NTNU – Trondheim
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Reliability of Watersupply Networks

Case study: Network of Skullerud, Oslo,

Nrway

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Acknowledgements

This report concludes the work of the master thesis, on reliability of water distribution networks. The work has proven interesting, and given a better understanding on how reliability of large complex distribution networks can be assessed/measured.

I have not been able to do all that I wanted for the thesis, as it proved too time consuming, but I feel that all important goals have been fulfilled. The testing and modeling of recommendations to improve reliability for the network of Skullerud has not been done. There have been some difficulties during work on the thesis, with failing of PCs and software. However these difficulties have not caused too much problems for the thesis.

I would like to thank my supervisor Rita Ugarelli, for her support and guidance during both the project thesis and master thesis. And I am grateful that she was quick to help and guide/push me forward, despite her busy schedule. I am also grateful that I was allowed to participate in the meeting between SINTEF and Hydroinformatics, Polytechnic university of Bari, regarding use and improvement of the WDNetXL software. The attendees were from SINTEF: Rita Ugarelli, Ingrid Selseth and Jon Røstum. Polytechnical university of Bari: Luigi Berardi and Orazio Giustolisi. Student: myself.

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I hereby acknowledge that the report has been written in accordance with the guidelines, and that all used references have been listed.

Trondheim: __/__-

Signed:____

Abstract

It is necessary to have an understanding of the reliability of water distribution network, in order to make right decisions on maintenance and expansion of an existing network. The purpose of the master thesis has been to find a method of assessing/estimating the reliability of a water distribution network. Reliability of a water distribution network can be regarded by the mechanical reliability of the components, and/or the networks ability to deliver water to recipients at a sufficient pressure, at both normal and failure situations. The later is hydraulic reliability of the network, and this has been the focus of this report. This report has focused on methods of measuring a water distribution networks ability to perform its required function, for mechanical failure events.

There are two ways of regarding the hydraulic reliability of a network, one way is to preform impact calculations for the network and then regard average impacts as well as impact distribution and maximum and minimum impacts. The other way is to use the impact and combine the mechanical reliability of the components. The first way is regarded as assessment of the reliability, while the second method is estimation of reliability. When estimating the reliability of a network, it is necessary to use time intervals in order to get a good perspective.

The report contains a suggested method for determining the reliability of water distribution networks for different time-spans, based on failure probabilities and impact assessments. The method that is suggested contains 10 steps, whereof 6 are considered necessary.

The method has been tested using a skeletonized version of the actual network of Skullerud in Oslo, Norway as a case study. The case network was provided by the municipality of Oslo, and no changes have been made by the student. Failure rates for the network have been made from registered failures in the network of Oslo, for the period of 1975-2011. The impact calculations were done with two different software solutions, with varying degree of consistency between the different calculations.

In addition the report also contains a short comparison of demand and pressure driven analysis, and how they impact results for supply criticality. It has not been found any clear indication of demand driven or pressure driven analysis, has in general a higher or lower impact on hydraulic criticality. There are large differences between how consistent the results are. Values for valves and pumps are quite consistent, while pipes are more varying. This is based on the case study.

With regards to the case study, the method indicates that the network of Skullerud can be considered to be both mechanically and hydraulically reliable, and that the expected loss off supply for the network is less than 2%, given a single failure event. The expected number of failures for the network within a month is 4, with the majority having a low impact on the network hydraulics.

Sammendrag

Det er nødvendig å ha en forståelse for vannforsynings ledningsnett sin pålitelighet, for å kunne gjøre riktige beslutninger for vedlikehold og utvidelse av eksisterende ledningsnett. Hensikten med master oppgaven har vært å finne en metode for å vurdere/estimere påliteligheten til et ledningsnett. Påliteligheten til et ledningsnett er bestemt av den mekaniske påliteligheten til ledningsnettets komponenter, og ledningsnettets evne til å levere forventet mengde vann til mottakere ved et tilstrekkelig trykk, i både normal og feil situasjoner. Denne rapporten har fokusert på måter å måle ledningsnett sin evne til å utføre gitte oppgaver, for mekaniske svikt i nettet. Ledningsnettet sin evne til å utføre sin hydrauliske oppgave for både normal og svikt situasjoner, er angitt som påliteligheten til ledningsnettet.

Det er to måter å vurdere et ledningsnett hydrauliske pålitelighet. Ene måten er å gjennomføre påvirknings analyser, og så vurdere gjennomsnittlig påvirkning til komponentene samt se på fordelingen av påvirkning til komponentene i tillegg til maksimum og minimums påvirkning. Den andre måten er å slå sammen den mekaniske påliteligheten med resultater fra påvirknings analyse. Den første måten ansett som vurdering av hydraulisk pålitelighet, mens den andre er estimering av hydraulisk pålitelighet.

Rapporten inneholder en foreslått metode for å bestemme påliteligheten til vannforsyningsnett, for forskjellige tids-intervaller, basert på feilprediksjoner og påvirkningsanalyser. Den foreslåtte metoden inneholder 10 steg, der 6 av stegene er betraktet som nødvendige.

Metoden er blitt testet ved å benytte en forenklet versjon av det faktiske drikkevanns ledningsnett for Skullerud i Oslo, Norge. Ledningsnettet benyttet i masteroppgaven er lånt fra Oslo kommune, ingen endringer på ledningsnettet er gjort av student. Feil rater for ledningsnettet har blitt laget basert på registrerte svikt i det totale ledningsnettet for Oslo, for perioden 1975-2011. Påvirknings analyser er blitt gjort med to forskjellige data programmer, med varierende grad av samsvar.

I tillegg inneholder også rapporten en svært kort sammenligning av trykk drevet og vann behovs drevet analyser, og hvordan de påvirker forsynings kritiske måleenhet. Det er ikke funnet noe tydelig bevis som angir en av analyseformene til å ha høyere eller lavere hydraulisk kritikalitet. Det er store spenn mellom resultatene, vann behovs drevet analyse har for ventiler og pumper lugget noe høyere men for ledninger er det ikke noe klart svar. Dette er basert på

Med hensyn på ledningsnettet som e r benyttet i mater oppgaven, så antyder den foreslåtte metoden at ledningsnettet er både mekanisk og hydraulisk pålitelig, og at den forventet ikke leverte vannmengde utgjør mindre enn 2% ved individuelle mekaniske svikter i systemet. Det forventede antall mekaniske svikt i ledningsnettet er forventet til ca. 4 pr måned.

Contents

1. Introduction

This report is written as the final product of the master thesis in water and wastewater management at the institute for Hydraulic and environmental engineering at NTNU, spring 2012. The report has been written individually by the author.

1.1 Purpose

The purpose of the master thesis has been to:

I. Establish an understanding of reliability of water distribution networks, with regard to failure of network components. And establish a way to measure or describe the reliability, and use it on a case network, and try to see if the method is practical for determining reliability of WDNs.
II. Assess the reliability of the water distribution network of Oslo, Norway as a whole. Based on existing reports
III. Perform impact calculations for the case study, of Skullerud in Oslo, using both Relnet and WDNetXL. And compare the results.
IV. Assess the reliability of the network of Skullerud using the impact results and failure rates from Oslo
V. Make recommendations to the municipality of Oslo

1.2 Structure of report

The report will begin with discussing reliability of water distribution networks, before explaining the software used for impact calculations. There is then given a brief description of the method, which was developed during the thesis work, for assessing and estimating reliability of distribution networks.

Then the case network of Skullerud will be presented, with the most important features and failure rates based on the overall network of Oslo, Norway. After the network has been presented, there will be an overview of the impact results. And then presenting the reliability assessment and estimation results.

1.3 Intended recipients

This report is intended for the censor, lectures at department of hydraulic and environmental engineering at NTNU, SINTEF and the municipality of Oslo

2. Reliability of Water Distribution Networks

In this chapter there will be a short description of the general function of water distribution networks (WDN), before discussing how the network reliability can be determined.

2.1 Function of a water distribution network

The general function of a water distribution network is to deliver safe and drinkable water, at a required pressure and satisfactory amounts. If one of the systems components fails, the system will fail to uphold the **total** required amount/pressure, or the required quality. For this project the assumption is that the quality aspects are satisfied; meaning the considered function of the WDN is here delivering required pressure and quantity. In other words water reliability considered here is the same as supply reliability of the network.

2.2 Reliability

Reliability (R) is defined as the ability of an item to perform required function, under given environmental and operational conditions and for a stated period of time (ISO8402). For this project, the reliability is given as the system ability to function given a failure of any component, either individual failure or for simultaneous failures.

Water distribution networks consist of several different components, such as pipes, valves, pumps and nodes. The components in the network may fail at a given rate, and thereby cause impact to the network. The network components are assumed to be mechanically independent, while being hydraulically dependent. This means that the mechanical failure of a link or junction, will affect the downstream links ability to perform its hydraulic function of supplying water.

Mechanical reliability is the ability of a component to maintain its form and function under normal conditions, as well as maintaining a required level of functioning given extra stress situations. While hydraulic reliability is the ability of water distribution network to supply water at a required or minimum pressure to nodes with demand. Required pressure is the pressure at which all demand is met, while minimum pressure is the level required for any fraction of supply. The minimum pressure may be considered as the level of the orifice, or it can be a set level in which considers any pressure below as unsupplied.

The hydraulic reliability of a distribution network can be improved through redundancy measures such as ring system and having more than one supply source. Mechanical reliability is a function of initial quality, though can be improved through maintenance.

2.3 Failures

Here there will here be given short descriptions of types of failures (F), which may affect a WDN. There are three basic states for all network components: fully functioning, partly functioning and not functioning. These states are valid for both hydraulic and mechanical conditions. For this project only fully functioning and complete failure is regarded. Failure is the state of a network component at which it can no longer perform its required function.

2.3.1 Mechanical failure

States of partial mechanical failure such as leakage, ingress and partial clogging has not been considered in this report. Note leakage has been taken in to account in simulations but has not been used to analyze impact the network.

The mechanical failure of a component is based on the age, material, length and initial quality (production method, design, integration into network) of the component. Mechanical failure can be estimated using either probability formulas or empirical failure rates, or combinational methods. For the project empirical values, registered in the database of Oslo water and wastewater department, have been used in order to make an estimate of the reliability of the case study.

Probability of failure is the probability that a given component fails a given time or within a given time interval, if using time dependent calculations. If one does not consider time dependent probability, one uses the static probability that a pip fails at any given time within a reasonable interval.

Probability of failure can also be applied to all components of a given type, giving the estimated number of failures. This can either be estimated by use of different formulas, or by statistical approximation based on available data for the type of component.

Failure rates is an empirical measurement based, based on collected data. Failure rates give the number of failures to expect from a given number of components, or it can denote the number of failures per year, length or year of construction. It provides an estimate for the probability of failure for a given component. The project has used this form of failure prediction.

2.3.2 Hydraulic failure

Hydraulic failure is a function of either a form of mechanical failure or initial conditions such as wrong dimensions compared to demand. There are three forms of hydraulic failures, failure of connection, failure of pressure and failure of delivery which are inter-dependent. The different forms of hydraulic failure triggered by a mechanical failure will be briefly explained.

Failure of connection happens if either the link connecting the node(s) to the remaining network or if the pressure prior to the nodes comes below zero. Failure of connection will then lead to subsequent failure of supply and pressure for the affected nodes

Pressure failure is a result of nodal demand being higher than what is available at a sufficient pressure, which .e.g. occurs when a supply link is removed and the water needs to use fewer links increasing velocity of water and thereby increases loss of pressure.

The failure of supply is dependent on either loss of connection or pressure failure, and is the state at which the nodal demand is not fully met.

