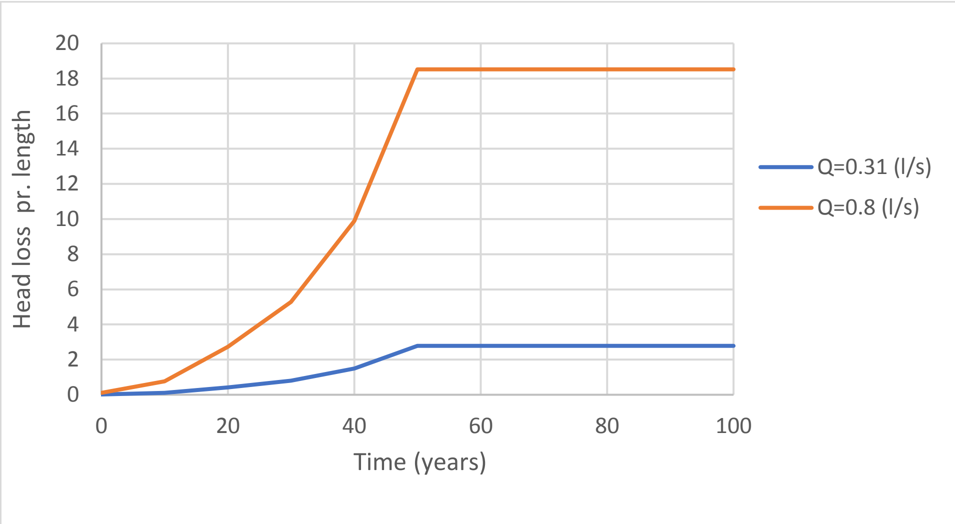


Figure 4-6: Pressure loss for MGA-33 by different demand

Figure (4-7) compares pressure loss of galvanized steel pipe with diameter of 63 (mm) when water flow rate is different. Comparing head loss in figure (4-6) and figure (4-7) shows that water flow and diameter of the pipe has a big impact on pressure loss.

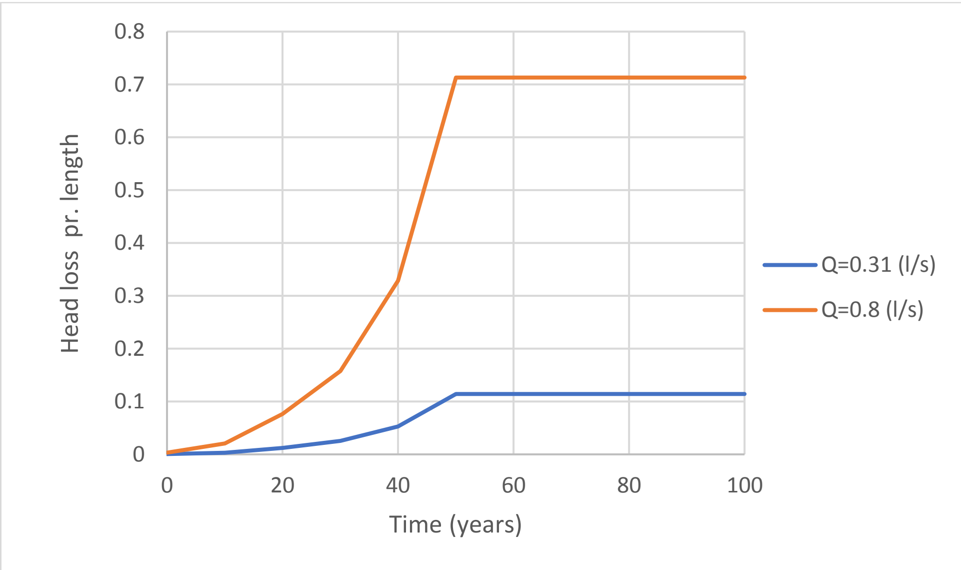


Figure 4-7: Pressure loss for MGA-62 by different demand

Figure (4-8) shows that cast iron pipes follows the same pattern as galvanized steel pipes.

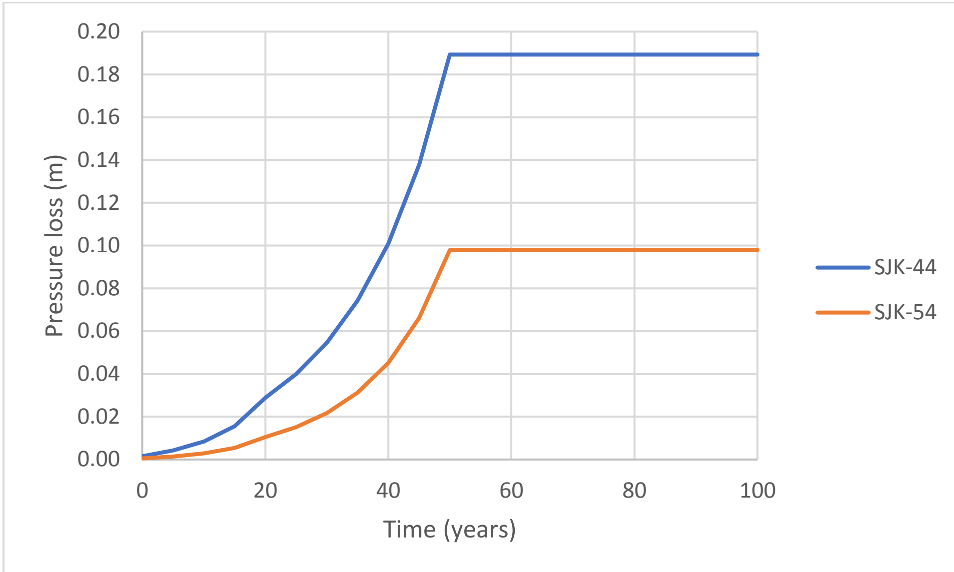


Figure 4-8: compare pressure loss for SJK-44 and SJK-54

4.2 Simulation Results:

4.2.1 Introduction:

Result from simulating the hydraulic model is presented in figures taken from Aquis. This will be divided into two parts as pervious calculations. First when system neglects decrease in pipes' diameter with time for iron-based pipes and second simulation result by considering the probable diameter reduction.

In each part, system will be analyzed for 3 values of water flow: peak hour demand, garden irrigation demand, and expected total water demand.

Pipes materials are mostly galvanized pipe and PE, according to chapter 3.4. Selecting galvanized pipe will make simulation over safe.

4.2.2 Roughness increases, diameter is constant

Beside the effect of roughness growth on pressure loss, it is also important to analyze the effect of water demand on pressure loss. In a process of analyzing the effect of roughness growth, a proper system ought to provide all these 3 demands.

Material type of pipes are selected, which specifies roughness growth and diameter of the pipe, next step is to define a water demand which system should be able to provide for users. The hydraulic system will be simulated for 3 types of demands as mentioned before: Peak hour demand, garden irrigation demand and expected total water demand for service lines.

When analyzing each condition, first figure shows the location of the consumers and type of water demand, and then pressure condition are provided in figures from simulated system.

4.2.2.1 Peak hour demand

Water distribution system provides the average water demand for consumers in each house varying by the number of people living there, presented by dark red circle in figure (4-9). When consumers are defined to the system, system will affiliate each consumer, to the nearest node. Figure (4-10) shows the simulation result for described situation and shows that system is able to gives the expected total water pressure for all residents. All blue pipes and nodes show the proper pressure of 20-90 (m) for consumers.

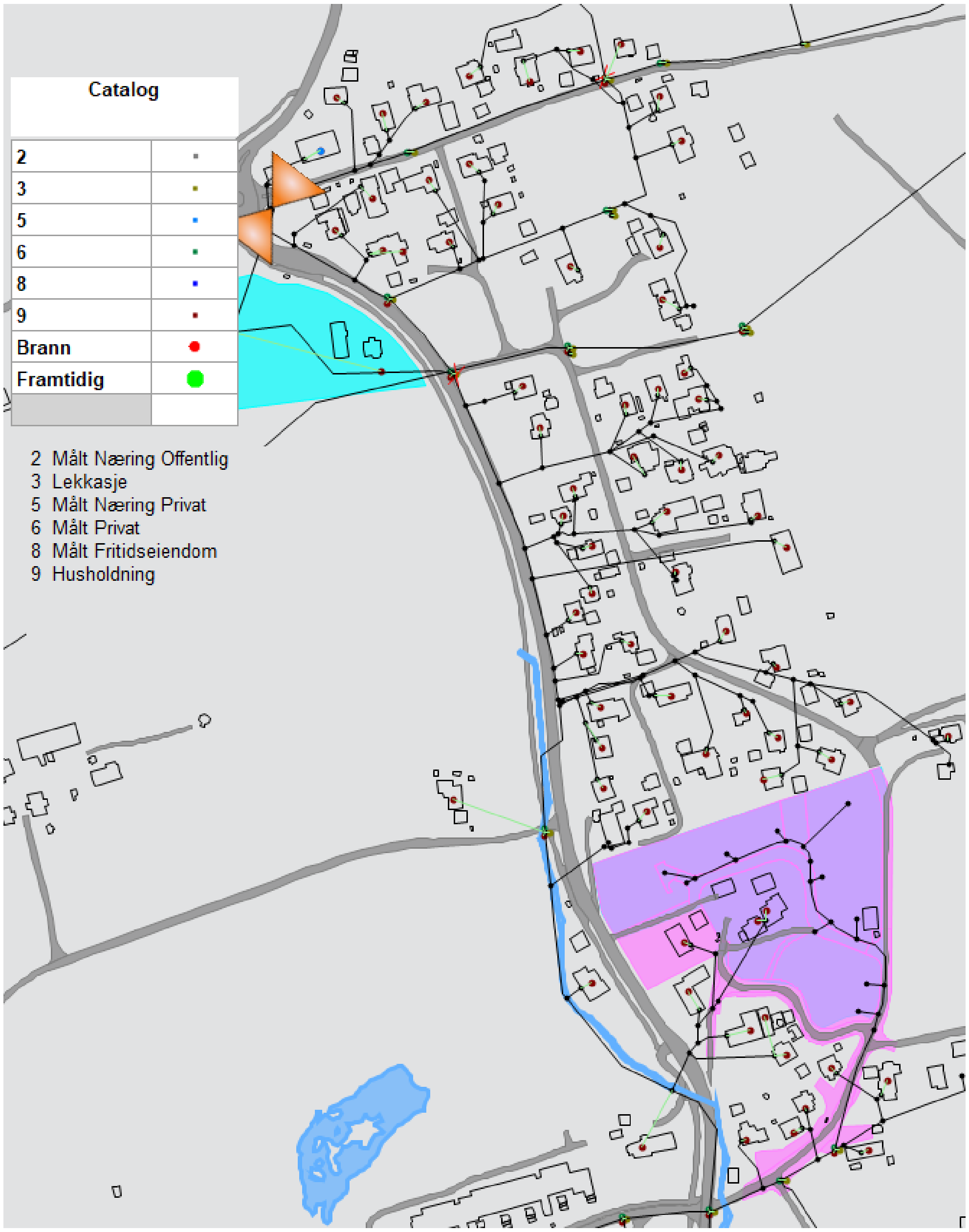


Figure 4-9:Average daily water demand for consumers in each house, affiliated to the nearest node.

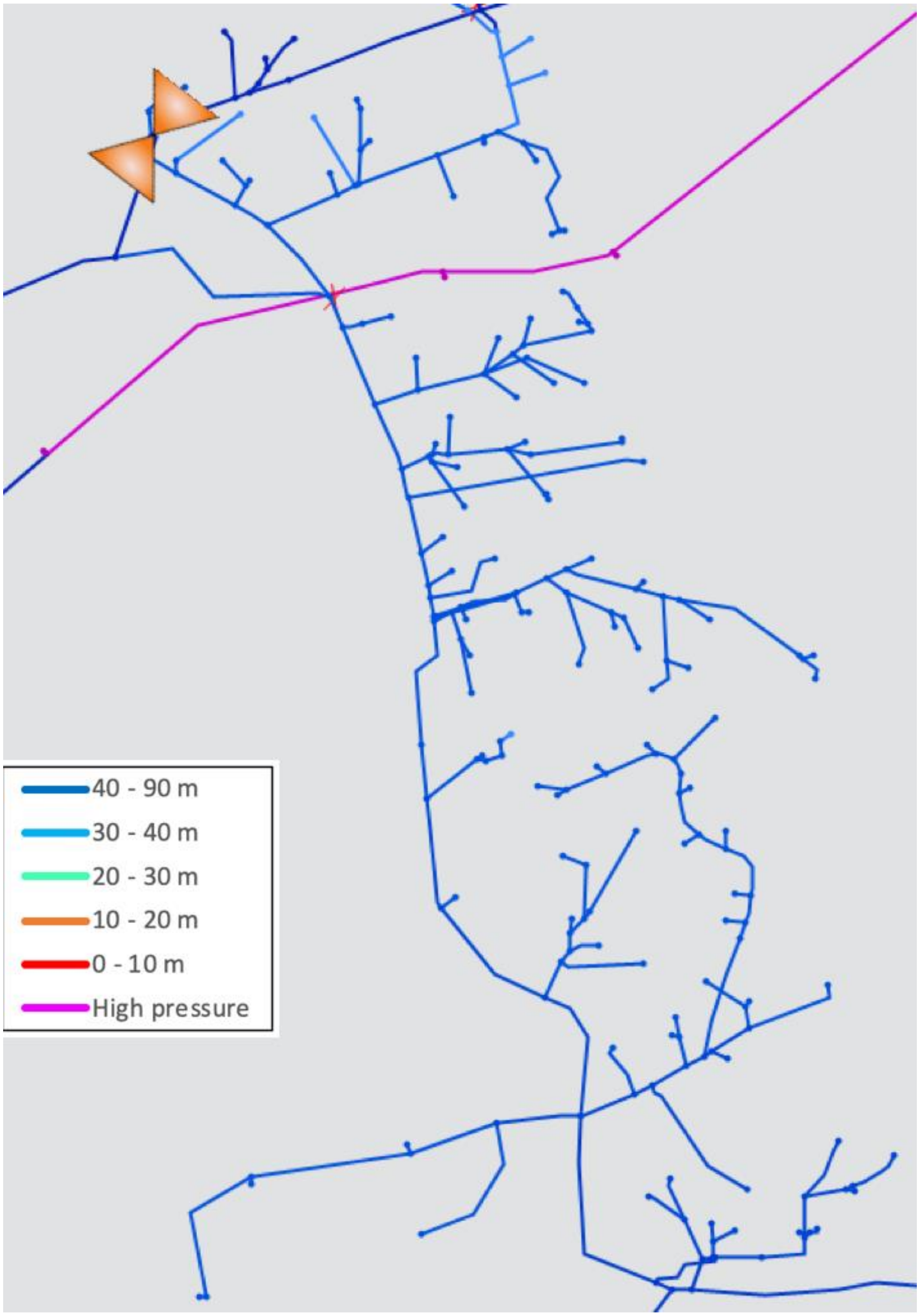


Figure 4-10: Pressure results for peak hour water demand

The result of the simulations shows pressures in the end nodes that satisfy all consumers.

4.2.2.2 Garden irrigation:

Distribution system should be able to provide the extra required amount of water for irrigating gardens. This extra amount will be defined to the hydraulic system in a new demand series as garden irrigation and are shown in yellow circles in figure (4-11), which are affiliated to nearest node. Figure (4-12) shows the simulation result, for irrigation demand at 8:00 to 10:00 in the morning, when daily demand is at the peak consumption. Results shows that the system is capable of providing a good water pressure for users, some users may meet lower pressure, but is not a noticeable change.