2.3.3 Events

To get a practical understanding of single failure and simultaneous failures, it is necessary to divide the number of simultaneous failures into event categories. An event (e) has for the project, been considered as the simultaneous failure in the network of one or more network components.

By simultaneous failure we mean failures that affect the network in the same time-interval, and not only failures that occur at the same time. The events have been divided into categories, depending on the number of simultaneous failures, denoted e: number of failures. When running a worst case scenario analysis with WDNetXL, it gave five event categories for links, and four event categories for node failures. The number of combinations of F is shown in Table 1.

Table 1: event categories

Event Category	Possibilities [Links]	Possibilities [Nodes]
e:1	5322	5059
e:2	1,42E+07	1,28E+07
e:3	2,51E+10	2,16E+10
e:4	3,34E+13	2,73E+13
e:5	3,55E+16	2,76E+16

2.4 Impact measurements

There are several ways of assessing the hydraulic impact of a mechanical failure on the network. First the impacts are divided into single categories, of supply, pressure and connectivity. These single categories are made for practical purposes, as almost no mechanical failure will impact only one category. The focus of the master thesis has been on assessing/estimating WDNs reliability in terms supply and pressure, and measurements of these categories are therefore focused on. In addition there is given a method for estimating how large portion of the network that is connected.

2.4.1 Hydraulic criticality

One form of measuring the supply reliability given a failure event is by regarding the fraction of total unsupplied demand. This is normally done by a method called hydraulic criticality, which gives the hydraulic criticality for each vent, giving a hydraulic criticality index value (HCI). HCI is found by first calculating the baseline supplied for total system demand, assuming all demand is met, and then calculating the new supply. The new supplied amount of water is then used, along with the baseline, to establish how much of the baseline that is unsupplied. The expressions for HCI is shown in (2.1)

$$HCI = \frac{Q_{tot} - \sum Q_{new,i}}{Q_{tot}} \tag{2.1}$$

The value for the hydraulic criticality is a number between 0 and 1, where closer to 1 is more critical. A value of 0 or near 0 means that the failure, has a small significance for the overall system. However the HCI method does not take into account which recipients that are affected by the failure. This can be done by assessing which sections or segments in the distribution system that is disconnected by a potential failure.

The supplied water is at a fixed amount for pressure above equal to or above optimal pressure P_{opt}. Supplied water for non-optimal situations, is calculated as a function of available pressure in each node, for pressure situations below P_{opt}. It is assumed that there is zero supply of water, for pressure conditions below required operational level P_{req}. The expression used for these calculations, are shown in (2.2), where ***i*** designates node ***e*** is the event and Q_{act} is the actual demand.

$$Q_{new,i|e} = \begin{cases} 0; P_{i|e} < P_{req} \\ Q_{act} \bullet \dfrac{\sqrt{P_{i|e}}}{\sqrt{P_{req}}}; P_{req} < P_{i|e} < P_{opt} \\ Q_{act}; P_{i|e} > P_{opt} \end{cases} \tag{2.3}$$

2.4.2 Reachability

Another form of reliability measurements for WDN is the measurement of reachability (RA). RA is the measurement of how large portion of the network that can be reached for a given number of failures and failure configurations. By reached, we only mean that the nodes are connected to the network, we do not account for pressure or supply. RA is based on connectivity (CN), which is a measurement of how connected the each node is for a given number simultaneous failures and configurations of each number of failures.

From a network reliability perspective, it is arguable that RA is the more important than CN, as it gives the overall view for the network. CN can be very useful for assessing individual nodes, though that has not been used in the project. The equations for CN and RA are in shown in (2.4) and(2.5), Giustolisi et.al (2008).

$$\begin{gathered} CN(i,k) = \frac{\sum_{s=1}^{Nc} C(i,s,k)}{Nc} \\ \Rightarrow C(i,s,k) = \begin{cases} 1, ith\_node\_is\_connected \\ 0, ith\_node\_is\_disconnected \end{cases} \end{gathered} \tag{2.4}$$

$$\begin{gathered} RA(k) = \frac{\sum_{s=1}^{Nc} R(s,k)}{Nc} \\ \Rightarrow C(i,s,k) = \begin{cases} 1 \mid \sum_{s=1}^{Nc} C(i,s,k) = n_n, network\_is\_connected \\ 0 \mid \sum_{s=1}^{Nc} C(i,s,k) \neq n_n, at\_least\_one\_node\_is\_disconnected \end{cases} \end{gathered} \tag{2.5}$$

Where Nc is the amount of possible combinations of ***k*** number of simultaneous failures for a given number of pipes n_p and ***s*** configurations, shown in equation(2.6).

$$Nc(n_p,k)=\frac{n_p!}{(n_p-k)!k!} \tag{2.6}$$

2.4.3 Pressure reliability

Pressure reliability is the networks ability to deliver required pressure, given a failure event. This can be measured by assessment of how many nodes that have suboptimal pressure conditions, and how many nodes that have less than required for operation. Or using the sum of average pressure divided by the normal situation pressure for all nodes. For the project it was chosen to use the fraction of nodes having at least a required pressure for a given number of k.

$$R_P(P_{req},k)=\frac{\frac{1}{Nc}\sum_{i=1}^{n_n} n_i(P_i \geq P_{req},k,s)}{n_n} \tag{2.7}$$

Based on work on the project it was found that(2.7), could be modified in order to show fraction that does not have required pressure. And that was most useful for singular failures, and being able to relate a measurement of pressure reliability to HCI. This has been named RP1, reliability of pressure 1, where the 1 stands for single failure, given in(2.8).

$$RP1=1-\frac{\frac{1}{Nc}\sum_{i=1}^{n_n} n_i(P_i \geq P_{req},k,s)}{n_n}=\frac{\sum_{i=1}^{n_n} n_i(P_i < P_{req},k,s)}{n_n} \tag{2.8}$$

Another form of measuring pressure reliability, used in WDNetXL shown in(2.9), is to use the sum of pressure divided by the sum of pressure at the normal situation. The equation gives a measurement of how well the pressure in the network is upheld for a given event.

$$R_P(e)=\frac{\sum_{i=1}^{n_n} P_i(e)}{\sum_{i=1}^{n_n} P_i(0)} \tag{2.9}$$

2.4.4 Unified impact indicator

During the project work it was considered, if the reliability should be measured for each impact category, or if it should be created an impact indicator based weighing of supply, pressure and connection. The question was what the weight factors for the different categories should be. Since supply is the most critical this is suggested to be weighted 75%, pressure is weighted 15% and connection is weighted 10%. The reason for this weighting is that both pressure and connection is to some extent accounted for in the HCI indicator. However this was not used for the case study, and was therefore discarded.

2.5 Assessment of water distribution network reliability

Here there will be given a short description on how the reliability of a WDN can be assessed or measured. There are two form reliability aspect of any WDN to consider, mechanical and hydraulically. First there will be given a short description of mechanical reliability, before discussing assessment/estimation of the hydraulic reliability of the network.

2.5.1 Mechanical reliability

Mechanical reliability is the probability that the component is functioning at the time interval of interest, the equation is shown in(2.10), were F_{mech} is the probability of mechanical failure. The probability of mechanical failure can be found using either empirical failure rates or probability density functions, or by failure equations, as stated in 2.3.1.

$$R_{mech} = 1 - F_{mech} \tag{2.10}$$

2.5.2 Hydraulic reliability

It is possible to make both assessment of the reliability based only on the impact results, and reliability estimates based on both the impact of a failure, and the probability of that failure. As failures in different pipes, valves, pumps or nodes located in different sections of a WDN will lead to different impacts in terms on loss supply, pressure or connection. It is necessary to divide the systems varying degree impacts into states (St).

Hydraulic states

A state is here defined as what level the network is still preforming its required hydraulic function, given the occurrence of a failure.

There are two main ways of assessing the state of a network, aggregated total network or on more in-depth nodal level. For this project the main focus has been on the overall function of the system. The nodal focus is more interesting when considering critical recipients, which has not been done during the project.

For the thesis a total of 6 failure states have been made, based on the fraction of demand supplied or sections/subsections connected or without required pressure. The division of states is given in Table 2. For this project less than 50% supplied or connected is considered a complete system failure. St0 which represents the “normal” situation has not been used in either the reliability assessment or estimation, as no component in the case network had zero impact.

Table 2: State of function

State	St0	St1	St2	St3	St4	St5
Degree of function [%]	100	<100 - 90	<90 - 80	<80 - 70	<60 -50	<50

Assessment of hydraulic reliability

If one only cares about assessing the networks reliability, which is too simply regard the distribution of impacts connected to the different links and junctions on an overall level, it is possible to do so. This is done by calculating the impacts for the different impact categories, and regarding the highs and lows of the results, in addition to calculating the average and finding the number of components which have an impact value above or below a defined limit.

Estimating hydraulic reliability

To estimate the reliability of the network, one needs both impact and probability. It is possible either use impact and probability for each individual component, or average values for components of a given criteria. For the master thesis it has been used average HCI and PR1 values for pipes of defined size categories, as this makes it easier to estimate the overall reliability of the case network.

When estimating the reliability of the network, it must be estimated for each of the hydraulic states and for a time interval of interest. For the master thesis it was used, day, week, month and year as time interval. This assumes that the probability for mechanical failure is independent. It becomes very complicated to estimate the probability of a network state without defining number of simultaneous failures. The probability of network state n, for k=1 is given in(2.11). Where $p_{nodes=n,i|t}$ is the probability for nodes resulting in St=n, for time interval t.

$$\begin{aligned} P(St=n,k=1\,|\,t) &= \sum_{i=1}^{n_{state=n}} p_{n_{state=n},i|t} \\ P(St=n,k=1\,|\,day) &= \sum_{i=1}^{n_{state=n}} p_{n_{state=n},i|day} \\ P(St=1,k=1\,|\,day) &= \sum_{i=1}^{n_{state=1}} p_{n_{state=1},i|day} \end{aligned} \tag{2.11}$$

It has not been made equations for other configurations of k, as this has not been used during work with the master thesis.

3. Software and simulations

It this chapter we will briefly present the different forms of analysis and simulations that have been used, as well as the two different software solutions used in the project. The forms of simulations will be presented first as they are necessary to better understand purpose of the software. Descriptions are mainly based on software literature for WDNetXL.

3.1 Simulations and analysis methods

First we will have a short description of different simulation and analysis methods. Simulations method is here considered as different forms of regarding the boundary conditions such as pressure and demand. While analysis methods, are based on what is used as the driving force.

3.1.1 Steady state simulation

A steady state (SS) simulation is a form of simulation in which the boundary conditions are constant. For this project, all simulations have been using SS simulations.

3.1.2 Extended period simulation

In an extended period (EP) simulation, changes in boundary conditions can occur gradually. This method can be used to analyze the impact of events over time, and can indicate at which time is the most critical for different areas. EP simulation has not been used during this project, as time dependent impact is not part of the project.

3.1.3 Demand driven analysis

In a demand driven simulation (DDA), all demands are expected to be fixed. The simulations are based on the mass balance equation. Leakages are assumed to be a given percentage of the total demand, and be independent from pressure in the pipes. This form of simulation therefore assumes all demands are met, regardless of available pressure. This may lead to calculations returning negative pressure in the system.

3.1.4 Pressure driven analysis

For pressure driven analysis (PDA), the demand is assumed to be a function of how much is available with a given pressure. A PDA is based on both mass balance and the energy (head) equation, and demand and leakage is there calculated as a function of available pressure. This form of analysis assumes that the demand will increase as long as there is sufficient pressure, for both consumer demand and leakages.