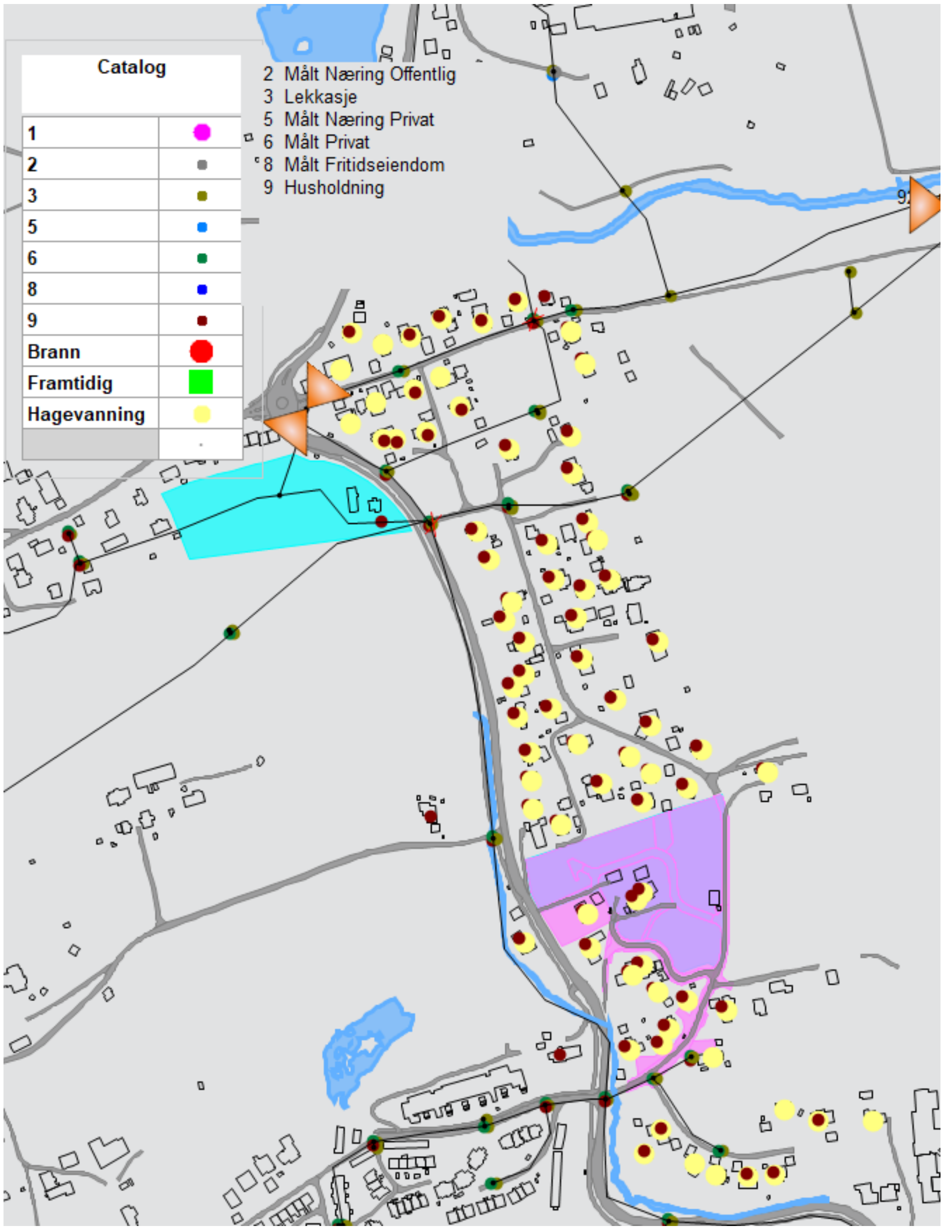


Figure 4-11: Extra water demand for garden irrigation in yellow circles

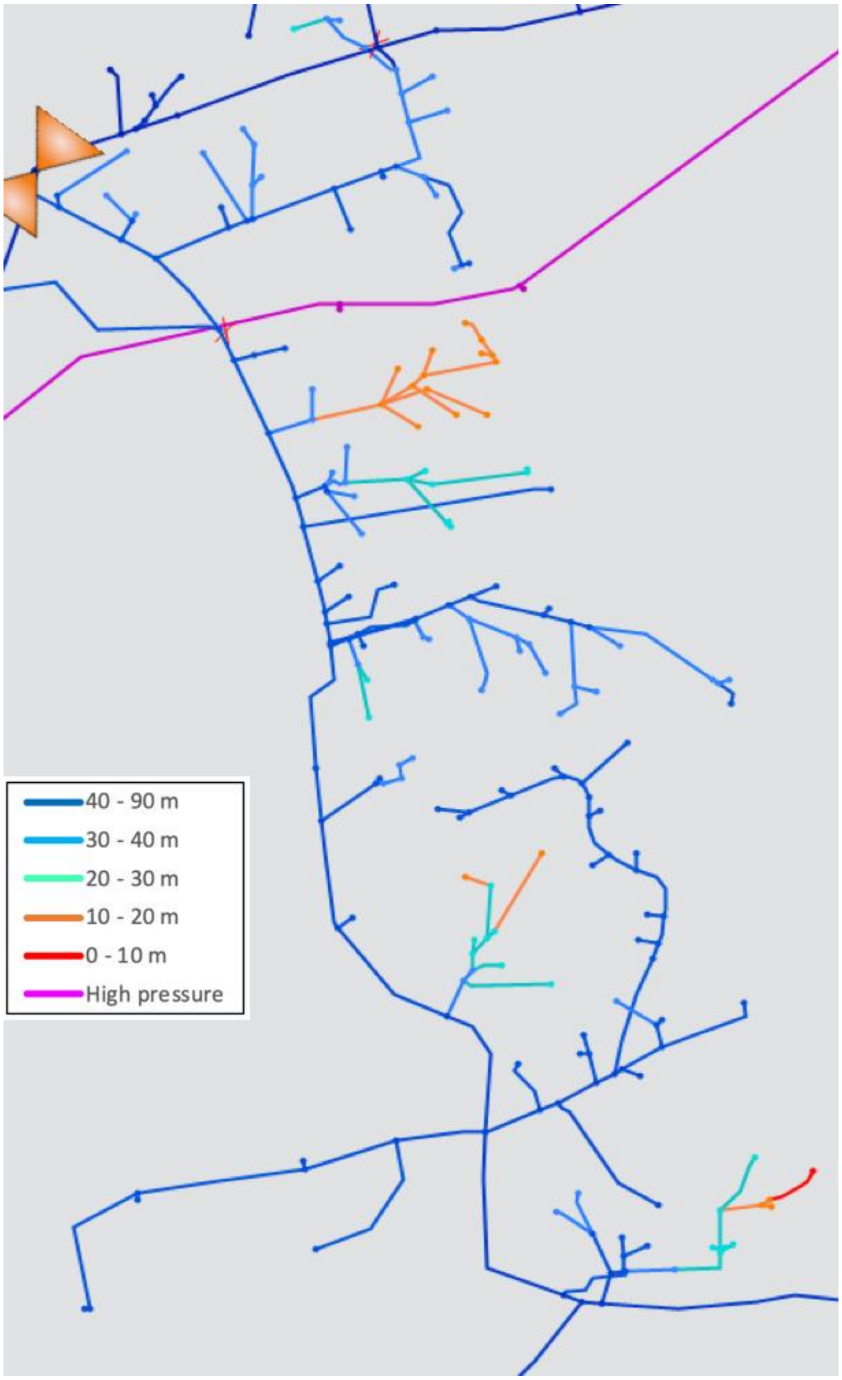


Figure 4-12: Pressure results, when all residents use irrigation water demand.

Although there is low pressure (lower than 20 m) at some points, the system in total works just fine.

4.2.2.3 Net maximum simultaneously demands:

Service lines in a hydraulic system, are required to provide expected total water demand of a house for a time interval of seconds or minutes.

In order to simulate the hydraulic system for expected total water demand for service lines, several random users are selected to see if the water system could deliver the required amount of water with proper pressure. Green dots at figure (4-13) represent the expected total water demand, defined for Aquis. Figure (4-14) shows pressure simulation results, which all blue line and node, represent a proper pressure of 20-90 (m) in the system.

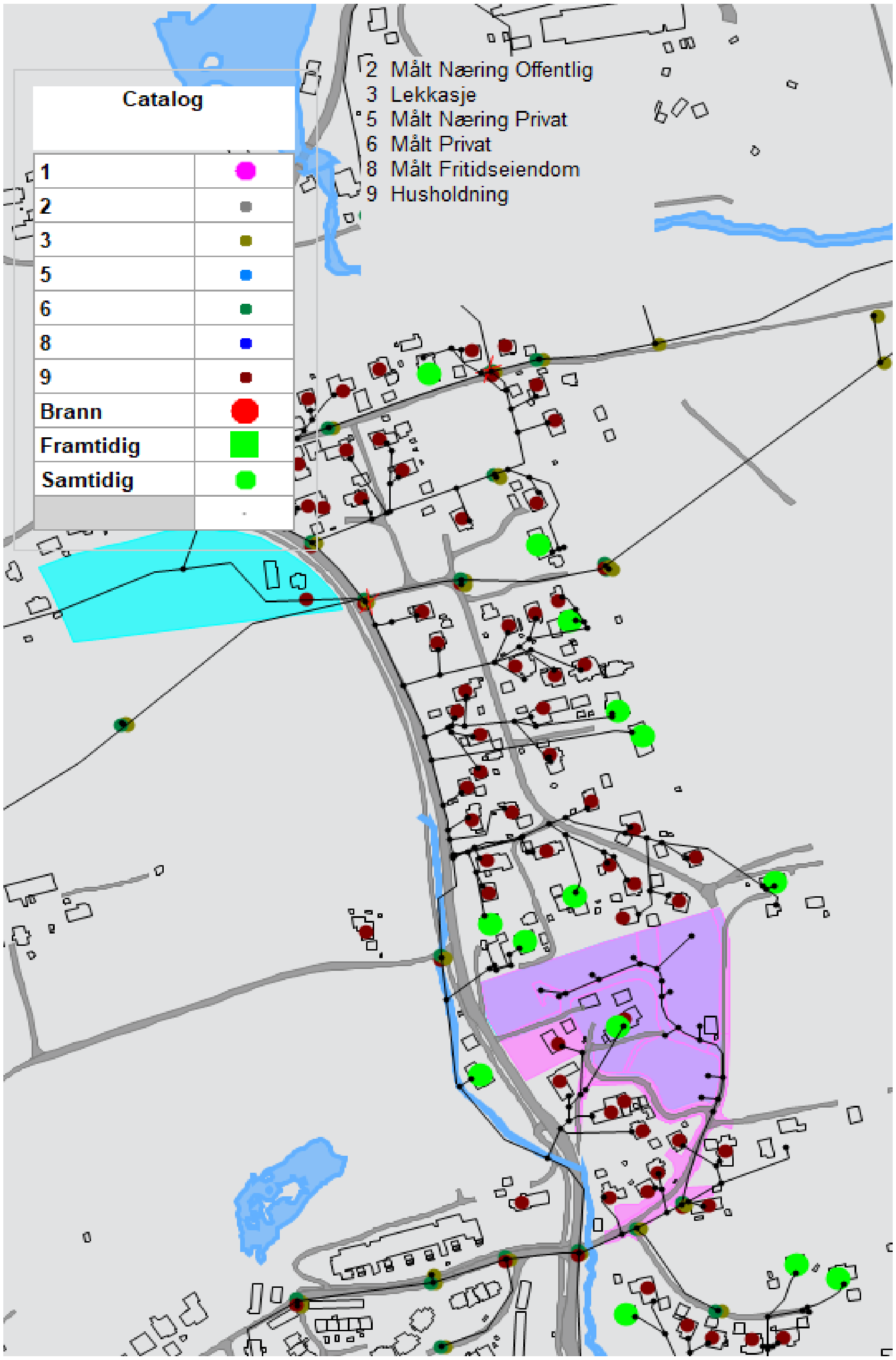


Figure 4-13: Green dots reprent the expexted total water demand

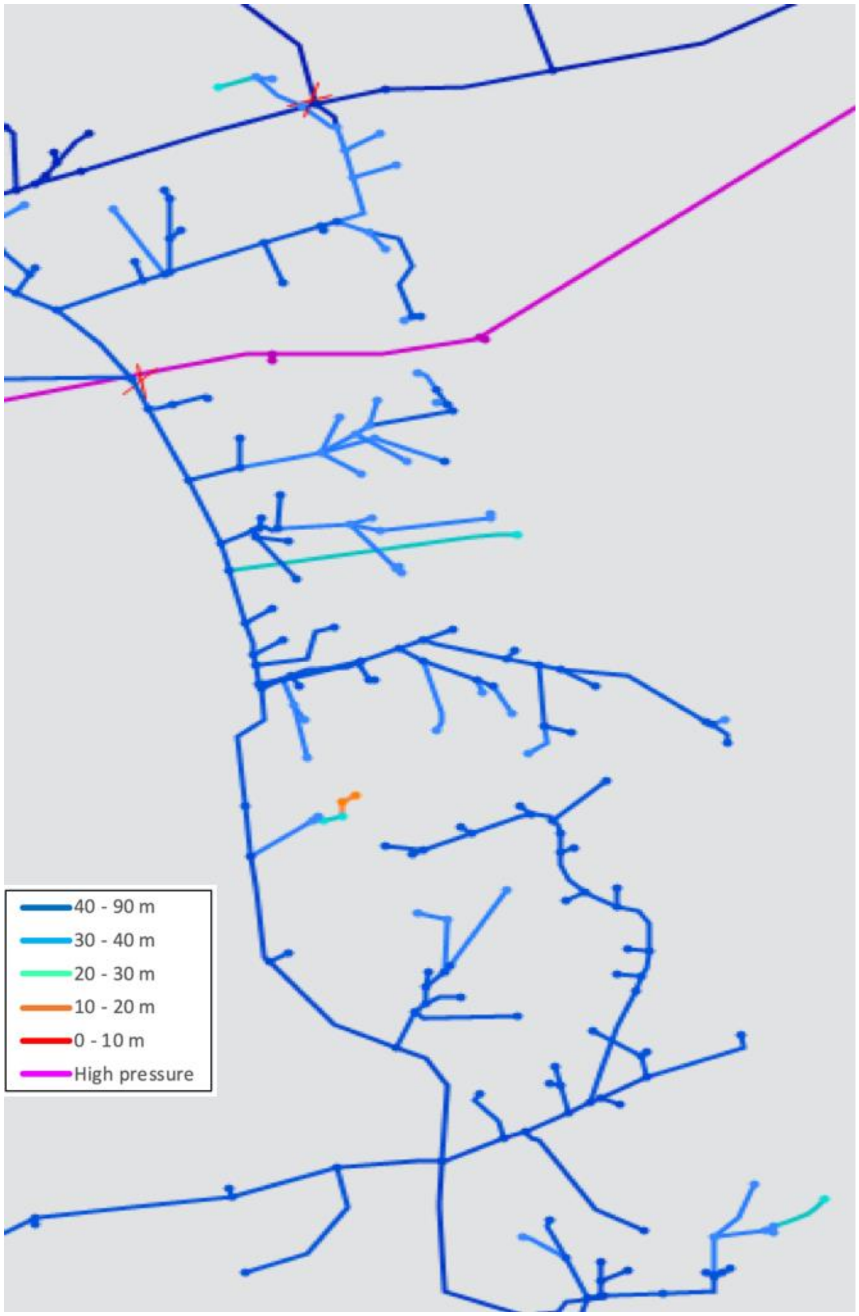


Figure 4-14: The simulation result for pressure for expected total water demand

Results shows that users will have a proper water pressure. Most of the receivers, except the point in orange, will have sufficient pressure, which shows system just works well.

4.2.3 Roughness increases, diameter decreases

Effect of roughness growth and diameter reduction on pressure loss will be analyzed in this part. Among material type of pipes in service line, the diameter of galvanized steel pipes and cast iron pipes, will reduce. This thesis assumed that diameter of these pipes reduced about 50% in 50 years and after 50 years, the changes are not noticeable. When pipes' materials are selected, which specifies roughness growth and diameter reduction of the pipe, then those 3 types of demands which was mentioned before, will be defined to the hydraulic model. Demand will be affiliated to nearest node and the hydraulic system will be simulated for affiliated demands which as mentioned before are: peak hour demand, garden irrigation demand and expected total water demand for service lines.

When analyzing each condition, first figure shows the location of the consumers and type of water demand, and then pressure condition are provided in figures from simulated system.

4.2.3.1 Peak hour demand:

Pressure results from simulation mode, presented in figure (4-15) shows that although dimeter of galvanized pipes has reduced to 50% and the roughness has increased, the system is still capable to provide proper water pressure for all residents. All blue pipes and nodes have the proper pressure of 20-90 (m) for consumers.

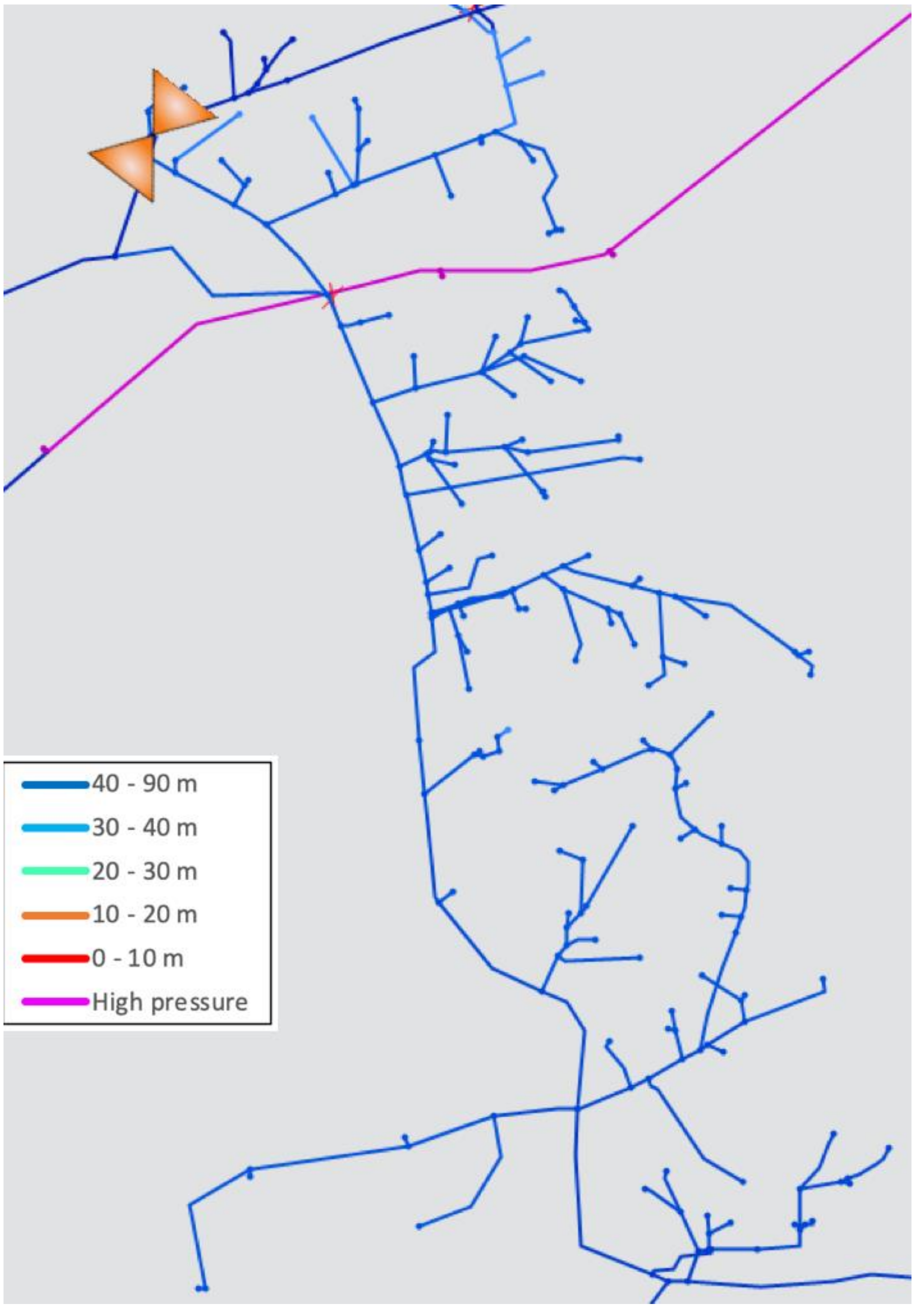


Figure 4-15: Simulation results, when roughness increases and diameter decreases

No low pressure was observed when analyzing the system for peak hour demand when diameter reduces and roughness increases.

4.2.3.2 Garden irrigation:

Water consumption increases in summer for irrigating gardens. This extra water consumption should be provided for residents with good pressure. Garden irrigation water demand is shown in yellow dots in figure (4-11) which are affiliated to nearest node. Figure (4-16) shows the simulation results for irrigation demand in summer. Aquis shows a very big negative pressure, for the purple pipes connected to nodes in red. Pipes in purple are generally high-pressure pipes, but are connected to red nodes which has have zero or very low pressure. These combination makes a big negative pressure. It may sound complicated since there is no such thing as negative pressure in reality, but this is how Aquis presents a disruption somewhere close to those pipes. In reality there is no water flowing in these pipes of the system.

When diameter of the pipe has reduced to 50% and roughness has increased, and also water flow rate is high, the system is not capable of delivering water with a good pressure.

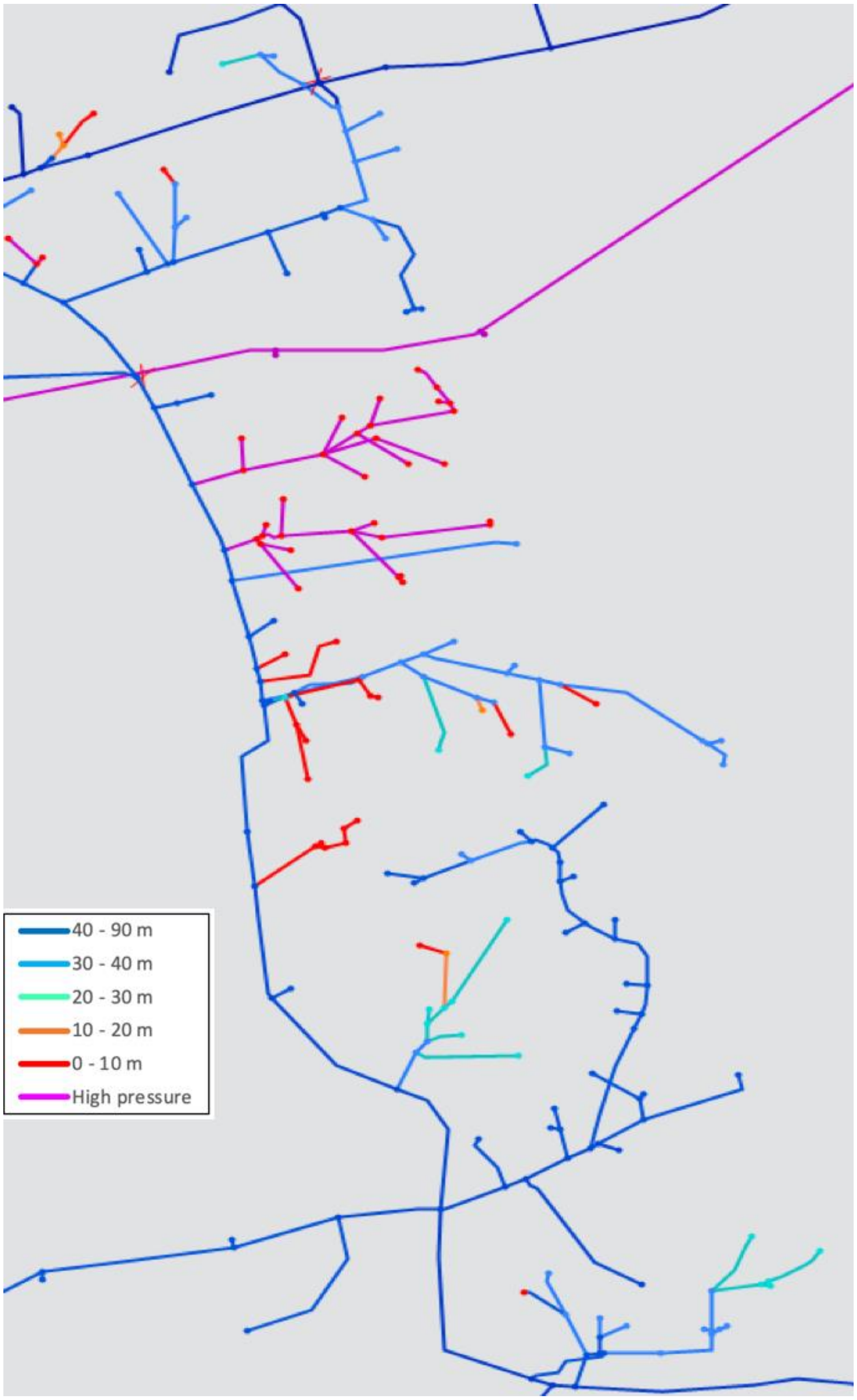


Figure 4-16: Water pressure for irrigation demand, when diameter reduction and roughness growth, are both considered.

4.2.3.3 Expected total water flow

Although service lines in a hydraulic system, are required to provide expected total demand for receivers, hydraulic system will be analyzed for one house at a time, since expected total water flow is a big value. Consumer with a blue circle in the figure (4-17) represents the expected total water demand, and other points with dark red, represent the average daily demand. Figure (4-18) shows the simulation pressure results. It shows that hydraulic system, in which diameter of galvanized steel pipes are reduced to 50% is not able to provide proper water pressure for residents. As figure (4-18) shows, not only the house with maximum simultaneously consumption has negative pressure, but also caused other pipes and nodes in pink to have low or negative pressure.

Location 1:

Figure 4-17:blue circle is expected total water demand- Location 1

Figure 4-18: simulation results for expected total demand- Location 1

Location 2:

Figure 4-19: blue circle is expected total water demand- Location 2

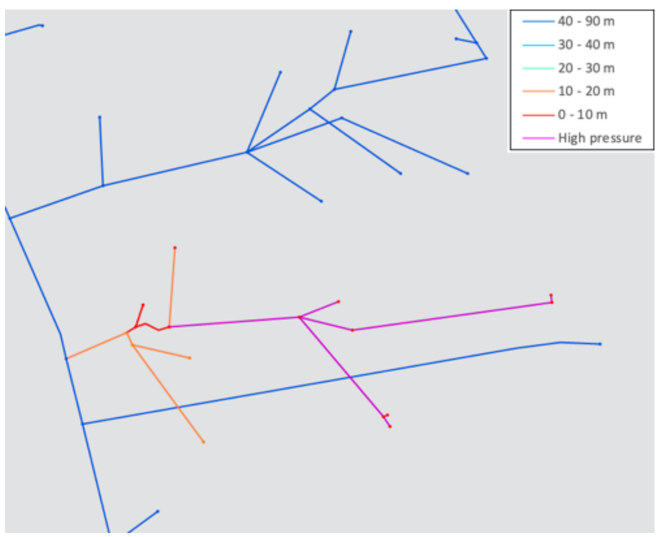


Figure 4-20: simulation results for expected total demand- Location 2

Simulation shows the water pressure when one user, consume the expected total water demand. Other users also meet the low water pressure as well.

Location 3:

Figure 4-21: blue circle is expected total water demand- Location 3

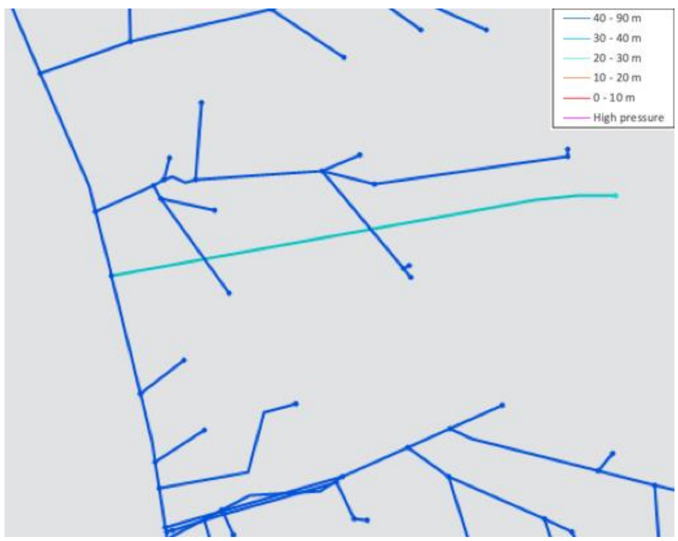


Figure 4-22: simulation results for expected total demand- Location 3

Material type of the pipe, connecting the user with expected total water demand to main pipe is PE80. Diameter of the pipe with material of PE80, does not change. Simulation result shows that the user does not meet low pressure.

Location 4:

Figure 4-23: blue circle is expected total water demand- Location 4

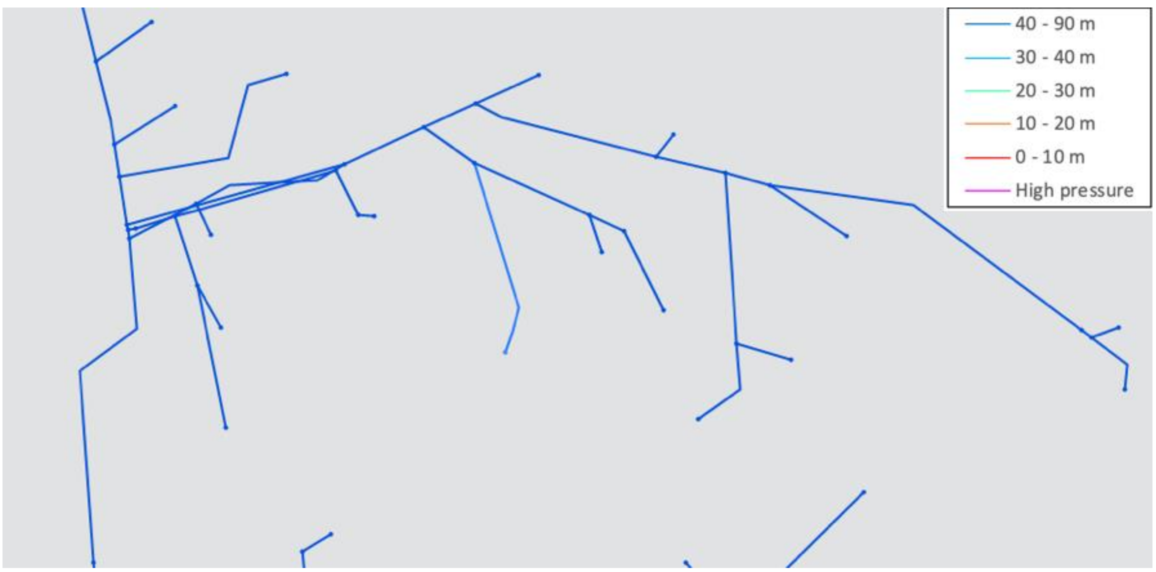


Figure 4-24: simulation results for expected total demand- Location 4

The light blue circle at figure (4-23) represents expected total water demand. Simulation result, as the figure (4-24) shows, the system does not have low pressure at any point.