3.1.5 Pressure-demand analysis

Pressure demand analysis uses a combination of PDA and DDA, in which the pressure based equations are used for situations where the pressure is below required level. The expression for this is given in (2.3).

3.2 Software description

There will here be given short descriptions of the three software solutions that have been used during the project. EPAnet will be explained first, the Relnet will be explained first of the impact analysis software as its calculations on HCI have been used as a baseline throughout the report. The user interface (UI) for analysis options for both Relnet and WDNetXL will be presented.

3.2.1 EPAnet

EPAnet is a hydraulic modeling and analysis software, which is commonly used to model water distribution networks. The software preforms both EP and SS simulation, using DDA. The EPAnet model is demand driven, and as such negative pressure may occur in the results.

EPAnet has for the project only been used to produce graphical representations of the case study, and to verification of the case network.

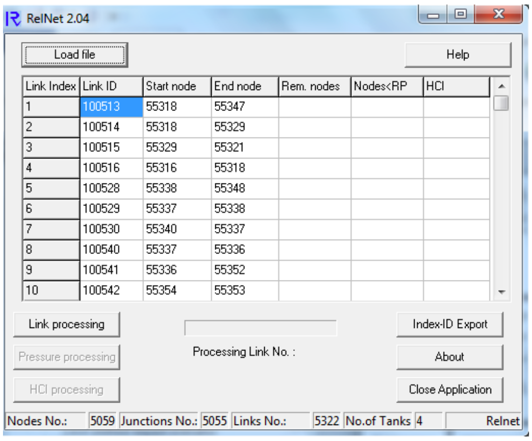
- *EPAnet is developed by the U.S Environmental Protection Agency*

3.2.2 Relnet

Relnet is standalone software based on the EPAnet hydraulic model, used for calculating the hydraulic impact index for each link in the system. Also for a demand driven simulation, Relnet partly solves this by using a pressure-demand approximation for supplied water, equal to equation xx. Relnet calculates the HCI value for single events and uses SS simulation.

Results of the calculations are exported to a Microsoft Excel and a text file. The results show the component closed down, nr of nodes disconnected from the system nodes with pressure lower than required and the HCI for the component.

The software gives in addition to results for HCI values, number of nodes that have been removed from the network and number of nodes that have below required pressure, for failure in a given pipe.



Link Index	Link ID	Start node	End node	Rem. nodes	Nodes<RP	HCI
1	100513	55318	55347			
2	100514	55318	55329			
3	100515	55329	55321			
4	100516	55316	55318			
5	100528	55338	55348			
6	100529	55337	55338			
7	100530	55340	55337			
8	100540	55337	55336			
9	100541	55336	55352			
10	100542	55354	55353			

Nodes No.: 5059 Junctions No.: 5055 Links No.: 5322 No.of Tanks 4 Relnet

Figure 1: Relnet UI

- *Relnet is developed at BUT, Brno, Czech republic*

3.2.3 WDNetXL

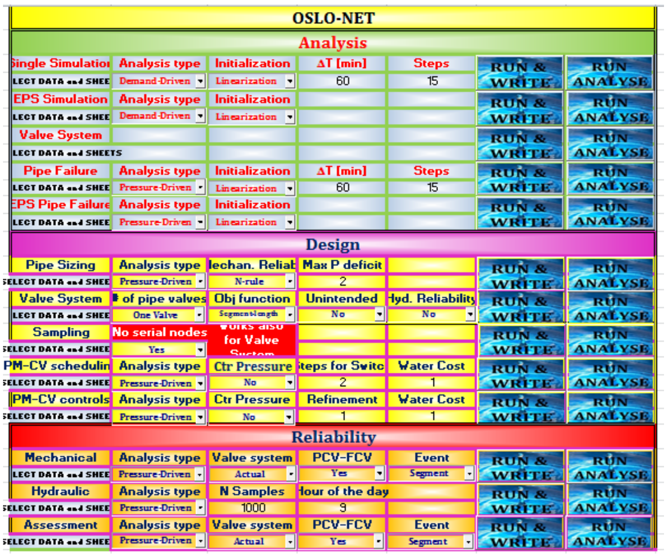
WDNetXL is a Microsoft Excel based software, and which uses the Matlab compiler (MCR). The software has several functions such as calculating the normal situation hydraulic simulations using both SS and EP, optimization of pipe size, valve location, failure events, hydraulic and mechanical reliability and hydraulic assessment. For this project only normal, failure simulation using SS simulation, for both DDA and PDA, and hydraulic assessment have been used.

WDNetXL is capable of running events with several simultaneous failures, however the pipes have to be selected manually in the on the event page in the Excel file. The software is also able to find the most critical events by using an optimization method called OPTIMOGA, that will be briefly explained.

The network is represented by tables and matrices, and the calculations are matrix based. Due WDNetXL ability to both graphically show the system, and calculate the topology, it can be used to show sections and segments disconnected from the overall network.

OPTIMOGA is a multi-objective (MO) genetic algorithm (GA) used to solve optimization problems. For the hydraulic assessment feature the optimization goal, had to objectives find simultaneous failures in the least possible components that lead to the lowest degree of supply.

WDNetXL has been used to find HCI values for 50 pipes and that was defined by Relnet as the most critical, and also HCI values for the valves and pumps, in order to get a foundation for comparison between the two software solutions. And to find the worst case scenarios using the hydraulic assessment feature.



OSLO-NET				
Analysis				
ingle Simulatio	Analysis type	Initialization	ΔT [min]	Steps
LECT DATA and SHEE	Demand-Driven	Linearization	60	15
EPS Simulation	Analysis type	Initialization		
LECT DATA and SHEE	Demand-Driven	Linearization		
Valve System				
LECT DATA and SHEETS				
Pipe Failure	Analysis type	Initialization	ΔT [min]	Steps
LECT DATA and SHEE	Pressure-Driven	Linearization	60	15
PS Pipe Failure	Analysis type	Initialization		
LECT DATA and SHEE	Pressure-Driven	Linearization		
Design				
Pipe Sizing	Analysis type	lechan. Reliab	Max P deficit	
SELECT DATA and SHEE	Pressure-Driven	N-rule	2	
Valve System	# of pipe valves	Obj function	Unintended	Hyd. Reliability
LECT DATA and SHEE	One Valve	Segment-length	No	No
Sampling	No serial nodes	Works also for Valve System		
SELECT DATA and SHEE	Yes			
PM-CV schedulin	Analysis type	Ctr Pressure	Steps for Switc	Water Cost
SELECT DATA and SHEE	Pressure-Driven	No	2	1
PM-CV controls	Analysis type	Ctr Pressure	Refinement	Water Cost
SELECT DATA and SHEE	Pressure-Driven	No	1	1
Reliability				
Mechanical	Analysis type	Valve system	PCV-FCV	Event
LECT DATA and SHEE	Pressure-Driven	Actual	Yes	Segment
Hydraulic	Analysis type	N Samples	Hour of the day	
SELECT DATA and SHEE	Pressure-Driven	1000	9	
Assessment	Analysis type	Valve system	PCV-FCV	Event
SELECT DATA and SHEE	Pressure-Driven	Actual	Yes	Segment

Figure 2: WDNetXL UI

- *WDNetXL is developed at Hydroinformatics/Polytechnic University of Bari, Bari, Italy*

4. Method

Here there will be given a short description of the proposed method for estimating the reliability of a WDN. It is this method that has been used on the case study. The suggested method developed during the project work consists of 10 steps, which will be explained. Of the 10 steps 6 are considered as necessary while the remaining 4 are regarded as useful for the understanding but not required. The steps are first listed and the briefly explained.

As this suggested method is a result of the project work, it will contain a lot of repetition with regards to rest of the report.

1. Assessing possible event categories
2. understanding the network topology
3. dividing network into groups of components
4. location critical recipients – not done for case study
5. knowledge of material and age of network components – not done for case study
6. failure rates and or probability models – used failure rates for the case study
7. formulation of assumptions to be tested
8. impact assessment and calculations
9. connecting failure rates and impacts to components and component groups
10. estimating reliability

1 Event categories and states

First we start with assessing possible event categories, based on what is assumed to be probable number of simultaneous failures. Formulate guide questions: What can go wrong? How many simultaneous failures are reasonable?

Then one should make up system states based on functioning of the network, and determine what is acceptable in terms of degree of function.

2 understanding the network topology

The impact of component failure is very dependent on where in the network the failure occurs, and if there are alternate links that can be used. It is also important to know how interconnected the network is, that is how many links each node is connected to. **Required step**

3 Dividing of network into sub-categories

In order to make the assessment of the network easier, it is advised to divide the network components into smaller categories. Dividing components into smaller groups will make it easier to connect results from impact calculations and probability measurements, to a specific category such as pipes with a given diameter. This makes it easy to assess the reliability and importance of each group of components, both on an overall scale and in detail. **Required step**

4 Location of critical recipients

The location of critical recipients such as hospitals and factories, is important do know as these recipients have operations that are dependent on continuous water supply. It can become costly for the water provider if they are set as liable for lost profit that may occur as the result of a failure event.

5 Knowledge of the material and age of the network

Knowledge about the networks age and material composition can be used as a guide for probability assessments as the dividing that has been used is more related to size or length of the network components.

6 Probability of failures

It is necessary to know the probability of failure for the different components, in order to calculate the reliability of the network. Probability can come from either empirical data, or failure prediction equations. **Required step**

7 Formulation of assumptions

It is advised to formulate assumptions about the networks reliability, based on the topology and failure predictions, in order to facilitate the reliability study.

8 Impact assessment and calculations

It is necessary to preform impact calculations, as they are they are used to find which state the network is in. This should be done with one or more software solutions, due to ease and time considerations. It is not necessary to use more than one software for the calculations, but it can be useful if the different software gives different forms of result. **Required step**

9 Connecting failure predictions and impact

The connection of probability of failure, along with results for impact calculation/simulation, will make it easier to identify the most critical groups of components, or individual components. For an easy overview it is suggested that impacts and probability of failures is averaged and connected to the components sub-categories. **Required step**

10 Calculating reliability

Reliability is as defined the ability of the network to perform its function. There are two ways which have been found to be useful to assess the networks reliability.

The first is to assume all pipe have an equal probability of failure, and then find what the average HCI values are and the HCI of the most critical pipes are. In addition to considering the distribution of impact connected to the pipes. A network were the majority of pipes have a low impact can therefore be assumed to have a high reliability. This way is not a measurement of reliability, but indication of how resilient the system is with regards to supply of water.

The second way is to find the impacts for all pipes, as done with Relnet for Skullerud, and then calculate the probable loss of supply, for the different event categories. This way also requires the use of time-spans for which the reliability is considered. Meaning it is necessary to define what a reasonable time-span for measuring reliability is. If we measure over a long enough periods, the network is bound to fail. We suggest four reasonable time spans which are: daily, weekly, monthly and yearly. A potential user of this way, should themselves choose the suitable time-spans for their study. **Required step**

5. Case study: Network of Skullerud

This chapter will give an understanding of the topology of the network Skullerud as well as failure rates for the network. All background material for the network has been supplied by the water and sanitation department of Oslo. In addition there will be a short list of expectations related to the expected results. And guideline vales for HCI for the network, based on a SINTEF project.

The network is shown with diameter size distribution, and nodal elevation in Figure 3. A short description of the topology will be given.