4.2.4 Discussion

Water consumption increases in summer for irrigating gardens.

Simulation the system for irrigation demand in summer shows that the system is not capable of delivering water with a good pressure, when diameter of old galvanized steel pipes has reduced to 50%. Reduced diameter of the galvanized pipes leads to pressure drop as a result of pipes' reduced flow capacity.

Simulation result in Aquis shows negative pressure in some nodes and pipes. It means that the system is unable to meet the required demand and in reality there is no water flowing in these pipes of the system

Aquis shows in figure (4-25), a very big negative pressure, which is a sign for disruption in the system. Purple pipes are connected to nodes in red. Pipes in purple are generally high-pressure pipes, but are connected to red nodes, which have zero or very low pressure. These combination makes a big negative pressure.

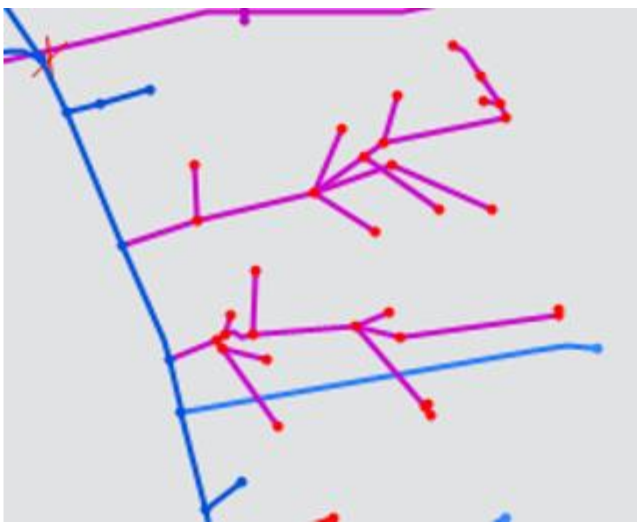


Figure 4-25: Negative pressure at pipes

Since but there was no complaint from residents, there could be several reasons for this:

- The first possible reason may be that pipes considered as galvanized steel are in fact copper pipes. It means that the estimation of the pipe's material type was wrong at the first place.
- Second reason may be that pipes' material would be galvanized steel, but the assumption that pipes' diameter reduces by 50% was failed. There could be a less reduction like 30%.
- The third possibility is that some residents may notice the low pressure, but they do not complain to municipality.

Analyzing water pressure at receiver who had complaint in summer 2018:

The receiver shown in black circle, is the one who complained about low water pressure at summer 2018. A worst-case scenario is simulated in Aquis, by irrigation water demand, increased roughness and galvanized pipe as pipes' material which their diameters has reduced by 50%. The result shows that the receiver who complaint about low water pressure, has a pressure more than 40 (m) and does not face low pressure.

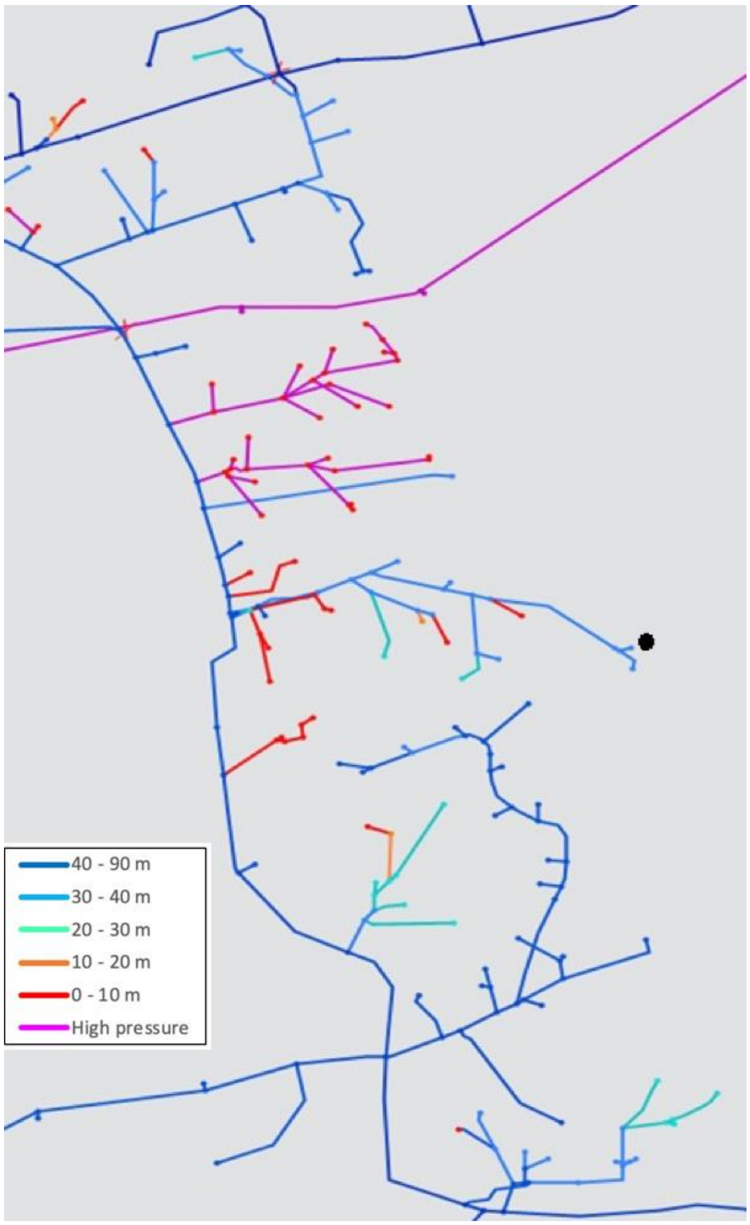


Figure 4-26: Analysis of pressure by irrigation demand, for the reciever who complaint about low pressure in summer 2018.

Since the receiver did not meet any low pressure by garden irrigation water demand, system was analyzed by expected maximum demand from service lines. Figure (4-27) shows water pressure at the receiver who had complaint about low pressure, simulated by expected maximum water demand. The result indicate that the receiver does not meet any low pressure.

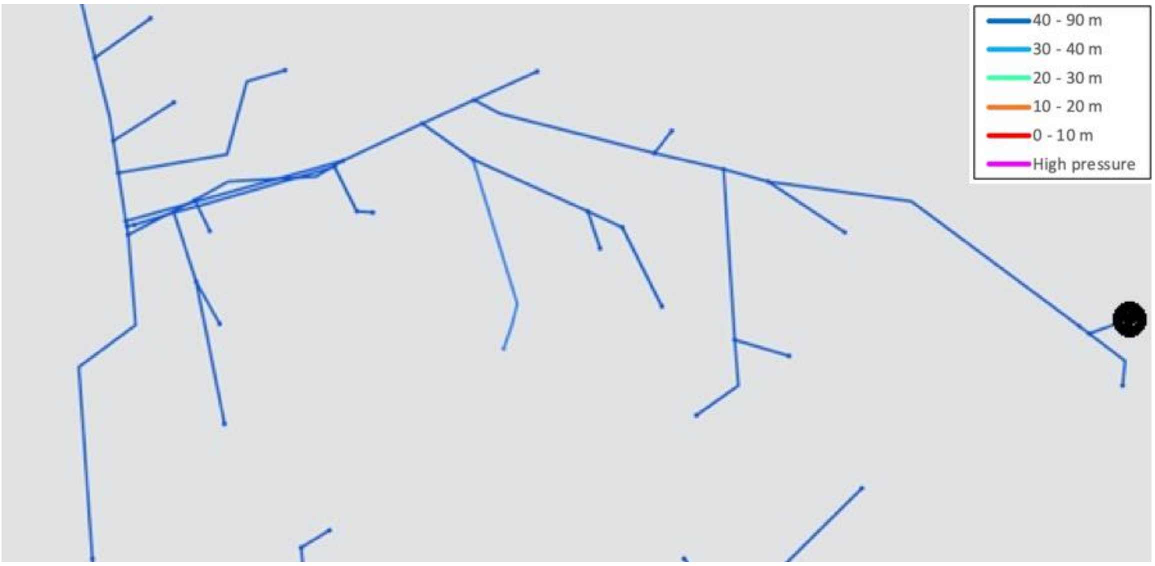


Figure 4-27: pressure result, for expected total water demand

Since there was no low pressure for the receiver, there could be several reasons for the complaint:

- The reason of low pressure would be probably the clogged pipes inside the house.
- The pipes inside the house has been dimensioned smaller than what is supposed to be.

How to fix low pressure at summer because of garden irrigation

Each municipality can provide a timetable for each resident, in order to irrigate gardens at summer. Peak hourly demand is usually around 8:00 to 10:00 in the morning. When analyzing pressure for garden irrigation water demand, the first step was to change the time series so that the system does not have to provide irrigation demand at the same time as peak hour demand.

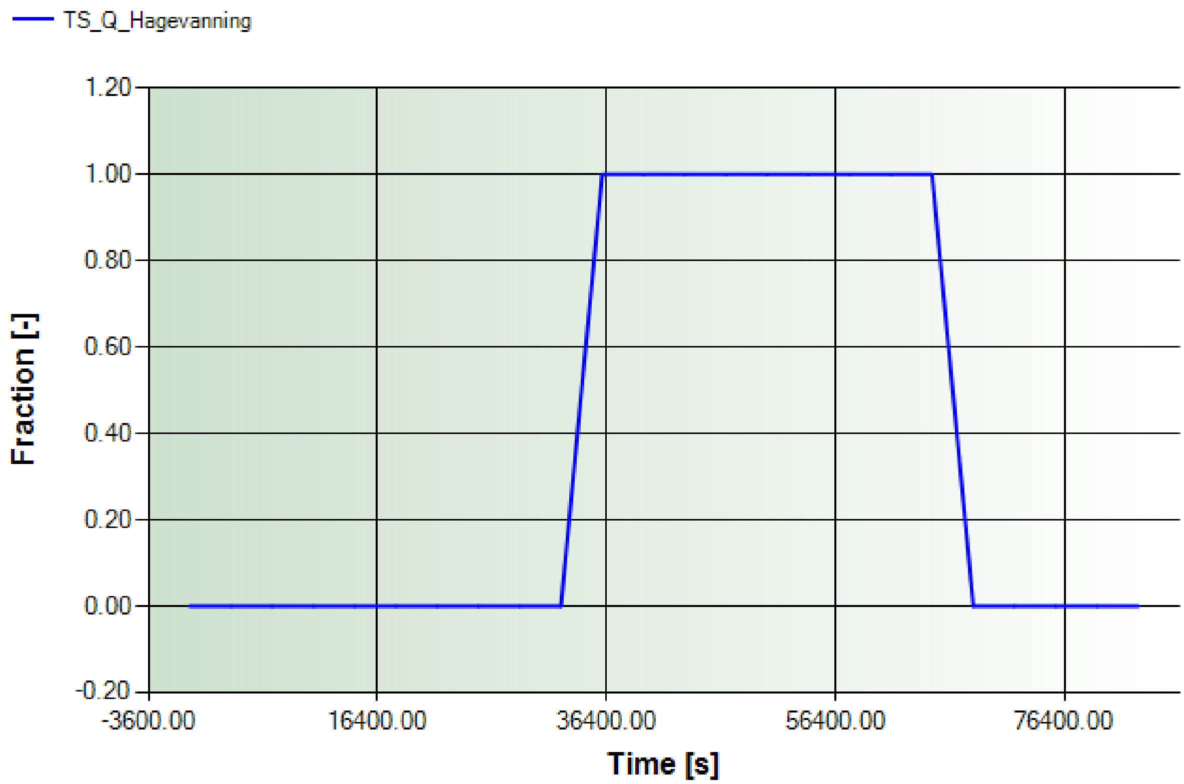


Figure 4-28: changed time series for garden irrigation

Next step is to change the hypothesis about reduction of diameter changes, so instead of 50 %, pipes' diameter will reduce up to 30%, 25% or even less.

If still the system meets low pressure or negative pressure, then the choice of pipes material was wrong from the first step.

Sensitivity analysis:

Sensitivity analysis is a technique to understand how independent variable values will effect a dependent variable (Pristine, 2018). Sensitivity analysis is done by changing one input while other inputs are constant and analyze the changes of output.

As previously discussed, most important parameters effecting fiction loss, directly or indirectly, are: roughness, inner diameter, water flow. Each of these parameters are affected by some other parameters. For example, roughness depends on water quality and material type of the pipe.

Sensitivity analysis for effect of roughness changes on pressure loss:

Roughness changes is a decisive factor for changes in friction factor and so for friction loss. Sensitivity analysis is required in order to understand how roughness will affect pressure loss and see how sensitive is the result, compare to changes in roughness values.

How to perform: There is an assumed range of growth in roughness. From 10% to 50%. Pressure loss for different roughness value is calculated. The ratio of pressure loss for changes in roughness is registered. The graph in figure (4-29) shows the ratio of changes in pressure loss according to increase in roughness. Horizonal axis is $(e + \%e)$, vertical axis represents $(\frac{H_{f-2}}{H_{f-1}})$.

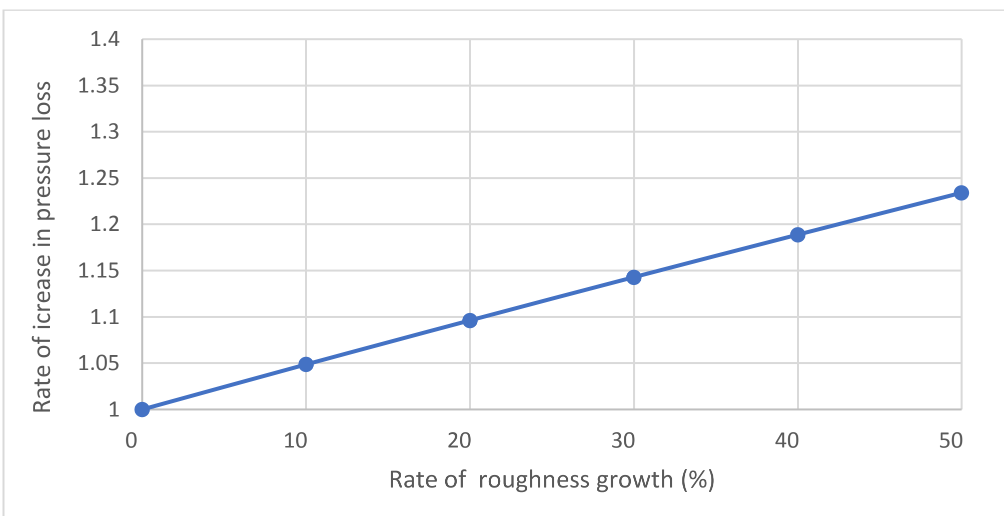


Figure 4-29: Effect of roughness change on pressure loss,

As figure 4-4 shows, it has a mild slope, it indicates that changes in roughness causes a small change in pressure loss.

On the other hand, pressure for any selected point in the system (Aquis-model) will have opposite reaction to roughness increases. In other words, if pressure loss increases, pressure of any selected point will decrease as a result of increase in roughness.