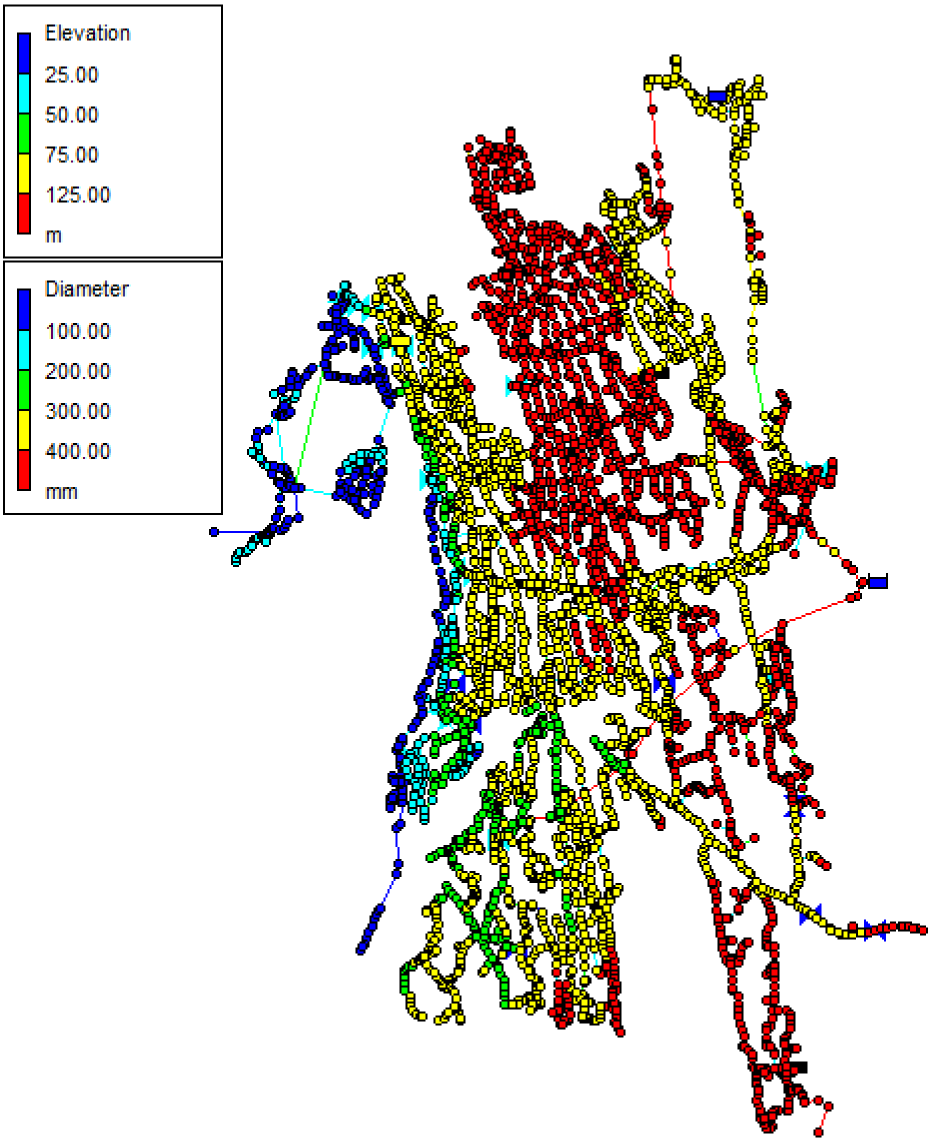


Figure 3: Network of Skullerud

5.1 The overall water reliability situation in Oslo

Before doing an analysis for the case study, it is necessary to have an idea of the reliability of the overall distribution network of Oslo, which the Skullerud network is a part of. The Norwegian research company SINTEF has done an evaluation of the reliability of Oslo, though the results are confidential we have extracted the two most important aspects of average hydraulic impact in terms of HCI values, and the highest HCI values.

The report shows that the overall situation in Oslo in terms of is in terms of supply reliability for the network itself (treatment to consumer) is relatively good, with less than 20% of the pipes having a HCI value of more than 0.027 for the "normal" situation, referring to normal demand, same situation as we are using. The Highest HCI values where in the area of 0.04 to 0.06, note that the overall network of Oslo has more tanks and sources and is therefore expected to be more resilient for single failure events than Skullerud.

The HCI values in the report were found with EPAnetrel. EPAnetrel is SINTEF's one version of the Relnet program, with the capability to import and work with more than 10.000 nodes and pipes. Relnet was also used, where possible, to find the HCI for integrated components such as valves. It is understood this was due to shortcomings of EPAnetrel, with regard to calculating impact of integrated components.

5.2 Topology

In this chapter there will be an overall presentation of the case study: network of Skullerud in Oslo, Norway. The water distribution network which is used is a skeletonized version of the actual Skullerud network. The skeletonizing has been performed by (Ingrid Selseth, SINTEF) before it was received by the author. The network used in this project consists of 5059 junctions and 5322 links.

The first point in the topology analysis is to assess and describe the junctions in the network, as these are both points of connection and demand/supply. After the junctions have been described, there will be a presentation of the links. Links have been the main focus of the reliability analysis of network.

The topology analysis has for the project been done using EPAnet and excel. During work on the master thesis there was also found methods that this could be done using matrix operations, however it was chosen no to attempt this due to insufficient knowledge.

5.2.1 Junctions

Junctions are comprised of nodes, tanks and reservoirs. Junctions are connected to one or more links. Junctions either extract or input water into the system. A junction which extracts water for the network is designated as a node. Junctions which both receive and input water into the network are tanks. While junctions that only input water into the system is reservoirs. It will here be highlighted the main aspects for all the different junctions found in the Skullerud network.

5.2.1.1 Nodes

Nodes make up the majority of the junction in the network, and number 5055 in total. In terms of the topology there are three questions essential for the overall understanding the network and pressure demands, and those are demands, how are nodes connected to the total network, and what the elevations are.

Demands

There has not been a large focus on were the demands are highest, but instead on number of nodes that have a demand beyond that of leakages. There are a total of 13 demand patterns used for the nodes, including leakage. There are in total 4142 nodes with population and industry demands, and 5039 nodes with leakage demand. 897 of the nodes have only leakage demands.

Even though there has not been a focus on location of high demand, it is still necessary to know the demand distribution. The demand distribution is shown in Figure 4, with values given in liter per second (LPS). It shows that there is a high concentration of nodes whit relatively high demand, in the middle of the network, near the pump VP12 shown in Figure 5.

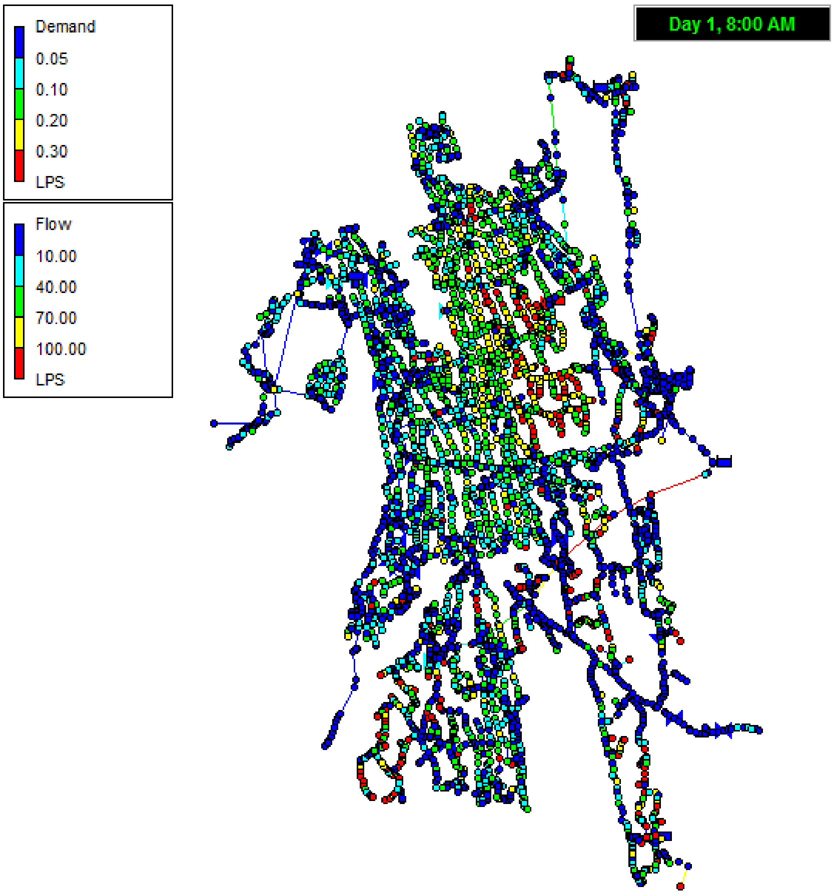


Figure 4: Demand distribution, network

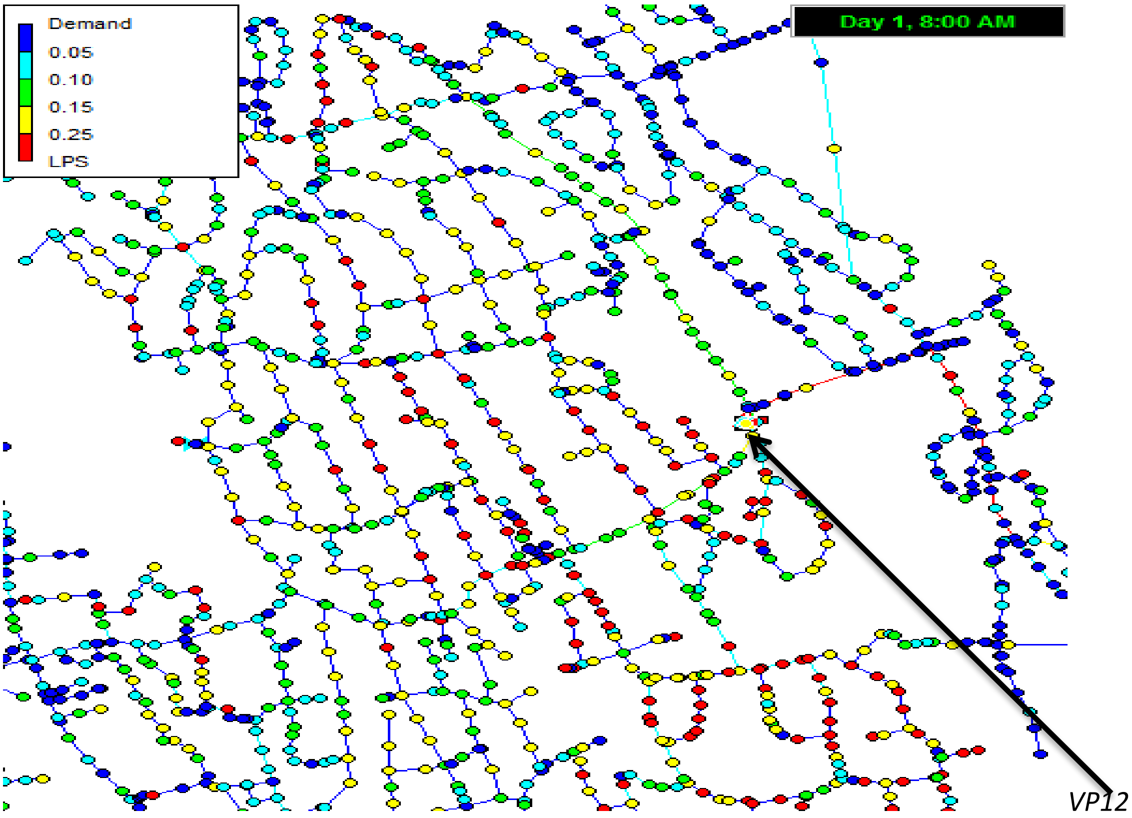
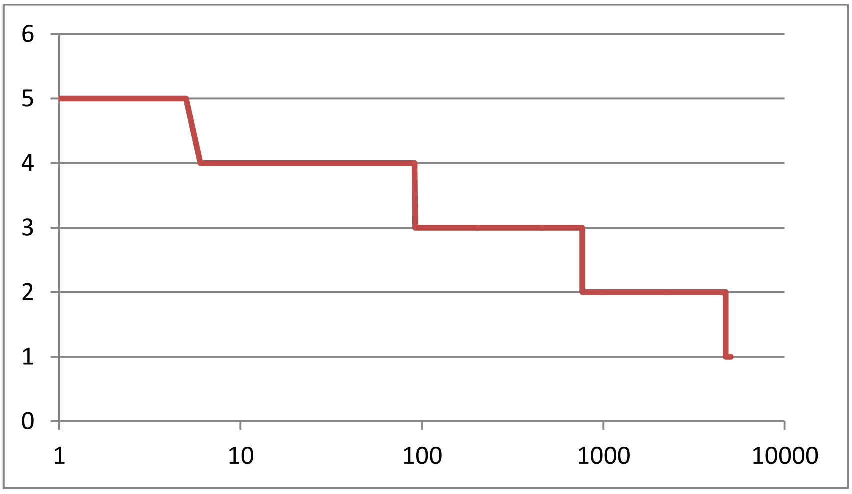


Figure 5: Demand distribution, near VP12

Pipes-Node

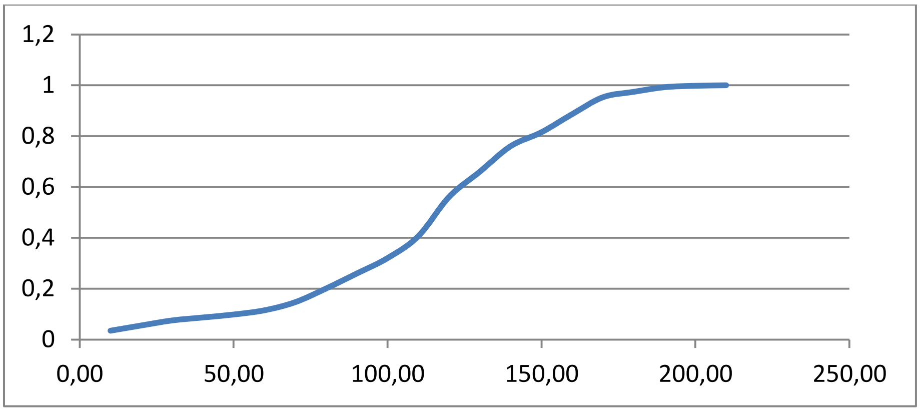
Pipes-node is the measurement of how many links a node is connected to. We will first look at how the nodes on average are connected to the network. Nodes are on average connected to the network by 2.10 links, and when removing end nodes the average number of links connecting the nodes is 2.18. End nodes are nodes connected to a single pipe. This means that the network is does not have a high ratio of pipes to nodes. However when considering the map of the network given in Figure 3, it is clear that there are areas with high ratio of pipes to nodes. This is particularly true for the area near VP12, shown in Figure 5. The distribution of pipes - node is given in Graph 1.



Graph 1: Pipes per node

Elevation

In terms of elevation, the majority (82.6%) of all nodes are located at an elevation above 75m. The percentagewise distribution of nodes in terms of elevation is shown in Graph 2. The elevation is represented by the x-axis, and the y-axis represents the percentage of nodes having a given elevation or lower. Graph 2 shows that 70% of all nodes are at an elevation of more than 100m.



Graph 2: Accumulated elevation distribution, nodes

In addition to the elevation distribution, we also need to know the location of nodes the different elevations. The elevation plot is shown in Figure 6.

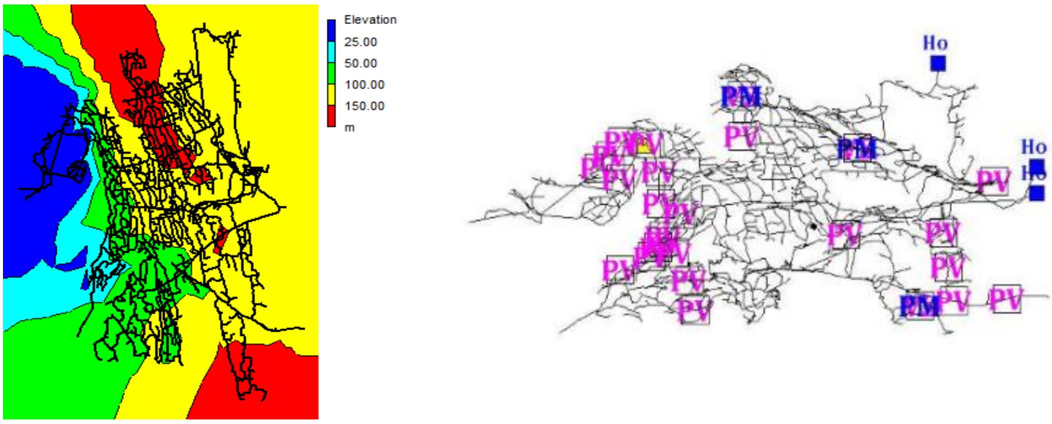


Figure 6: Network topography

5.2.1.2 *Tanks and reservoirs*

In addition to demand nodes, there are a total of 4 supply nodes, which are nodes that deliver water to the system. Of these four nodes, three are reservoirs which self-sustaining sources. Two of these are the same water treatment plant (WTP) with different level of output pressure. The last supply node is a tank, which is dependent on being filled in order to supply water over time. The location of the supply nodes are highlighted in Figure 7, by black symbols. It is not possible to see the two WTP of Skullerud located at the middle of the right side at normal resolution, as they are located on top of each other. This is the main WTP in Skullerud.

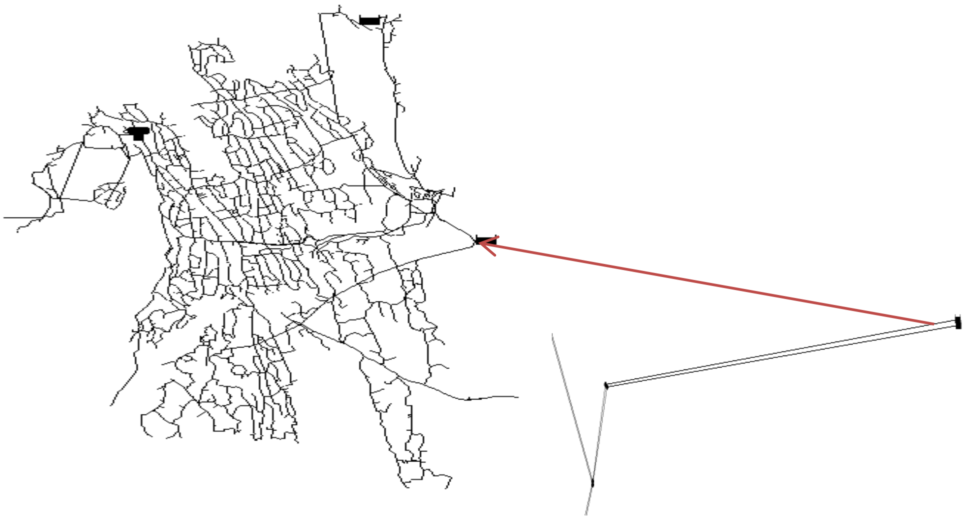


Figure 7: Location of Tanks and reservoirs

5.2.2 Links

There are a total of 5233 links in the system, comprised of pipes, valves and pumps. Links are components that connect the nodes to the network, and transport water throughout the system. All links are connected to two junctions. The most dominant group of links is pipes, numbering 5295 in total, and will therefore be the focus of the links section. After the pipes have been described, there will be a short summary of the valves and pumps.

5.2.2.1 Pipes

When regarding the pipes, it is important to know the size distribution, location of the different size groups and length distribution. The most important feature of the pipes is the size, as it is the indicator of flow. For the case study it was made tables for length distribution, however this was discarded from the report due to focus on size distribution.

Size

In terms of size distribution most of the pipes in the network a defined as medium, with the majority of pipes having a diameter between 100 and 300mm. The size distribution for pipes is shown in Table 3. The large pipes are primarily. The table shows that pipes in the size category medium 1, account for 50% both in terms of total length and number of pipes. This means that a randomly selected pipe is likely to have a diameter between 100 and 200mm.

Table 3: Size distribution of pipes

Size category	Number of pipes	Total length [m]	Average length [m]	Percentage of total pipes	Percentage of total length
Small (0<D<100)	91	5699.4	62.6	1,7 %	2.4 %
Medium 1 (100<D<200)	2790	121371.1	43.5	52,7 %	50.7 %
Medium 2 (200<D<300)	1114	47880.0	43.0	21,0 %	20.0 %
Medium 3 (300<D<400)	842	36003.9	42.8	15,9 %	15.0 %
Large (400<D)	458	28490.1	62.2	8,6 %	11.9 %

When considering the location pipes with different size categories, it was found as expected that most of the large diameter pipes were located near the supply junctions. The size distribution is shown in Figure 8.

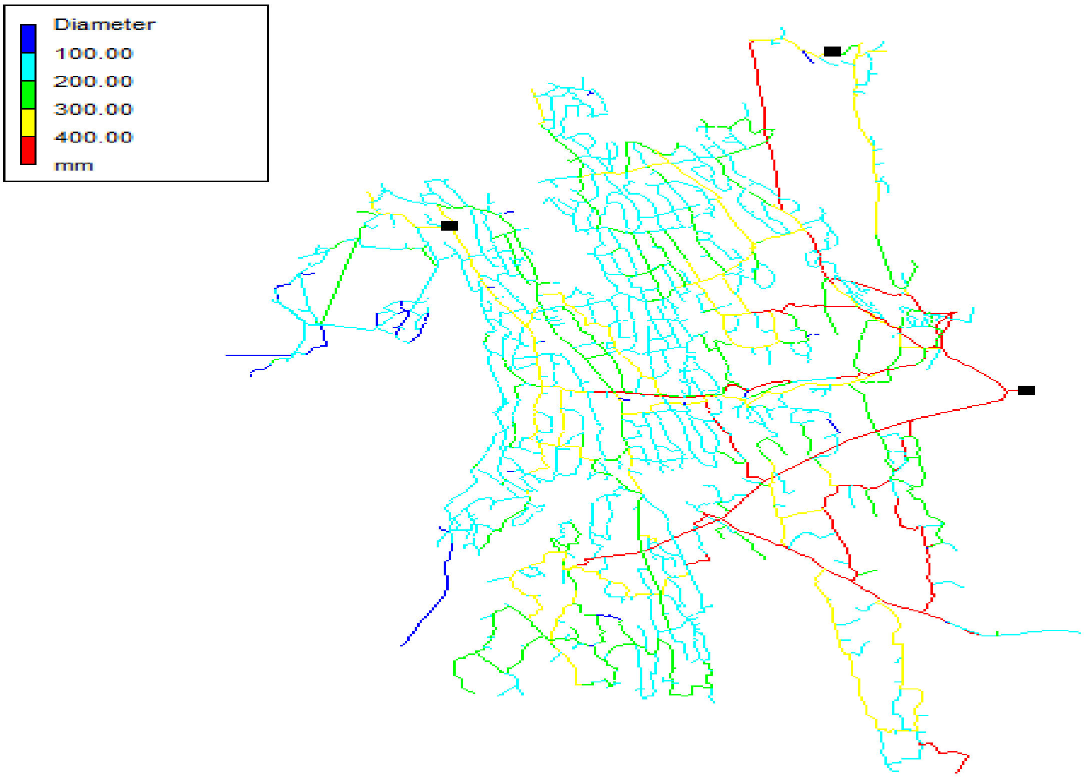


Figure 8: Map of size distribution

For the large diameter pipes, the table shows that they on average are longer than the medium category pipes. The large diameter pipes makes up most of the main suplly lines, represented by red color in Figure 8. Due to the location, and connection of the large pipes, it is assumed that they will be more hyraulicly critical.