Sensitivity analysis for effect of diameter changes on pressure loss:

Another important parameter which cause the changes in friction loss is changes in diameter. Sensitivity analysis is required in order to understand how diameter will affect pressure loss and how sensitive is the result, compare to changes in pipes size.

Following the same process of analyzing the effect of roughness on pressure loss, for sensitivity analysis of diameter reduction, a diameter reduction range is assumed, from 10% to 50%. Pressure loss for different diameters are calculated. The ratio of pressure loss for changes in roughness is registered and showed in a graph.

The graph in figure (4-30), shows the ratio of pressure loss changes according to reduction of diameter. Horizonal axis is $(D - \%D)$, vertical axis is $(\frac{H_{f-2}}{H_{f-1}})$.

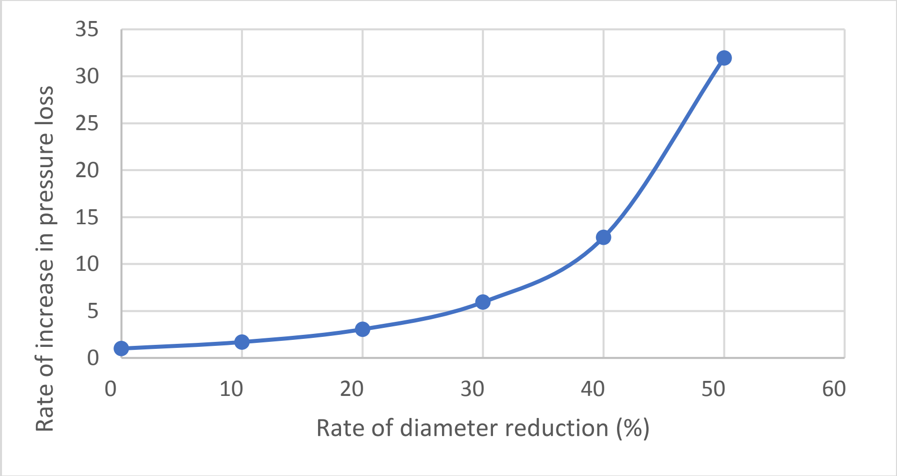


Figure 4-30: Effect of roughness change on pressure loss,

Sensitivity analysis for effect of diameter changes on pressure loss:

In order to be able to compare the effects of changes in roughness and changes in diameter both are plotted in one graph. figure (4-31) shows the relation between same range of decrease in diameter and increase in roughness, and the ratio of pressure loss.

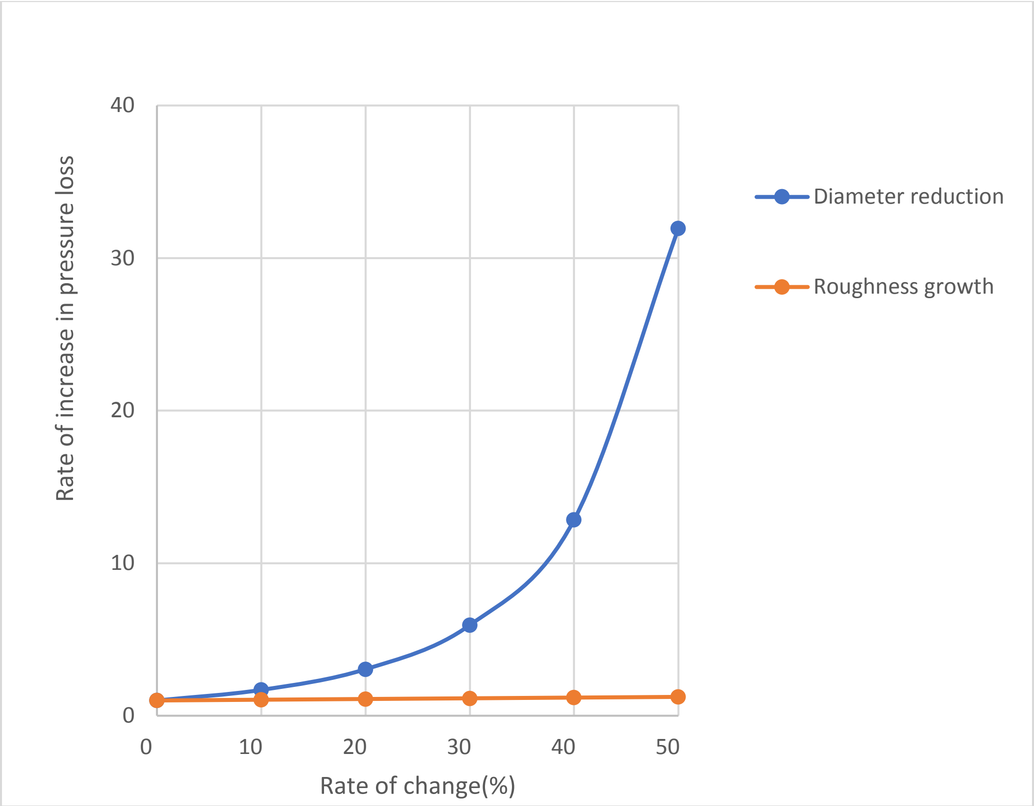


Figure 4-31: Comparing the effect of roughness growth and diameter reduction on pressure loss

Figure (4-31) shows, sensitivity analysis for roughness changes when diameter is constant (red line), diameter changes when roughness change is neglected (blue curve). Horizonal axis is $(e + \%e)$ or $(D - \%D)$, and vertical axis represents ($\frac{H_{f-2}}{H_{f-1}}$).

Sensitivity analysis for diameter changes gives a line which has a mild slope. Sensitivity analysis for diameter changes gives a curve which has a steep slope. When original diameter has reduced about 50% (as galvanized steel pipes do), the ratio of pressure loss is about 34.

Comparing the effect of roughness growth and diameter reduction on pressure loss shows that pressure loss is affected by roughness growth, but compared to the effect of diameter reduction, roughness growth does not have significant effect on pressure loss.

Sensitivity analysis of water flow rate:

Another critical parameter which cause the changes in friction loss is changes in flow rate.

For sensitivity analysis of changes of flow rate, a flow rate increasing range is assumed, from 10% to 50%. Pressure loss for different flow rates are calculated. The ratio of pressure loss for changes in flow rate is registered and showed in a graph.

The graph in figure (4-32), shows the ratio of pressure loss changes according to increases of flow rates. Horizonal axis is $(Q + \%Q)$, vertical axis is $(\frac{H_{f-2}}{H_{f-1}})$

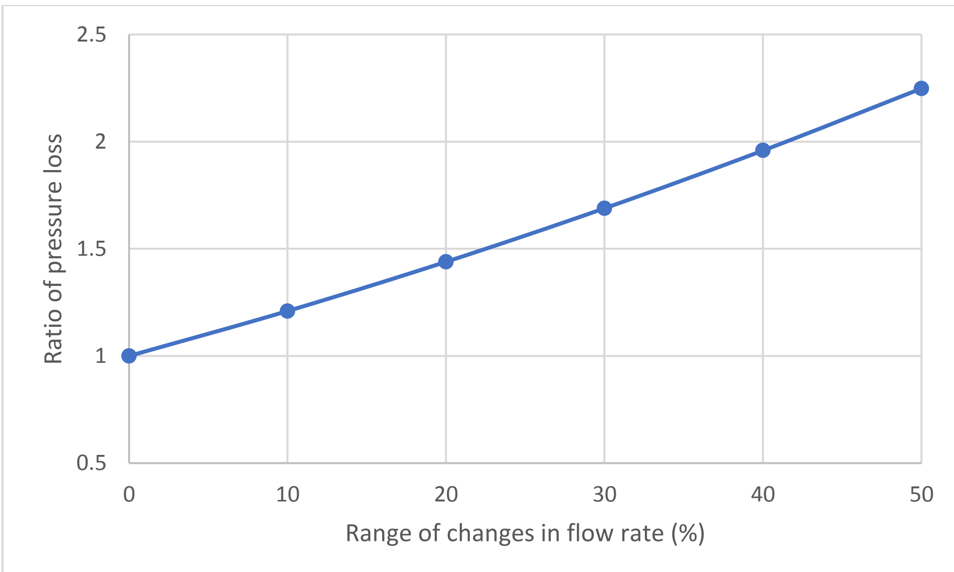


Figure 4-32: Sensitivity analysis of water flow

Sensitivity analysis for comparing all parameters:

To understand which parameter changes has the biggest effect on changes in pressure loss, figure (4-33) and (4-34) are presented:

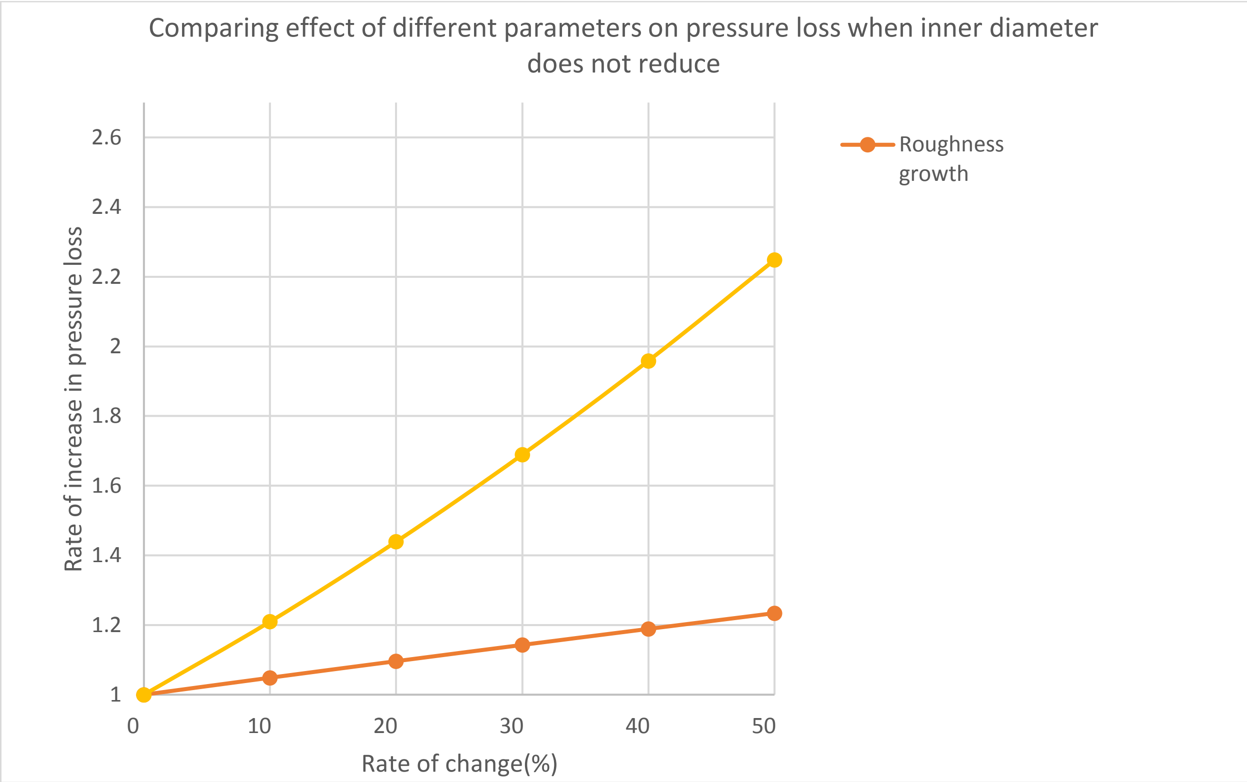


Figure 4-33: Comparing effect of roughness and flow rate changes

Figure (4-33) compares effect of different parameters like roughness growth and water flow rate on pressure loss, for the pipes which their diameter does not change over time or diameter reduction is neglectable. Vertical axis shows the ratio of pressure loss ($\frac{H_{f-2}}{H_{f-1}}$)

Figure (4-34) compares effect of different parameters like roughness growth, diameter reduction, water flow rate by changing rate (reduction or growth) of :10, 20, 30, 40, 50%. Vertical axis shows the ratio of pressure loss ($\frac{\mathrm{H_{f-2}}}{\mathrm{H_{f-1}}}$) in vertical axis.

The result by comparing the effect of these parameter is that for those pipe (like galvanized steel pipes) which inner diameter reduces over time, this has the most effect on pressure loss and is critical when analyzing pressure loss in a system.

For those pipes which their inner diameter does not change over time, the changes in water flow rate, effects the pressure loss in the system.

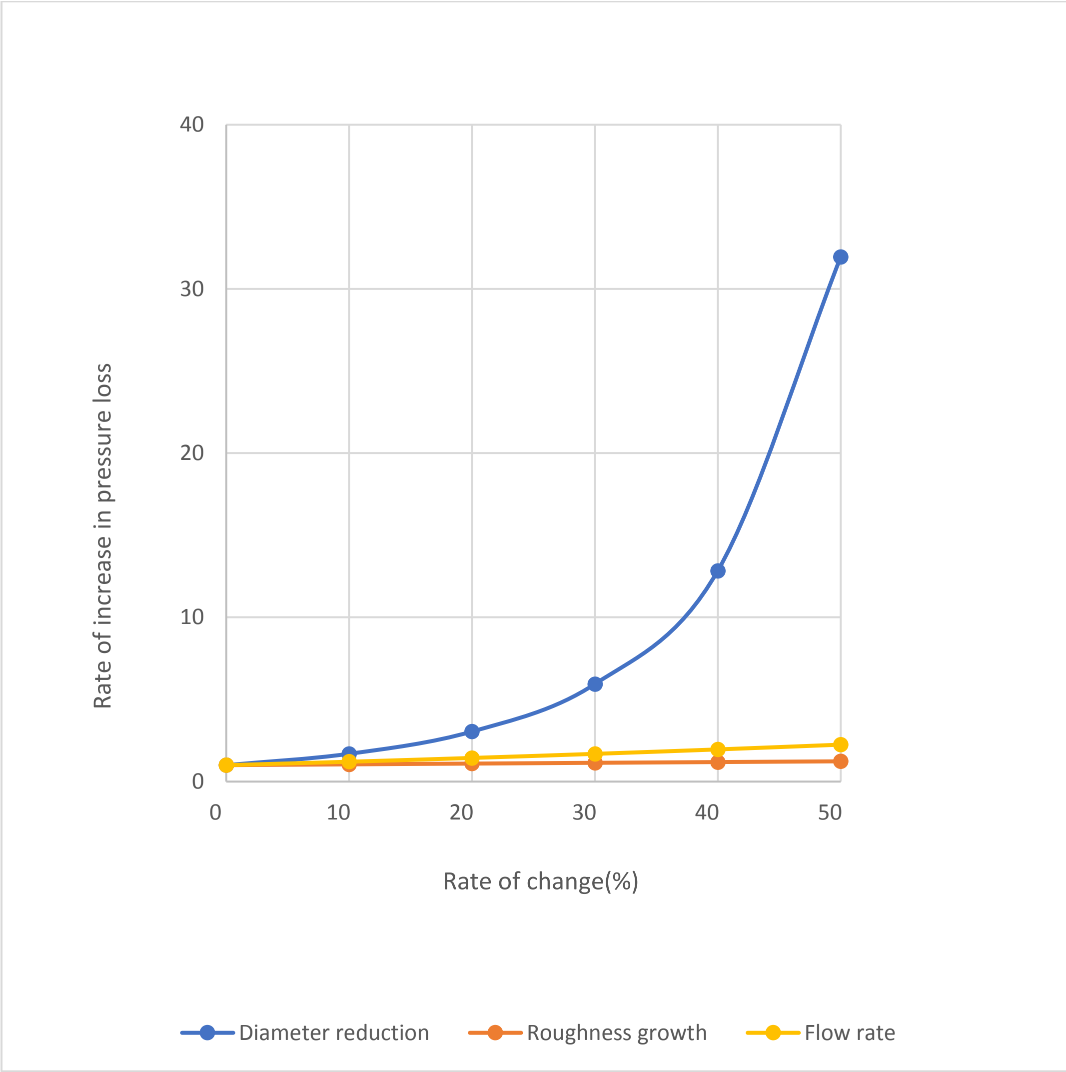


Figure 4-34: Comparing effect of different parameters on pressure loss

4.3 Local pressure loss in tapping sleeves on Total head loss:

The first branch from a municipality pipeline is called main branch and is tapped into municipality's pipe. There are several branches afterwards, in service lines, but these pipelines are connected to each other by T-junctions. Although several local pressure losses may happen from municipality's pipeline to end point (receivers), the only considerable minor loss is at the tapped point between municipalities' pipeline and the main branch of service lines.