5.2.2.2 Valves

There are in total 24 valves in the network, 1 pressure sustaining valve (PSV) and 23 pressure reduction valves (PRV). The valves are shown in Figure 9. 12 of the PRVs are located along the line with elevations are going from around 75m to around 25, right to left. Isolation valves (IV) used for isolating segments, in case of repair or other forms of maintenance, has been used as a part of the segments and is therefore not regarded individually.

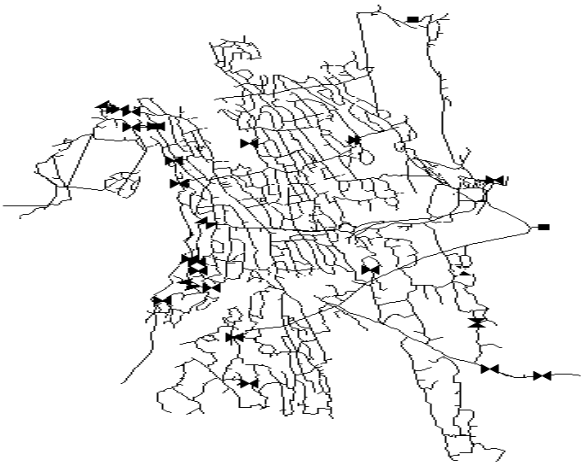


Figure 9: Valve locations

5.2.2.3 Pumps

There are three pumps in the network; all pumps are variable speed pumps (VSP). The locations of the pumps are shown in Figure 10. Based on the location of the pumps, only one is assumed to have large HCI value. The pump that is assumed to have a large HCI value is located near the center of the network, VP12.

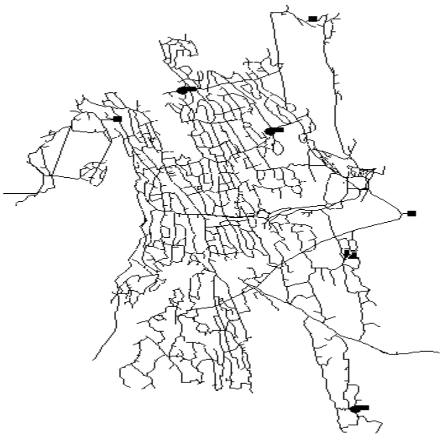


Figure 10: Pump locations

5.2.3 Segments

Segments are the smallest sections a network can be divided into. Segments can consist only of single elements such as a valves, pipe, pumps or segments can consist of several components. For the study network, links were divided into segments using serial. Serial pipes are pipes connected by nodes with one or two links connected. When a node has more than two links connected, the serial pipe ends. Segments are divided using IVs at the end of each serial pipes. The IVs are not given by the actual network model, but have been calculated by WDNetXL.

By using the serial pipe segmentation in WDNetXL, there are 1408 segments in the Skullerud network, and 2774 IVs. Map of the segments is shown in Figure 11. From Figure 11, it is clear that segments are more useful to get an overview of the network, in terms of interconnections of the network than individual pipes.

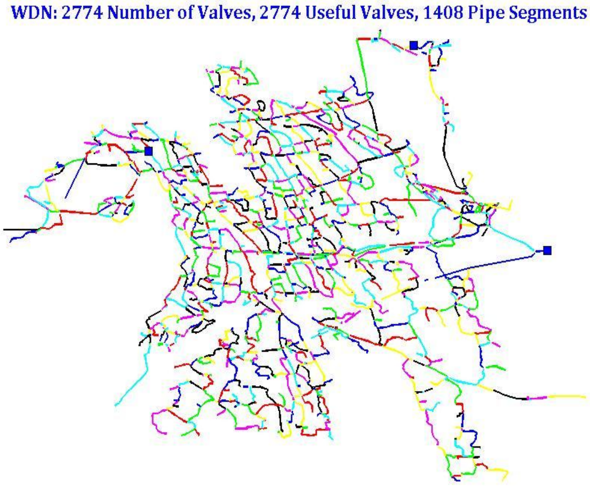
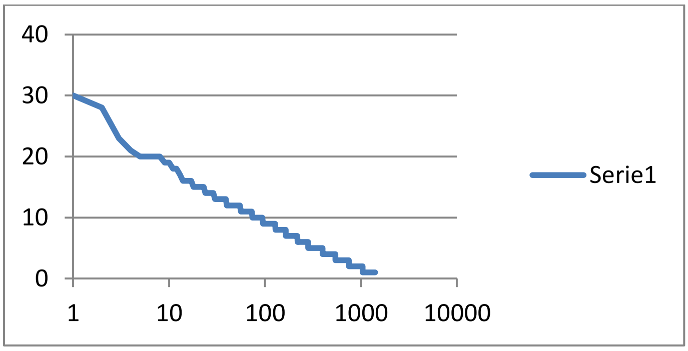


Figure 11: Segment map

We should also consider the number of pipes in a segment, since it affects the segments probability of failure. The average number of pipes in a segment is 3.8, and the highest number of pipes in a single segment is 30. The logarithmic distribution of number of pipes in a segment is presented in Graph 3



Graph 3: Distribution of number of pipes in segments

5.3 Failure rates for Oslo

There will here be given an overview of failure rates for the different pipes, for the WDN of Oslo. Size and length has been considered, while material is not considered. Failure rates are based on the recorded failures for the total distribution network of Oslo, for the period of 1975 – 2011. Pipes that have been registered to 2012, total of 3, have been removed from the material. The overall municipal network of Oslo consists of 23757 municipal pipes, where 16 are without recorded diameter and has therefore not been used. The 16 pipes that are removed had 4 recorded failures. I addition 50 of the pipes are not registered with year of construction, though are used as the age of pipes is not considered.

5.3.1.1 Total failures

First we consider the total amount of failures for all pipes in the system, using both pipes that have been removed from the network and pipes that are still in use. As stated only failures registered in the interval of 1975 – 2011 are considered. The total recorded failures in the time-period are 3975, with the majority belonging to the medium 1 size category. The distribution of failures and amount of pipes are shown inTable 4. Comparing it to Table 3, we see a high degree of similarity and can therefore say that it is reasonable to use to estimates from the overall network of Oslo as estimates for Skullerud.

Table 4: Total failures for Oslo

	Total failures	Total pipes	Percentage of pipes	Percentage of failures
Small (0<D<100)	26	184	1 %	1 %
Medium 1 (100<D<200)	2666	13185	55 %	67 %
Medium 2 (200<D<300)	735	5369	23 %	18 %
Medium 3 (300<D<400)	381	3336	14 %	10 %
Large (400<D)	167	1686	7 %	4 %

As we now have established that it is reasonable to use total recorded failures in Oslo to produce failure estimates for Skullerud, we need to find intervals that are useful. We first need to time intervals which are of interest. For the study case, it was used four time intervals, day, week, month and year.

5.3.1.2 Failure rates for size categories

In order to find failure rates, we must first know the average number of failures per year for each size category. This will then be used to find the average failure rate for the selected time interval, for the size category as a whole and for each individual pipe. We will begin by looking at the failure rate for each pipe in a size category per year and the expected number of failures per year, as shown in xx.

From Table 5, we see that the average probability for failure within a year for a medium1 sized pipe is 1%, while the other medium categories and the small diameter pipes have roughly 0.3% chance of failing. Large diameter pipes have 0.5% chance of failing within a year.

Table 5: Failure rates for categories, pipes

Category, pipe	per year pipe	Per month	per week	Per day
Small (0<D<100)	3,72E-03	3,10E-04	7,15E-05	1,02E-05
Medium 1 (100<D<200)	1,06E-02	8,87E-04	2,05E-04	2,92E-05
Medium 2 (200<D<300)	3,70E-03	3,08E-04	7,12E-05	1,01E-05
Medium 3 (300<D<400)	3,11E-03	2,59E-04	5,98E-05	8,52E-06
Large (400<D)	2,41E-02	2,01E-03	4,63E-04	6,60E-05

However we also need the probability of failure for the entire group of pipes, considering pipe failures as disjoint in order to get an estimate. The equation used for calculating the estimated group probability is shown in (5.1), where F(c:i) is the probability of failure for size category i. This gives the total probability for each group, as shown in xx. It shows that one can expect approximately 2 failures per month of medium1 sized pipes, and 29 failures for medium1 sized pipes.

$$F(c:i) = \bigcap p_{c,i} - \sum \prod p_{c,i} \approx \bigcap p_{c,i} = p_{c,1} + \ldots + p_{c,n_p} = \overline{p_{c,1}} \sum n_{p,c:i} \tag{5.1}$$

Table 6: Failure rates for categories, total

Category, total	per year total	Per month	per week	Per day
Small (0<D<100)	0,3384	0,0282	0,0065	0,0009
Medium 1 (100<D<200)	29,6914	2,4743	0,5710	0,0813
Medium 2 (200<D<300)	4,1217	0,3435	0,0793	0,0113
Medium 3 (300<D<400)	2,6195	0,2183	0,0504	0,0072
Large (400<D)	11,0290	0,9191	0,2121	0,0302

Furthermore it shows that the category medium1 is 7 times more likely to fail than anmedium2, and 11 times more likely than medium3 category pipes. In addition medium1 is 87 times more likely to fail than the small category. Comparing group medium1 to the large diameter group, then medium1 is only 2.7 times as likely to fail. It is therefore reasonable to use the categories of medium1 and large, as focus points for the reliability calculations.

5.3.1.3 Segment failure

The probability of failure for a segment should be the sum of probabilities of all pipes in the segment, since whether the pipes failed individually or not would be without consequence.

During the project it was attempted to relate the HCI values and probability of failures for the segments. The idea was that the highest HCI value found with Relnet for any pipe in a segment should be a good estimate for the HCI value of the segment. This was based on the assumption that the loss of supply for nodes in the segment, can be negligible compared to the total loss of supply.

The probability of failure for the segment would be the probability of all pipes in the segment, since whether the pipes failed individually or not would be without consequence. The reason segment failure is suggested, is that it will be easier to assess the reliability of the network in a easier manner than by using individual pipes.

AVG Segments	**F(day)**	**F(Week)**	**F(Month)**	**F(year)**
Small (0<D<100)	4,43E-05	3,10E-04	1,24E-03	1,62E-02
Medium 1 (100=<D<200)	1,02E-04	7,14E-04	2,86E-03	3,73E-02
Medium 2 (200=<D<300)	4,33E-05	4,33E-05	3,03E-04	1,21E-03
Medium 3 (300=<D<400)	3,21E-05	2,25E-04	8,99E-04	1,17E-02
Large (400<D)	3,16E-04	2,21E-03	8,85E-03	1,15E-01

5.3.1.4 Valves and pumps

It has not been received any failure rates for valves or pumps, as this is not formally recorded by the water and wastewater department of Oslo municipality. This is partly considered insignificant due to the dominance of pipes, in terms of numbers. It has also been attempted to

5.4 Expectations

Based on the failure rates and topology, it was formed a few basic expectations which will is listed in Table 7. The expectations do not have any ranking.