In order to find the actual pressure in any node, minor pressure loss should be subtracted from the pressure of each node in Aquis.

$$H_{Actual} = H_{Aquis} - H_{minor-loss}$$

Minor pressure loss where the main branch is tapped into municipality pipeline, relates to a group of pipes connected to the main branch.

Actual pressure at any node in these connected pipes, when the system is simulated for average daily demand with concern to dimeter reduction, is presented in tables.

Figure 4-13 shows the yellow pipes connected to each other. The main branche is tapped to municipality pipeline where black circle is located. Neglecting other connecting points, which is normally a T-junction, minor pressure loss at tapping sleeve should be calculated. Actual pressre at these nodes are calculated by subtracting this minor pressure loss from the pressure Aquis gives when neglecting this minor loss. (easy to undrestand?)

Loss coefficient for all of these calculation when (d/D=0.6), is assumed to be as:

$$k_{1-\mathrm{minor-loss}} = 15.6$$

Loss coefficient for all of these calculation when (d/D=0.33), is assumed to be as:

$$k_{2-\mathrm{minor-loss}} = 200.6 \approx 200$$

Figure 4-35: group of service connected to main branch-1

Aquis shows the velocity of flow on the main branch as 0.31 (m/s),

Minor head loss when $k_{1-\mathrm{minor-loss}} = 15.6$ according to equation (18) is 0.076 (m).

Minor head loss when $k_{1-\mathrm{minor-loss}} = 200$ according to equation (18) is 0.979 (m)

Table 4-1: Actual pressure in (m)-location1

Pressure in Aquis	41,160	40,965	40,967	40,971	44,918	41,062
P, when k=15	41.083	40.889	40.891	40.895	44.841	40.985
P, when k=200	40.180	39.986	39.988	39.992	43.938	40.082
Pressure in Aquis	40,771	44,731	44,223	44,932	44,531	42,073
P, when k=15	40.694	44.655	44.147	44.855	44.454	41.997
P, when k=200	39.791	43.752	43.243	43.952	43.551	41.094
Pressure in Aquis	41,561	40,967	44,932	42,919		
P, when k=15	41.485	40.890	44.855	42.842		
P, when k=200	40.582	39.987	43.952	41.939		

Figure 4-36: group of service connected to main branch-2

Aquis shows the velocity of flow on the main branch as 0.32 (m/s),

Minor head loss when $k_{1-\mathrm{minor-loss}} = 15.6$ according to equation (18) is 0.081 (m).

Minor head loss when $k_{1-\mathrm{minor-loss}} = 200$ according to equation (18) is 1.043 (m)

Table 4-2: Actual pressure in (m) -location2

Pressure in Aquis	39,314	39,414	45,774	43,537	42,864	39,315
P, when k=15	39.232	39.332	45.693	43.456	42.782	39.233
P, when k=200	38.270	38.370	44.730	42.493	41.820	38.271
Pressure in Aquis	45,667	44,877	43,576	44,041	46,189	39,311
P, when k=15	45.585	44.796	43.495	43.960	46.108	39.230
P, when k=200	44.623	43.833	42.532	42.998	45.145	38.267
Pressure in Aquis	39,413	44,877	46,285	39,321		
P, when k=15	39.332	44.796	46.203	39.239		
P, when k=200	38.369	43.833	45.241	38.277		

Figure 4-37: group of service connected to main branch-3

Aquis shows the velocity of flow on the main branch as 0.03 (m/s),

Minor head loss when $k_{1-\mathrm{minor-loss}} = 15.6$ according to equation (18) is 0.00071 (m).

Minor head loss when $k_{1-\mathrm{minor-loss}} = 200$ according to equation (18) is 0.00917 (m)

Table 4-3: Actual pressure in (m) -location 3

Pressure in Aquis	41,543	44,415	41,374	42,721	40,214	44,519
P, when k=15	41.543	44.415	41.374	42.720	40.214	44.519
P, when k=200	41.535	44.416	41.375	42.721	40.215	44.520
Pressure in Aquis	40,895	42,417	41,917	48,256	41,439	45,615
P, when k=15	40.895	42.417	41.917	48.255	41.439	45.615
P, when k=200	40.895	42.418	41.917	48.256	41.439	45.615
Pressure in Aquis	42,808	42,912	43,098	40,807	45,713	40,667
P, when k=15	42.807	42.912	43.097	40.807	45.713	40.666
P, when k=200	42.808	42.913	43.098	40.807	45.714	40.667
Pressure in Aquis	44,819	42,924	41,744	47,518	41,544	42,718
P, when k=15	44.819	42.924	41.744	47.518	41.544	42.718
P, when k=200	44.819	42.924	41.745	47.519	41.545	42.719
Pressure in Aquis	45,715	43,613	44,126	44,063	43,013	42,809
P, when k=15	45.715	43.613	44.126	44.063	43.013	42.809
P, when k=200	45.715	43.614	44.126	44.063	43.014	42.810

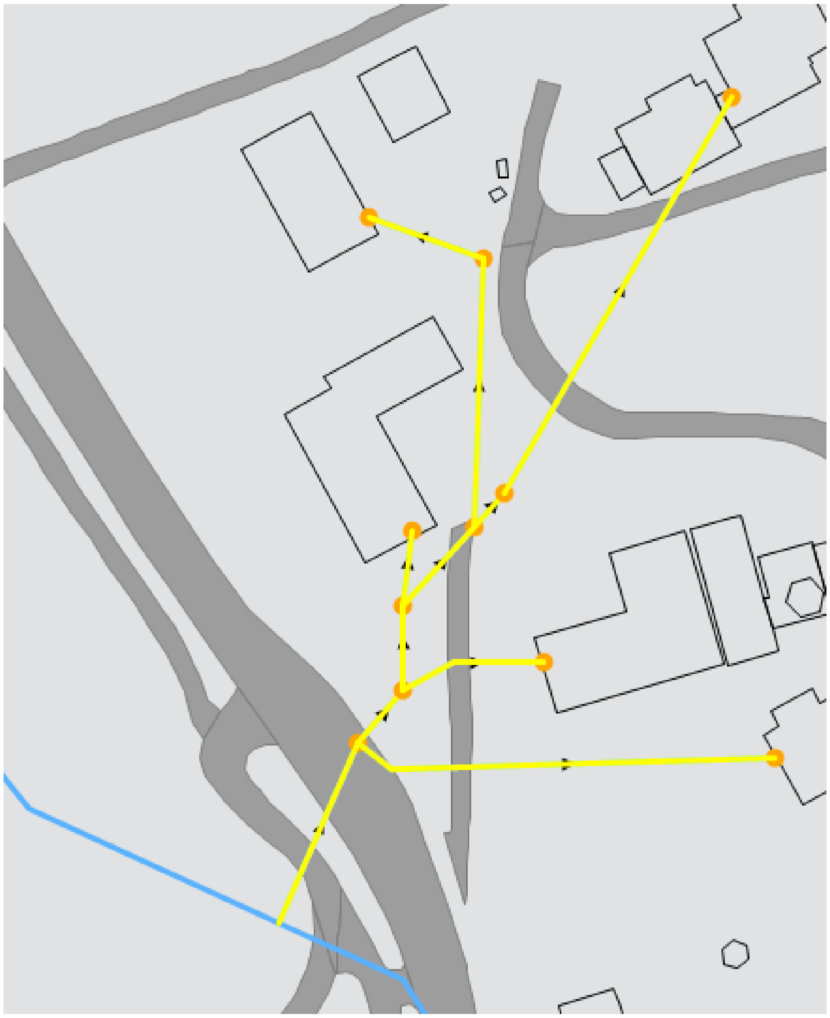


Figure 4-38: group of service connected to main branch-4

Aquis shows the velocity of flow on the main branch as 0.07 (m/s),

Minor head loss when $k_{1-\mathrm{minor-loss}} = 15.6$ according to equation (18) is 0.0038 (m).

Minor head loss when $k_{1-\mathrm{minor-loss}} = 200$ according to equation (18) is 0.0499 (m)

Table 4-4: Actual pressure in (m) -location 4

Pressure in Aquis	48,698	46,295	42,897	41,174	43,691	41,690
P, when k=15	48.694	46.291	42.893	41.170	43.688	41.686
P, when k=200	48.648	46.245	42.847	41.124	43.642	41.640
Pressure in Aquis	41,685	44,594	43,096	50,001	44,492	
P, when k=15	41.681	44.590	43.092	49.997	44.488	
P, when k=200	41.635	44.544	43.046	49.951	44.442	

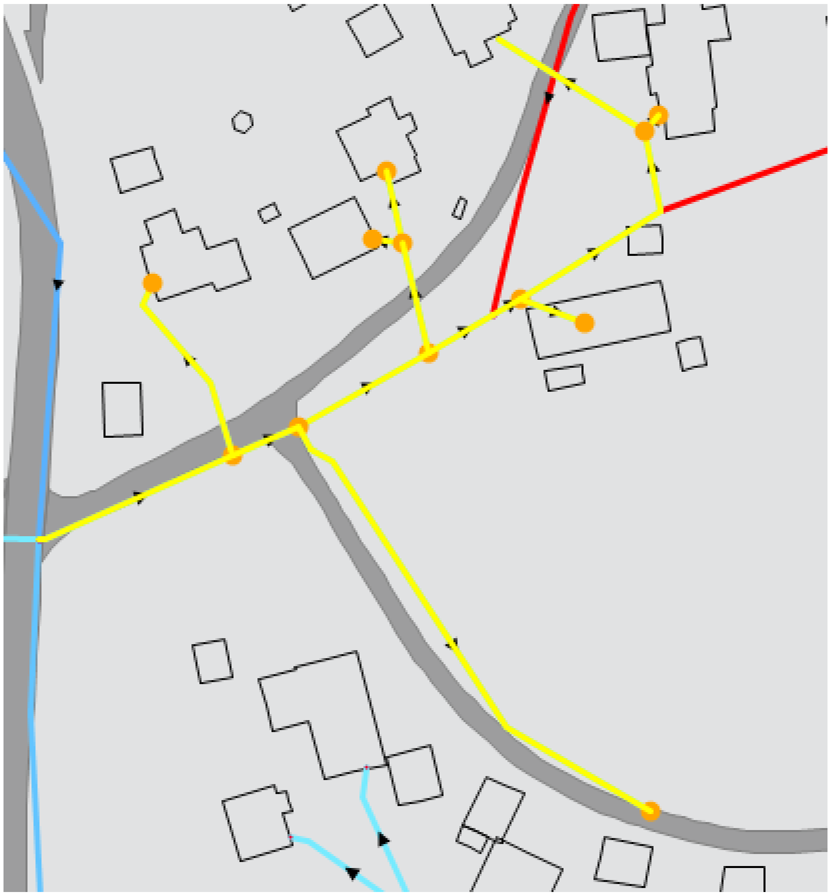


Figure 4-39: group of service connected to main branch-5

Aquis shows the velocity of flow on the main branch as 0.01 (m/s),

Minor head loss when $k_{1-\text{minor}-\text{loss}} = 15.6$ according to equation (18) is 0.000079 (m).

Minor head loss when $k_{1-\text{minor}-\text{loss}} = 200$ according to equation (18) is 0.0010 (m)

Table 4-5: Actual pressure in (m) -location 5

Pressure in Aquis	52,37536	46,97260	48,05903	53,35571	45,86751	49,26990
P, when k=15	52.375	46.973	48.059	53.356	45.867	49.270
P, when k=200	52.374	46.972	48.058	53.355	45.866	49.269
Pressure in Aquis	47,56845	48,06939	53,37576	53,67461	47,16768	54,92613
P, when k=15	47.568	48.069	53.376	53.675	47.168	54.926
P, when k=200	47.567	48.068	53.375	53.674	47.167	54.925

4.3.1 Discussion:

Comparing the results and as related formula (equation () and ()), represent that minor head loss is very based on velocity of water through first branch (which is a function of diameter of the pipe), and diameter of the hull of the cutout.

In part 2 which velocity is 0.32 (m/s), the diameter of the pipes is reduced from 21 mm to 15 mm. velocity has increased from 0.32(m/s) to 0.60(m/s). the local pressure loss increases from 0.078 to 0.275 m.

Reduction in diameter of the cutout or reduction in diameter of the tapped pipe, both reduces the amount of water flowing through branch.

By combining equation () and ():

$$H_s = k_s \times \frac{v^2}{2g}$$

$$v = \frac{Q}{A}$$

$$H_s = (1.97 \times (\frac{d}{D})^{-4}) \times (\frac{Q^2 \times 8}{\pi^2 \times g \times D^4})$$

Which gives:

$$H_s = \frac{0.163 \times Q^2}{d^4}$$

Since flow demand is based on consumers consumption (what is assumed in this paper), this is a diameter of the cutout hull, which has the most effect on local pressure loss.

In other words, local head loss, compared to other losses in the system, are small. It becomes an issue when the hull area become totally clogged which no water flow through branches.

5 CONCLUSION

Effect of time on different characteristics of old pipes is an important issue. Roughness and inner diameter of some pipes will change over time. The Investigation to predict pressure losses through old pipes, shows that roughness growth in pipes depends highly on **material type** of the pipe and **quality of water** flowing through pipes. These are two parameters effecting changes in diameter of the pipes as well as roughness growth. Exact relation of roughness growth and diameter change is still not clear. Diameter reduction is neglected most of the time in hydraulic simulation models. Galvanized pipes are the among most corrosive pipes which its **roughness will grow** considerably over time. These results are presented in tables (A-1) to (A-24) in appendix.

There is not a reliable method to **predict reduction in diameter** of galvanized pipe and cast-iron pipes. As mentioned before, quality of water from a treatment plant could have been different from current quality since the standards and regulation have developed by time. There is no access to data for quality of water in past. Even by assuming the current quality of water as the constant quality, distinguish between exact effect of each process through pipe is not possible. This paper came to conclusion to assume 50% diameter reduction over 50 years for galvanized and cast-iron pipes. Predicted pressure losses according to this reduction in diameter are presented in tables (B-25**Error! Reference source not found.**) to (B-40) in appendix.

By investigating the **effect of roughness and diameter changes** to pressure loss, which is presented in graph (4-34) and (4-33), it is clear that pressure loss is more effected by reduction in diameter than increase in roughness. So, neglecting diameter changes when analyzing the system is not reasonable.

Tapping sleeves: The diameters of both cutout hole and inner pipe tapped into the municipality pipe are affecting pressure loss. The ratio of these two diameters is important for loss coefficient and diameter of the tapped pipe is an important for velocity of water in pipe. The cutout hole effects directly the pressure loss. If it gets clogged, then now water can flow through tapped pipe and local loss will be very big.

Water demand: water flow rate together with inner diameter of the pipe define the velocity of the water through pipe and so friction loss through pipes. Comparing exact same situation with different water flow rates, resulted to a big difference of pressure loss.

Simulation results: Setting old service lines in a simulation model, for garden irrigation water demand, reduced diameter and increased roughness value has given negative pressure for many receivers, which indicates that one of input data was incorrect. The receivers who had complaint about low water pressure on the other hand meets no low pressure, this indicates that the problem is not from the pipeline outside the house. The inside pipes need to be investigated.

As total conclusion: All the parameters discussed here, influence the pressure loss, but effect of diameter reduction seems to be greater than the others. As a suggestion on this issue, investigate deeper into diameter changes of galvanized pipe could be an opening section for many unknown parameters in the case of pressure loss. Probability estimation is suggested to collect data for the old galvanized pipes, which get repaired or replaced by new pipes, register and collect their data about age and reduced diameter. When statistical sample is ready, it will be a safe estimation for diameter reduction of old galvanized pipe.

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Appendix

As the basis of this paper, tables will be presented in two main scenarios, one in which diameter changes are neglected and another scenario in which diameter changes in time are variable in time.

Each table include relative roughness, Reynold number, friction factor, friction loss over length of the pipe and a specified name. Each pipe is named and specified by its material, outer diameter (mm), age of the pipe. MGA-33-10 for example, represents galvanized steel- with 33 mm outer diameter (inner diameter for cast-iron ductile and gray), last number in the name represent age of the pipe. zero is for the pipes when they are new)

Predict pressure loss when diameter changes with time is neglected.

Each table, for galvanized pipe and cast iron which their roughness increases with time, is categorized by special size (diameter), decided water flow rate, and predict pressure loss according to the age of the pipe, when diameter will not change.

Tables, for copper pipe and plastic pipes, which their roughness does not change with time, is categorized by decided water flow rate, and predict pressure loss according to the diameter od the pipe, when diameter and roughness will not change by time.

For galvanized steel pipes:

Galvanized pipe (MGA-33):

Table A-1 predict friction loss for a galvanized pipe with diameter of 33 mm, when water flowing through pipe is 0.31 (l/s).

Table A-2 predict friction loss for the same pipe, when water flowing through pipe is 0.8 (l/s).

Galvanized pipe (MGA-42):

Table A-3 predict friction loss for a galvanized pipe with diameter of 42mm, when water flowing through pipe is 0.31 (l/s).

Table A-4 predict friction loss for the same pipe, when water flowing through pipe is 0.8 (l/s).

Galvanized pipe (MGA-48):

Table A-5 predict friction loss for a galvanized pipe with diameter of 48mm, when water flowing through pipe is 0.31 (l/s).

Table A-6 predict friction loss for the same pipe, when water flowing through pipe is 0.8 (l/s).

Galvanized pipe (MGA-62):

Table A-7 predict friction loss for a galvanized pipe with diameter of 62mm, when water flowing through pipe is 0.31 (l/s).

Table A-8 predict friction loss for the same pipe, when water flowing through pipe is 0.8 (l/s).

Table A-1: Pressure loss for MGA-33, when Q=0.31 (l/s) and no change in pipe's diameter

Age	e (mm)	D (mm)	e/D	Re	f	Hf/L
0	0.15	27.3	0.005	9518	0.031	0.01638
10	2.47	27.3	0.090	9518	0.096	0.05049
20	4.23	27.3	0.155	9518	0.132	0.06909
30	5.43	27.3	0.199	9518	0.155	0.08141
40	6.07	27.3	0.222	9518	0.168	0.08800
50	6.15	27.3	0.225	9518	0.170	0.08883

Table A-2: Pressure loss for MGA-33, when Q=0.8 (l/s) and no change in pipe's diameter

Age	e (mm)	D (mm)	e/D	Re	f	Hf/L
0	0.15	27.3	0.005	24562	0.031	0.10904
10	2.47	27.3	0.090	24562	0.096	0.33591
20	4.23	27.3	0.155	24562	0.132	0.45954
30	5.43	27.3	0.199	24562	0.155	0.54145
40	6.07	27.3	0.222	24562	0.168	0.58523
50	6.15	27.3	0.225	24562	0.169	0.59073

Table A-3: Pressure loss for MGA-42, when Q=0.31 (l/s) and no change in pipe's diameter

Age	e (mm)	D (mm)	e/D	Re	f	Hf/L
0	0.15	36	0.004	7217	0.029	0.00378
10	2.47	36	0.069	7217	0.084	0.01097
20	4.23	36	0.118	7217	0.112	0.01466
30	5.43	36	0.151	7217	0.130	0.01705
40	6.07	36	0.169	7217	0.139	0.01830
50	6.15	36	0.171	7217	0.141	0.01846

Table A-4: Pressure loss for MGA-42, when Q=0.8 (l/s) and no change in pipe's diameter

Age	e (mm)	D (mm)	e/D	Re	f	Hf/L
0	0.15	36	0.004	18626	0.029	0.02516
10	2.47	36	0.069	18626	0.083	0.07297
20	4.23	36	0.118	18626	0.112	0.09752
30	5.43	36	0.151	18626	0.130	0.11334
40	6.07	36	0.169	18626	0.139	0.12167
50	6.15	36	0.171	18626	0.140	0.12271

Table A-5: Pressure loss for MGA-48, when Q=0.31 (l/s) and no change in pipe's diameter

Age	e (mm)	D (mm)	e/D	Re	f	Hf/L
0	0.15	41.9	0.004	6401	0.028	0.00181
10	2.47	41.9	0.059	6401	0.078	0.00508
20	4.23	41.9	0.101	6401	0.102	0.00671
30	5.43	41.9	0.130	6401	0.118	0.00775
40	6.07	41.9	0.145	6401	0.127	0.00830
50	6.15	41.9	0.147	6401	0.128	0.00836

Table A-6: Pressure loss for MGA-48, when Q=0.8 (l/s) and no change in pipe's diameter

Age	e (mm)	D (mm)	e/D	Re	f	Hf/L
0	0.15	41.9	0.004	16003	0.028	0.01127
10	2.47	41.9	0.059	16003	0.077	0.03171
20	4.23	41.9	0.101	16003	0.102	0.04190
30	5.43	41.9	0.130	16003	0.118	0.04838
40	6.07	41.9	0.145	16003	0.126	0.05176
50	6.15	41.9	0.147	16003	0.127	0.05219

Table A-7: Pressure loss for MGA-62, when Q=0.31 (l/s) and no change in pipe's diameter

Age	e (mm)	D (mm)	e/D	Re	f	Hf/L
0	0.15	53.10	0.003	5051	0.026	0.00051
10	2.75	53.10	0.052	5051	0.073	0.00146
20	5.35	53.10	0.101	5051	0.102	0.00205
30	7.95	53.10	0.150	5051	0.129	0.00259
40	10.55	53.10	0.199	5051	0.156	0.00311
50	13.15	53.10	0.248	5051	0.182	0.00364

Table A-8: Pressure loss for MGA-62, when Q=0.8 (l/s) and no change in pipe's diameter

Age	e (mm)	D (mm)	e/D	Re	f	Hf/L
0	0.15	53.10	0.003	12628	0.026	0.00322
10	2.75	53.10	0.052	12628	0.073	0.00912
20	5.35	53.10	0.101	12628	0.102	0.01280
30	7.95	53.10	0.150	12628	0.129	0.01616
40	10.55	53.10	0.199	12628	0.155	0.01945
50	13.15	53.10	0.248	12628	0.182	0.02275

Cast iron:

Cast iron- ductile (SJK-44):

Table A-9 predict friction loss for a Cast iron-ductile pipe with diameter of 44 mm, when water flowing through pipe is 0.31 (l/s).

Table A-10 predict friction loss for the same pipe, when water flowing through pipe is 0.8 (l/s).

Cast iron- ductile (SJK-55):

Table A-11 predict friction loss for a Cast iron-ductile pipe with diameter of 55 mm, when water flowing through pipe is 0.31 (l/s).

Table A-12 predict friction loss for the same pipe, when water flowing through pipe is 0.8 (l/s).

Cast iron- Gray (SJG-32):

Table A-13 predict friction loss for a Cast iron-ductile pipe with diameter of 44mm, when water flowing through pipe is 0.31 (l/s).

Table A-14 predict friction loss for the same pipe, when water flowing through pipe is 0.8 (l/s).

Cast iron- Gray (SJG-40):

Table A-15 predict friction loss for a Cast iron-ductile pipe with diameter of 55 mm, when water flowing through pipe is 0.32 (l/s).

Table A-16 predict friction loss for the same pipe, when water flowing through pipe is 0.8 (l/s).

Table A-9: Predicted friction loss for SJK-44, when Q= 0.31 (l/s) and no change in pipe's diameter

Age	e (mm)	D (mm)	e/D	Re	f	Hf/L
0	0.25	44	0.006	5905	0.032	0.001523
10	2.57	44	0.058	5905	0.077	0.003718
20	4.33	44	0.098	5905	0.101	0.004866
30	5.53	44	0.126	5905	0.116	0.005596
40	6.17	44	0.140	5905	0.124	0.005978
50	6.28	44	0.143	5905	0.126	0.006043

Table A-10: Predict friction loss for SJK-44, when Q= 0.8 (l/s) and no change in pipe's diameter

Age	e (mm)	D (mm)	e/D	Re	f	Hf/L
0	0.25	44	0.006	15240	0.032	0.01013
10	2.57	44	0.058	15240	0.077	0.02472
20	4.33	44	0.098	15240	0.101	0.03235
30	5.53	44	0.126	15240	0.116	0.037202
40	6.17	44	0.140	15240	0.124	0.039735
50	6.28	44	0.143	15240	0.125	0.040167

Table 0A-11: Predict friction loss for SJK-54, when Q= 0.31 (l/s) and no change in pipe's diameter

Age	e (mm)	D (mm)	e/D	Re	f	Hf/L
0	0.25	54	0.005	4811	0.030	0.00051
10	2.85	54	0.053	4811	0.074	0.00127
20	5.45	54	0.101	4811	0.103	0.00177
30	8.05	54	0.149	4811	0.129	0.00223
40	10.65	54	0.197	4811	0.155	0.00267
50	13.25	54	0.245	4811	0.181	0.00312

Table A-12: Predict friction loss for SJK-54, when Q= 0.8 (l/s) and no change in pipe's diameter

Age	e (mm)	D (mm)	e/D	Re	f	Hf/L
0	0.25	54	0.005	12417	0.030	0.00342
10	2.85	54	0.053	12417	0.073	0.00846
20	5.45	54	0.101	12417	0.102	0.01178
30	8.05	54	0.149	12417	0.129	0.01482
40	10.65	54	0.197	12417	0.154	0.01779
50	13.25	54	0.245	12417	0.180	0.02077

Table A-13: Predict friction loss for SJG-32, when Q= 0.31 (l/s) and no change in pipe's diameter

Age	e (mm)	D (mm)	e/D	Re	f	Hf/L
0	0.150	32	0.005	8120	0.030	0.00706
10	2.470	32	0.077	8120	0.089	0.02099
20	4.230	32	0.132	8120	0.120	0.02832
30	5.430	32	0.170	8120	0.140	0.03311
40	6.070	32	0.190	8120	0.151	0.03564
50	6.150	32	0.192	8120	0.152	0.03596

Table A-14: Predict friction loss for SJG-32, when Q= 0.8 (l/s) and no change in pipe's diameter

Age	e (mm)	D (mm)	e/D	Re	f	Hf/L
0	0.150	32	0.005	20955	0.030	0.04696
10	2.470	32	0.077	20955	0.089	0.13961
20	4.230	32	0.132	20955	0.120	0.18836
30	5.430	32	0.170	20955	0.140	0.22014
40	6.070	32	0.190	20955	0.150	0.23697
50	6.150	32	0.192	20955.23	0.152	0.23908

Table A-15: Predict friction loss for SJG-40, when Q= 0.31 (l/s) and no change in pipe's diameter

Age	e (mm)	D (mm)	e/D	Re	f	Hf/L
0	0.150	40	0.004	6496	0.028	0.00217
10	2.470	40	0.062	6496	0.079	0.00615
20	4.230	40	0.106	6496	0.105	0.00816
30	5.430	40	0.136	6496	0.122	0.00944
40	6.070	40	0.152	6496	0.130	0.01011
50	6.150	40	0.154	6496	0.131	0.01019

Table A-16: Predict friction loss for SJG-40, when Q= 0.8 (l/s) and no change in pipe's diameter

Age	e (mm)	D (mm)	e/D	Re	f	Hf/L
0	0.150	40	0.004	16764	0.028	0.01441
10	2.470	40	0.062	16764	0.079	0.04090
20	4.230	40	0.106	16764	0.105	0.05423
30	5.430	40	0.136	16764	0.121	0.06273
40	6.070	40	0.152	16764	0.130	0.06719
50	6.150	40	0.154	16764	0.131	0.06774

Copper pipe with nominal diameter of 28 mm, (MCU-28), 35mm, (MCU-35), 42 mm, (MCU-42), 54 mm, (MCU-54):

Table A-17 predict friction loss for a copper pipe with different diameter, when water flowing through pipe is 0.31 (l/s).

Table A-18 predict friction loss for the same pipe, when water flowing through pipe is 0.8 (l/s).

Table A-17: Predict friction loss for Copper pipes (MCU), when Q= 0.31 (l/s).

Pipes' name In Aquis	e (mm)	D ((mm)	e/D	Re	f	Hf/L
MCU_15	0.0015	12.6	0.00011	20622	0.0124	0.30982
MCU_18	0.0015	15.6	0.000096	16656	0.0119	0.10224
MCU_22	0.0015	19	0.000078	13676	0.0115	0.03676
MCU_28	0.0015	25	0.000060	10393	0.0109	0.00886
MCU_35	0.0015	31	0.000048	8382	0.0105	0.00291
MCU_42	0.0015	38	0.000039	6838	0.0101	0.00101
MCU_54	0.0015	50	0.000030	5196	0.0097	0.00025

Table 0-18: Predict friction loss for Copper pipes (MCU), when Q= 0.8 (l/s).

Pipes' name In Aquis	e (mm)	D ((mm)	e/D	Re	f	Hf/L
MCU_15	0.0015	12.6	0.00011	53219	0.0124	2.06290
MCU_18	0.0015	15.6	0.000096	42985	0.0119	0.68072
MCU_22	0.0015	19	0.000078	35293	0.0115	0.24477
MCU_28	0.0015	25	0.000060	26822	0.0109	0.05902
MCU_35	0.0015	31	0.000048	21631	0.0105	0.01937
MCU_42	0.0015	38	0.000039	17646	0.0101	0.00675
MCU_54	0.0015	50	0.000030	13411	0.0096	0.00163

Plastic pipes:

Predicted friction loss for plastic pipes, in PVC and PE are presented in following tables, categorize by different water flow.

Table (A-19) presents predict friction loss for a PVC pipes with different diameter, when water flowing through pipe is 0.31 (l/s).

Table (A-20) present predict friction loss for a PVC pipes with different diameter, when water flowing through pipe is 0.8 (l/s).

Table A-19: Predict friction loss for PVC pipes, when Q= 0.31 (l/s).

Pipes' name In Aquis	e (mm)	D (mm)	e/D	Re	f	Hf/L
PVC_16	0.0015	12.8	0.000117	20300	0.012	0.28548
PVC_20	0.0015	16.2	0.000092	16039	0.012	0.08405
PVC_25	0.0015	20.4	0.000073	12737	0.011	0.02542
PVC_32	0.0015	26.2	0.000057	9917	0.011	0.00695
PVC_40	0.0015	33	0.000045	7874	0.010	0.00210
PVC_50	0.0015	41.4	0.000036	6276	0.010	0.00065

Table A-20: Predict friction loss for PVC pipes, when Q= 0.8 (l/s).