Table 7: Expectations for Skullerud

Assumptions:
The most critical event is the simultaneous failure of all reservoirs and the tank
The supply pipes from Skullerud WTP are the most critical single pipes
Based on the
The PRVs along the left side of the network will have little impact on the HCI, as there are few nodes located downstream from them
The majority of the most critical pipes will be large supply pipes, given single failure events
The pump VP12 (Lamberseter) located between VP6 and VP7 in the map, is assumed to much more critical than the two other pumps
Due to a high degree of interconnection, most pipes are assumed to have low HCI value
Based on the SINTEF report, it is assumed an average HCI near 0.027 and a highest HCI value of around 0.5, for the Relnet results.
Based on the high ratio of pipes to nodes, in the more concentrated areas (in terms of nodes), it can be assumed that pipes in this area should have low hydraulic impact
Based on the location of the valves, they are expected to have a low impact on the overall network

6. Impact results

In this chapter there will a look at the results of the impact analyses, starting with the Relnet results as it was it was used as the baseline in the project. Then there will be shown comparison of HCI values found with Relnet and WDNetXL, for 50 of the most critical pipes, in addition to all valves and pumps. Before showing the worst case scenarios, found with WDNetXL. The focus of the results is on supply and pressure impact.

6.1 Relnet results

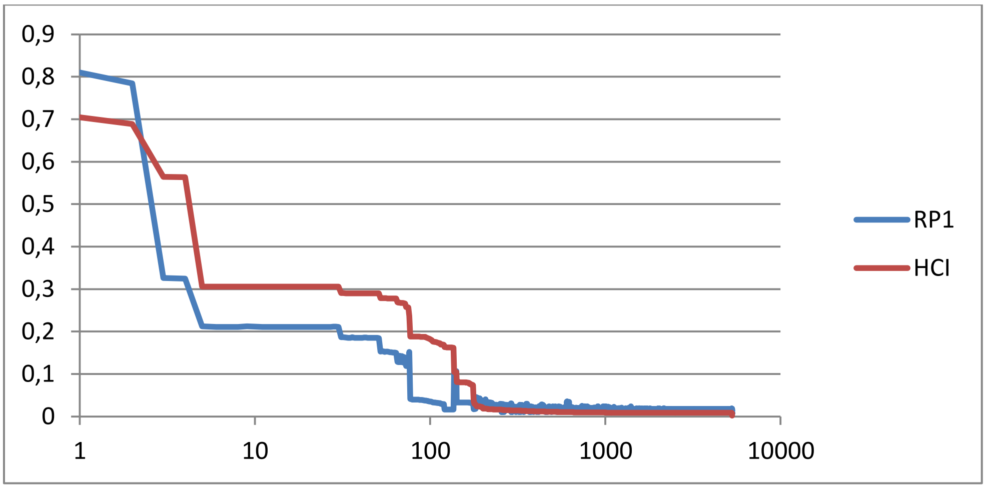
We will start looking at the HCI values and PR values, and then go deeper with the 25 most critical components. Then we will assess the networks reachability. The reason measurements of supply and pressure impact is considered together, is to see the correlation between reduced pressure and supply. All simulations have been done with all reservoirs considered as independent, meaning the main WTP of Skullerud with two outputs is considered as two independent WTP.

6.1.1 Hydraulic criticality and pressure reliability

The HCI values are based on the peak hour (08:00). HCI values are divided into, pipes, pumps and valves, and will be assessed in that order. After the different link categories have been assessed individually, there will be a look at the average hydraulic criticality of the pipe size categories.

6.1.1.1 Pipes

For pipes the HCI value is between 0.704 and 0.008, and the PR1 value is between 0.810 and 0.010. The HCI and PR1 values for all pipes are shown in Graph 4. The graph shows that the majority of the pipes (96%) have a relatively low HCI value of less than 0.02.



Graph 4: HCI and PR for pipes

Graph 4 also shows that the highest hydraulic impact for a singular pipe 0.704, which is considered as a complete network failure. The results also show that 4 network components have a HCI value higher than 0.500, with the fifth most critical component having a HCI value of 0.306. The average HCI value for a network link is 0.0157, meaning the expected consequence given a singular event is that more than 98% of base demand is met at the peak hour assuming equal failure rates for all components. When looking at the result with regards to pressure reliability/supply criticality it is clear that the large majority of the pipes have a larger impact on pressure than supply of water.

Based on the nature of the network, larger pipes used as supply pipes, while smaller pipes are used more for local supply, it is a given that the impact of links with different diameters, will have different hydraulic impact on the system. The average HCI values for the size categories used in the project, is listed in Table 8.

Table 8: HCI values for size categories

Size category	HCI
Small (0<D<100)	0,0086
Medium 1 (100<D<200)	0,0088
Medium 2 (200<D<300)	0,0092
Medium 3 (300<D<400)	0,0271
Large (400<D)	0,0539

Most supply-critical

When regarding the 25 most critical links in terms of supply, all of which are pipes, we find that they located at various places near the Skullerud reservoirs. The locations of the most critical pipes are shown in xx. One interesting finding is that the long supply pipes, divided up after the supply pipes from Skullerud are not in the 25 most critical pipes, this may be due to that there are in total four supply lines from the splitting point.

Another interesting finding is that pipes in the same segment have different HCI values, may be hard to see from xx, which is interesting as the failure one pipe in a segment should lead to the failure of all pipes in that segment.

Figure 12: Location of 25 most supply-critical pipes

With regards to impact of the 25 most critical links, we see that they have an average HCI value of roughly 0.358 and a maximum of 0.704. It should also be mentioned that despite there not being any pumps among the 25 most critical components, one of the pumps (VP12) is among the 50 most critical components ranked as number 33.

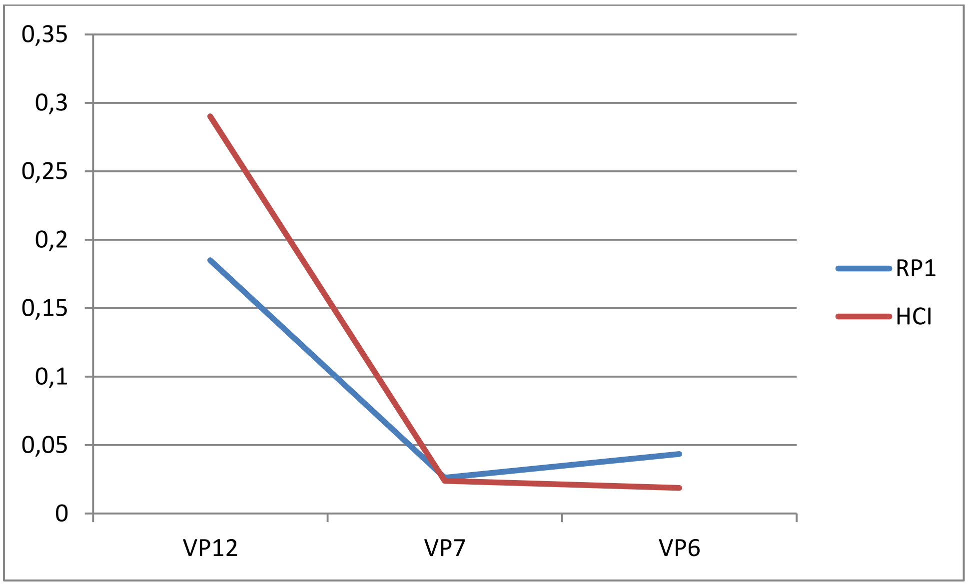
All the 25 most critical pipes are listed in Table 9: 25 most critical pipes, with length and diameter. The 4 most critical pipes are the supply pipes coming from Skullerud WTP, and are as stated the only links with a HCI value above 0.5

Table 9: 25 most critical pipes

Rank	Pipe id	Diameter [mm]	Length [m]	HCI
1	309680	1000	128	0,704
2	200606	1000	17	0,689
3	309681	1000	129	0,564
4	200590	1000	18	0,564
5	153200	300	5	0,306
6	153455	300	15	0,306
7	147853	400	3	0,306
8	153412	300	5	0,306
9	153201	278	52	0,306
10	147855	400	54	0,306
11	148525	600	76	0,306
12	153413	300	8	0,306
13	268026	600	2	0,306
14	148512	600	54	0,306
15	152974	400	41	0,306
16	153126	300	37	0,306
17	142881	400	162	0,306
18	148935	400	23	0,306
19	153095	400	79	0,306
20	153109	400	52	0,306
21	153122	300	19	0,306
22	148526	600	28	0,306
23	153079	400	29	0,306
24	153459	300	45	0,306
25	148963	400	54	0,306

6.1.1.2 Pumps

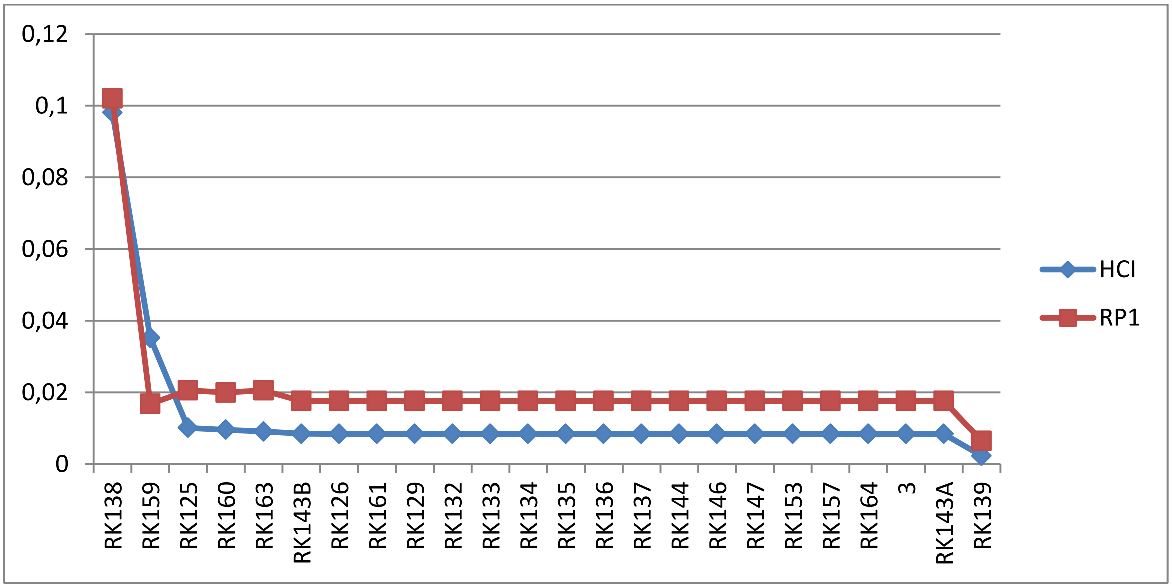
HCI and PR1, for pumps are shown in Graph 6. The graph shows that only VP12 have a significant impact on the network in terms of pressure and supply of water. The impact of failure in VP12 is shown graphically in Figure 14.



Graph 5: HCI and RP1 for pumps

6.1.1.3 Valves

When assessing the HCI and PR of valves, shown in Graph 6, we see that all valves have a HCI below 0.1. We also see that the impact on required pressure is low, on average below 0.025. The most critical valve is RK138, which has a HCI value of 0.098 and a RP1 value of 0.102.



Graph 6: HCI and RP1 for valves

The location of RK138, is shown in Figure 13. The figure shows that the valve is in the intersection of 4 sections.