Pipes' name In Aquis	e (mm)	D (mm)	e/D	Re	f	Hf/L
PVC_16	0.0015	12.8	0.000117	52388	0.012	1.90090
PVC_20	0.0015	16.2	0.000092	41393	0.012	0.55965
PVC_25	0.0015	20.4	0.000073	32870	0.011	0.16930
PVC_32	0.0015	26.2	0.000057	25594	0.011	0.04629
PVC_40	0.0015	33	0.000045	20320	0.010	0.01401
PVC_50	0.0015	41.4	0.000036	16197	0.010	0.00433

Table A-21. Predict friction loss for PE, PEL (Low density) pipes, Q=0.31 (l/s).

Pipes' name In Aquis	e (mm)	D (mm)	e/D	Re	f	Hf/L
PE_16	0.0015	10.4	0.000141	24985	0.012863	0.839527
PE_20	0.0015	13.2	0.000113	19685	0.012281	0.243331
PE_25	0.0015	16.6	0.000090	15653	0.011757	0.074064
PE_32	0.0015	21.4	0.000070	12142	0.011215	0.019842
PE_40	0.0015	26.8	0.000055	9695	0.010766	0.006184
PE_50	0.0015	33.6	0.000044	7733	0.010342	0.001918

Table A-22. Predict friction loss for PE, PEL (Low density) pipes, Q= 0.8 (l/s).

Pipe name In Aquis	e (mm)	D (mm)	e/D	Re	f	Hf/L
PE_16	0.0015	10.4	0.000141	64477	0.013	5.59010
PE_20	0.0015	13.2	0.000113	50800	0.012	1.62019
PE_25	0.0015	16.6	0.000090	40395	0.012	0.49313
PE_32	0.0015	21.4	0.000070	31334	0.011	0.13211
PE_40	0.0015	26.8	0.000055	25021	0.011	0.04117
PE_50	0.0015	33.6	0.000044	19957	0.010	0.01277

Table A-23. Predict friction loss for both PEH (High density) and PE50, Q= 0.3 (l/s).

Age	e (mm)	D ((mm)	e/D	Re	f	Hf/L
PE_16	0.0015	12.0	0.000125	21653	0.013	0.39917
PE_20	0.0015	15.4	0.000097	16873	0.012	0.10932
PE_25	0.0015	19.4	0.000077	13394	0.011	0.03300
PE_32	0.0015	25.0	0.000060	10393	0.011	0.00886
PE_40	0.0015	31.4	0.000047	8275	0.010	0.00272
PE_50	0.0015	39.4	0.000038	6595	0.010	0.00084

Table A-24. Predict friction loss for both PEH (High density) and PE50, Q= 0.8 (l/s).

Age	e (mm)	D ((mm)	e/D	Re	f	Hf/L
PE_16	0.0015	12.0	0.000125	55880	0.013	2.65784
PE_20	0.0015	15.4	0.000097	43543	0.012	0.72786
PE_25	0.0015	19.4	0.000077	34565	0.011	0.21971
PE_32	0.0015	25.0	0.000060	26822	0.011	0.05902
PE_40	0.0015	31.4	0.000047	21355	0.010	0.01812
PE_50	0.0015	39.4	0.000038	17019	0.010	0.00560

Roughness increases, diameter decreases

Among the pipes used in service lines, iron-based pipes like galvanized and cast iron are the most corrosive. Diameter of these pipes will decrease with time.

Following tables provide the predicted roughness, diameter and friction loss.

Each table, for galvanized pipe and cast iron which their roughness increases with time, is categorized by special size (diameter), decided water flow rate, and predict pressure loss according to the age of the pipe and 50% reduction in diameter.

Tables, for copper pipe and plastic pipes, which their roughness does not change with time, is categorized by decided water flow rate, and predict pressure loss according to the diameter of the pipe, when diameter and roughness will not change by time.

Galvanized steel pipes:

Galvanized pipe (MGA-33):

Table B-25 predict friction loss for a galvanized pipe with diameter of 33 mm, and assumption of 50% decrease of diameter in 50 years, when water flowing through pipe is 0.32 (l/s).

Table B-26 predict friction loss for the same pipe, when water flowing through pipe is 0.8 (l/s).

Galvanized pipe (MGA-42):

Table B-27 predict friction loss for a galvanized pipe with diameter of 42 mm, and assumption of 50% decrease of diameter in 50 years, when water flowing through pipe is 0.32 (l/s).

Table B-28 predict friction loss for the same pipe, when water flowing through pipe is 0.8 (l/s).

Galvanized pipe (MGA-48):

Table B-29 predict friction loss for a galvanized pipe with diameter of 48 mm, and assumption of 50% decrease of diameter in 50 years, when water flowing through pipe is 0.32 (l/s).

Table B-30 predict friction loss for the same pipe, when water flowing through pipe is 0.8 (l/s).

Galvanized pipe (MGA-62):

Table B-31 predict friction loss for a galvanized pipe with diameter of 62 mm, and assumption of 50% decrease of diameter in 50 years, when water flowing through pipe is 0.32 (l/s).

Table B-32 predict friction loss for the same pipe, when water flowing through pipe is 0.8 (l/s).

Table B-25: MGA-33 pipes, 50% reduction in diameter, water flow rate 0.31 (l/s).

Age	e (mm)	D (mm)	e/D	Re	f	Hf/L
0	0.15	27.30	0.005	9518	0.031	0.01638
10	2.47	23.21	0.090	11197	0.096	0.11377
20	4.23	19.11	0.155	13597	0.132	0.41083
30	5.43	17.31	0.199	15012	0.155	0.79415
40	6.07	15.51	0.222	16757	0.168	1.48703
50	6.15	13.70	0.225	18960	0.169	2.78311

Table B-26: MGA-33 pipes, 50% reduction in diameter, water flow rate 0.8 (l/s).

Age	e (mm)	D (mm)	e/D	Re	f	Hf/L
0	0.15	27.30	0.005	24562	0.031	0.10904
10	2.47	23.21	0.090	28897	0.096	0.75698
20	4.23	19.11	0.155	35089	0.132	2.73350
30	5.43	17.31	0.199	38742	0.155	5.28402
40	6.07	15.51	0.222	43244	0.168	9.89476
50	6.15	13.70	0.225	48930	0.169	18.52059

Table B-27: MGA-42 pipes, 50% reduction in diameter, water flow rate 0.31 (l/s).

Age	e (mm)	D (mm)	e/D	Re	f	Hf/L
0	0.15	36.00	0.004	7217	0.029	0.00378
10	2.47	30.60	0.069	8491	0.084	0.02472
20	4.23	25.20	0.118	10311	0.112	0.08719
30	5.43	22.82	0.151	11384	0.130	0.16626
40	6.07	20.45	0.169	12707	0.139	0.30919
50	6.15	18.07	0.171	14378	0.140	0.57817

Table B-28: MGA-42 pipes, 50% reduction in diameter, water flow rate 0.8 (l/s).

Age	e (mm)	D (mm)	e/D	Re	f	Hf/L
0	0.15	36.00	0.004	18626.8677	0.029	0.02516
10	2.47	30.60	0.069	21913.9621	0.083	0.16443
20	4.23	25.20	0.118	26609.8111	0.111	0.58005
30	5.43	22.82	0.151	29379.9176	0.130	1.10606
40	6.07	20.45	0.169	32793.7812	0.139	2.05706
50	6.15	18.07	0.171	37105.3142	0.140	3.84705

Table B-29: MGA-48 pipes, 50% reduction in diameter, water flow rate 0.31 (l/s).

Age	e (mm)	D (mm)	e/D	Re	f	Hf/L
0	0.15	41.90	0.004	6401.60	0.028	0.00181
10	2.47	35.62	0.059	7531.29	0.078	0.01145
20	4.23	29.33	0.101	9145.14	0.102	0.03992
30	5.43	26.56	0.130	10097.16	0.118	0.07561
40	6.07	23.80	0.145	11270.42	0.126	0.14016
50	6.15	21.03	0.147	12752.18	0.127	0.26199

Table B-30: MGA-48 pipes, 50% reduction in diameter, water flow rate 0.8 (l/s).

Age	e (mm)	D (mm)	e/D	Re	f	Hf/L
0	0.15	41.90	0.004	16003.9914	0.028	0.01127
10	2.47	35.62	0.059	18828.2252	0.077	0.07145
20	4.23	29.33	0.101	22862.8448	0.102	0.24920
30	5.43	26.56	0.130	25242.8886	0.118	0.47207
40	6.07	23.80	0.145	28176.0412	0.126	0.87509
50	6.15	21.03	0.147	31880.4609	0.127	1.63590

Table B-31: MGA-62 pipes, 50% reduction in diameter, Q= 0.31 (l/s).

Age	e (mm)	D (mm)	e/D	Re	f	Hf/L
0	0.15	53.10	0.003	5051	0.026	0.00051654
10	2.75	45.14	0.052	5942	0.073	0.00329361
20	5.35	37.17	0.101	7216	0.102	0.01220328
30	7.95	33.67	0.150	7967	0.129	0.02527486
40	10.55	30.16	0.199	8893	0.155	0.05267528
50	13.15	26.66	0.248	10062	0.182	0.11424089

Table B-32: MGA-62 pipes, 50% reduction in diameter, Q= 0.8 (l/s).

Age	e (mm)	D (mm)	e/D	Re	f	Hf/L
0	0.15	53.10	0.003	12628	0.026	0.00322526
10	2.75	45.14	0.052	14856	0.073	0.02055633
20	5.35	37.17	0.101	18040	0.102	0.07616459
30	7.95	33.67	0.150	19918	0.129	0.15774251
40	10.55	30.16	0.199	22233	0.155	0.32875384
50	13.15	26.66	0.248	25156	0.181	0.71302625

Cast Iron:

Cast Iron- Ductile (SJK-44)

Table B-33 predict friction loss for a galvanized pipe with diameter of 40mm, when water flowing through pipe is 0.32 (l/s).

Table B-34 predict friction loss for the same pipe, when water flowing through pipe is 0.8 (l/s).

Cast Iron- Ductile (SJK-54)

Table B-35 predict friction loss for a galvanized pipe with diameter of 50mm, when water flowing through pipe is 0.32 (l/s).

Table B-36 predict friction loss for the same pipe, when water flowing through pipe is 0.8 (l/s).

Cast Iron- Gray (SJG-32)

Table B-37 predict friction loss for a galvanized pipe with diameter of 32mm, when water flowing through pipe is 0.32 (l/s).

Table B-38 predict friction loss for the same pipe, when water flowing through pipe is 0.8 (l/s).

Cast Iron- Gray (SJG-40)

Table B-39 predict friction loss for a galvanized pipe with diameter of 40mm, when water flowing through pipe is 0.32 (l/s).

Table B-40 predict friction loss for the same pipe, when water flowing through pipe is 0.8 (l/s).

Table B-33: SJK-44 pipes, 50% reduction in diameter, Q= 0.31 (l/s).

Age	e (mm)	D (mm)	e/D	Re	f	Hf/L
0	0.25	44.00	0.006	5905	0.032	0.00152
10	2.57	37.40	0.058	6947	0.077	0.00838
20	4.33	30.80	0.098	8436	0.101	0.02893
30	5.53	27.90	0.126	9314	0.116	0.05457
40	6.17	24.99	0.140	10397	0.124	0.10098
50	6.25	22.09	0.142	11764	0.125	0.18870

Table B-34: SJK-44 pipes, 50% reduction in diameter, Q= 0.8 (l/s).

Age	e (mm)	D (mm)	e/D	Re	f	Hf/L
0	0.25	44.00	0.006	15240	0.032	0.01013
10	2.57	37.40	0.058	17929	0.077	0.05571
20	4.33	30.80	0.098	21771	0.101	0.19241
30	5.53	27.90	0.126	24038	0.116	0.36301
40	6.17	24.99	0.140	26831	0.124	0.67172
50	6.25	22.09	0.142	30358	0.125	1.25544

Table B-35: SJK-54 pipes, 50% reduction in diameter, Q= 0.31 (l/s).

Age	e (mm)	D (mm)	e/D	Re	f	Hf/L
0	0.25	54.00	0.005	4811	0.030	0.00051
10	2.85	45.90	0.053	5661	0.074	0.00287
20	5.45	37.80	0.101	6874	0.102	0.01054
30	8.05	34.24	0.149	7589	0.129	0.02175
40	10.65	30.67	0.197	8471	0.155	0.04523
50	13.25	27.11	0.245	9585	0.180	0.09791

Table B-36: SJK-54 pipes, 50% reduction in diameter, Q= 0.8 (l/s).

Age	e (mm)	D (mm)	e/D	Re	f	Hf/L
0	0.25	54.00	0.005	12417	0.030	0.00342
10	2.85	45.90	0.053	14609	0.073	0.01907
20	5.45	37.80	0.101	17739	0.102	0.07009
30	8.05	34.24	0.149	19586	0.129	0.14464
40	10.65	30.67	0.197	21862	0.154	0.30074
50	13.25	27.11	0.245	24736	0.180	0.65111

Table B-37: SJG-32 pipes, 50% reduction in diameter, Q= 0.31 (l/s).

Age	e (mm)	D (mm)	e/D	Re	f	Hf/L
0	0.150	32.00	0.005	8120	0.030	0.00706
10	2.470	27.20	0.077	9553	0.089	0.04729
20	4.230	22.40	0.132	11600	0.120	0.16841
30	5.430	20.29	0.170	12807	0.140	0.32290
40	6.070	18.18	0.190	14296	0.150	0.60216
50	6.150	16.06	0.192	16175	0.152	1.12641

Table B-38: SJG-32 pipes, 50% reduction in diameter, Q= 0.8 (l/s).

Age	e (mm)	D (mm)	e/D	Re	f	Hf/L
0	0.150	32.00	0.005	20955	0.030	0.04696
10	2.470	27.20	0.077	24653	0.089	0.31461
20	4.230	22.40	0.132	29936	0.119	1.12042
30	5.430	20.29	0.170	33052	0.140	2.14830
40	6.070	18.18	0.190	36893	0.150	4.00646
50	6.150	16.06	0.192	41743	0.152	7.49533

Table B-39: SJG-40 pipes, 50% reduction in diameter, Q= 0.31 (l/s).

Age	e (mm)	D (mm)	e/D	Re	f	Hf/L
0	0.150	40.00	0.004	6496.12	0.028	0.002165
10	2.470	34.00	0.062	7642.494	0.079	0.013856
20	4.230	28.00	0.106	9280.172	0.105	0.048486
30	5.430	25.36	0.136	10246.25	0.122	0.092026
40	6.070	22.72	0.152	11436.83	0.130	0.170744
50	6.150	20.08	0.154	12940.48	0.131	0.31919

Table B-40: SJG-40 pipes, 50% reduction in diameter, Q= 0.8 (l/s).

Age	e (mm)	D (mm)	e/D	Re	f	Hf/L (m)
0	0.150	40.00	0.004	16764.18	0.028	0.01441
10	2.470	34.00	0.062	19722.57	0.079	0.09217
20	4.230	28.00	0.106	23948.83	0.105	0.32253
30	5.430	25.36	0.136	26441.93	0.121	0.61218
40	6.070	22.72	0.152	29514.4	0.130	1.13591
50	6.150	20.08	0.154	33394.78	0.131	2.12373

Norges miljø- og biovitenskapelige universitet
Noregs miljø- og biovitskapelege universitet
Norwegian University of Life Sciences

Postboks 5003
NO-1432 Ås
Norway