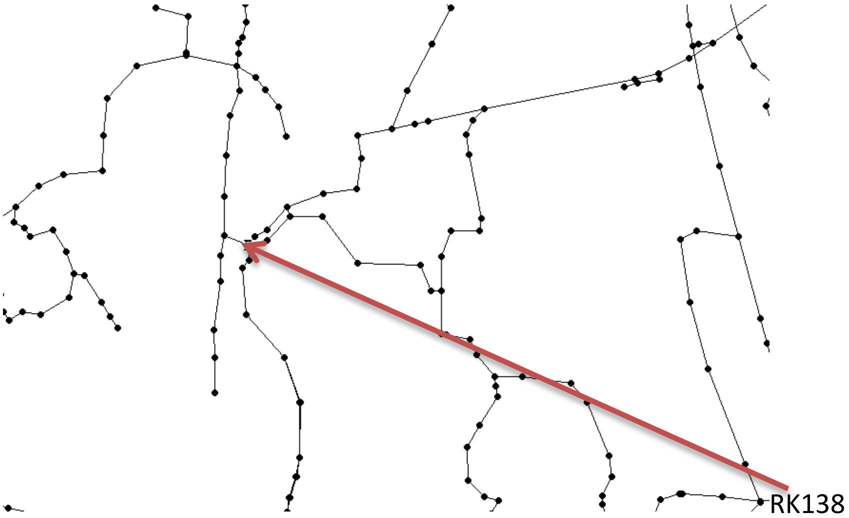


Figure 13: Location of valve RK138

6.1.1.4 Segments

The HCI of segments is based on the idea was that the highest HCI value found with Relnet for any pipe in a segment, should be a good estimate for the HCI value of the segment. This is based on the assumption that the loss of supply for nodes in the segment, can be negligible compared to the total loss of supply in the network.

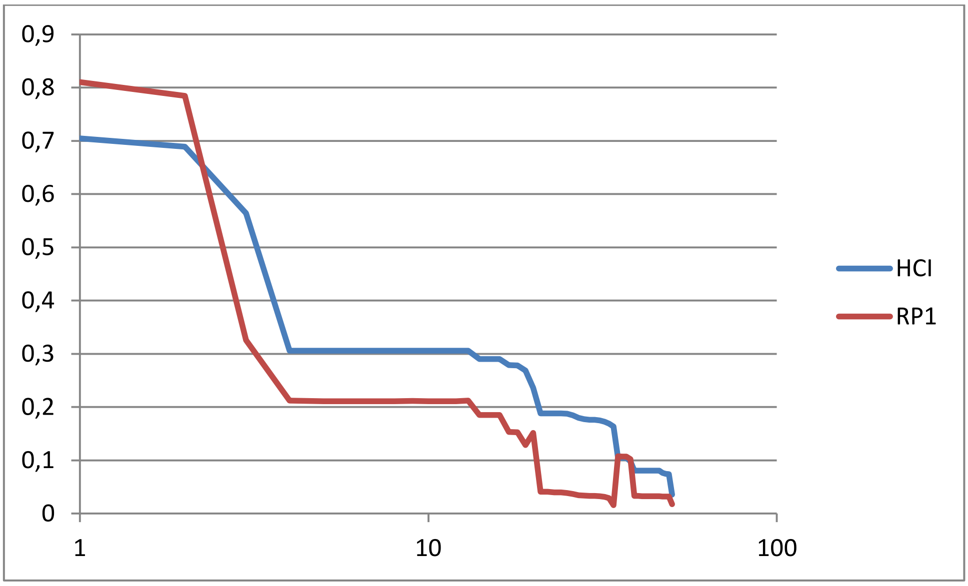
The aggregated segments divided by size is given in Table 10. Comparing the results to that of Table 8, it shows a high degree of similarity.

Table 10: Aggregated segments, HCI and RP1

Size category	**Number of segments**	**HCI**	**RP1**
Small (0<D<100)	26	8,69E-03	1,79E-02
Medium 1 (100<D<200)	821	1,11E-02	1,88E-02
Medium 2 (200<D<300)	255	1,20E-02	8,57E-09
Medium 3 (300<D<400)	216	2,25E-02	6,35E-09
Large (400<D)	52	6,62E-02	5,99E-02

Most supply-critical

In addition to the average values for segments in the network, it is also useful to know the HCI distribution of the 25 most supply critical segments. This shown in Graph 7, which is almost the same as Table 9: 25 most critical pipes.



Graph 7: HCI and RP1 for 25 most critical segments

6.1.1.5 Reachability

The reachability of the network has been found using**Feil! Fant ikke referansekilden.** (2.5) is 0.776, for single failure events. This means that for more than 77% of the singular failures, all of the network remains connected. Which shows that the redundancy of the network, is mostly sufficient to have all of the network connected.

The largest number of disconnected nodes for a singular failure was 84, which is equivalent to 1.66% of all nodes in the network being disconnected. There are in total 26 events that will lead to a disconnection of 1.00% up to 1.66% of the network at any one time.

6.1.1.6 Network connectives

When regarding the fraction of nodes having at least the required pressure, using (2.7) and summarizing for all events, the result shows the network is capable of on average meeting 97.9% of the required pressure demand.

6.2 WDNetXL results

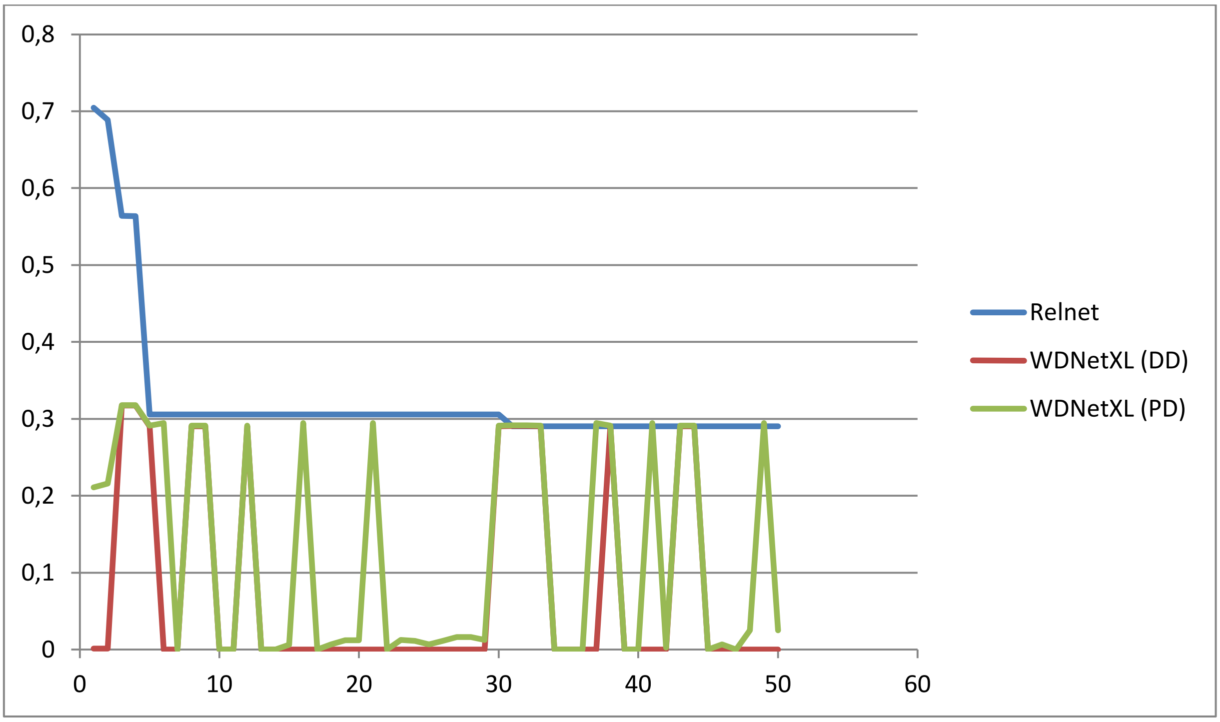
There will here be given an overview of the results from WDNetXL simulations. The main focus of the WDNetXL simulation was to find the most critical events and also show the impact on individual nodes. WDNetXL has also been used to find some HCI results, though not for all links as this would have been too time consuming. We will start by comparing HCI results from WDNetXL with the HCI baseline values found with Relnet. And then look at the worst case scenarios results.

6.2.1 HCI comparison

The HCI comparison was done in order to better understand how results from the two software solutions relate to each other. We will look at the HCI for a selection of links, using 50 of the most critical pipes, defined by Relnet simulation, in addition to all pumps and valves. The HCI values for WDNetXL have been calculated by running SS simulations for the events, for both DDA and PDA.

6.2.1.1 Pipes

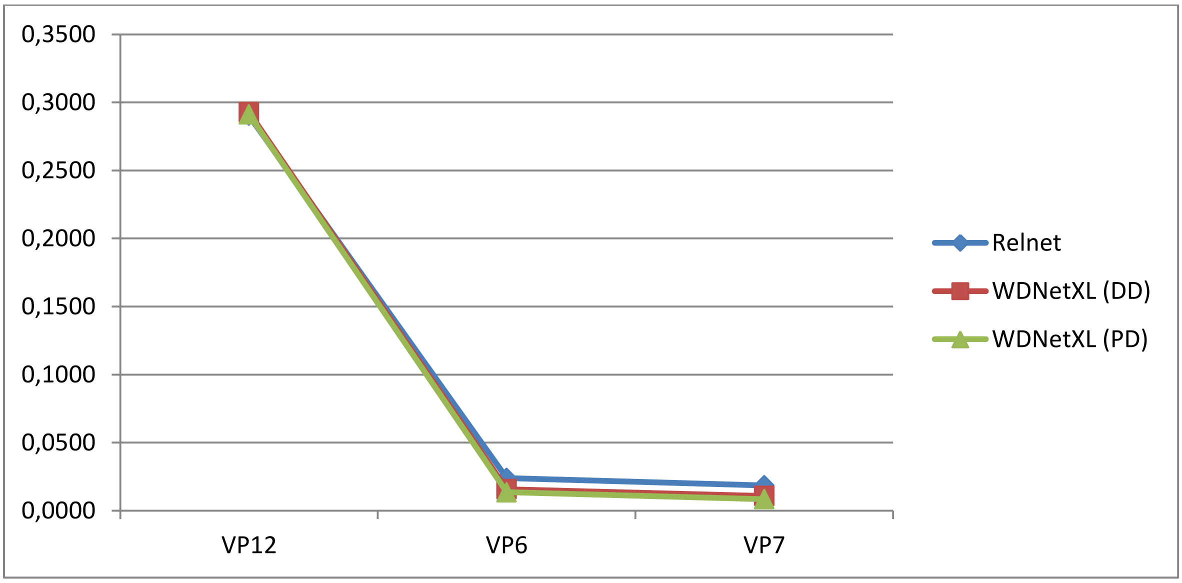
When comparing HCI values for the 50 most critical pipes, shown in Graph 8, it is clear that there is a clear difference between Relnet and WDNetXL for both DDA and PDA. Graph 8 makes it hard to see the exact values, this given in xx. In addition to the difference between results from the software solutions, it is also a large difference between HCI values for DDA and PDA from WDNetXL. Where several of the pipes are considered as insignificant based on the DDA analysis.



Graph 8: HCI comparison, Pipes

6.2.1.2 Pumps

For pumps there is a very high similarity between the HCI values, obtained by both software solutions as shown in Graph 9. The results show that there is a slightly higher HCI values for DDA than for PDA. Results from WDNetXL are also listed in Table 11.



Graph 9: HCI comparison, Pumps

The HCI results for pumps show that nearly 30% of the networks total demand will be unsupplied if VP12 fails. This loss of supply is not evenly distributed throughout the network, but affects a specific area shown in Figure 14. The figure shows the result from the PDA in WDNetXL, the DDA is similar and is therefore no shown.

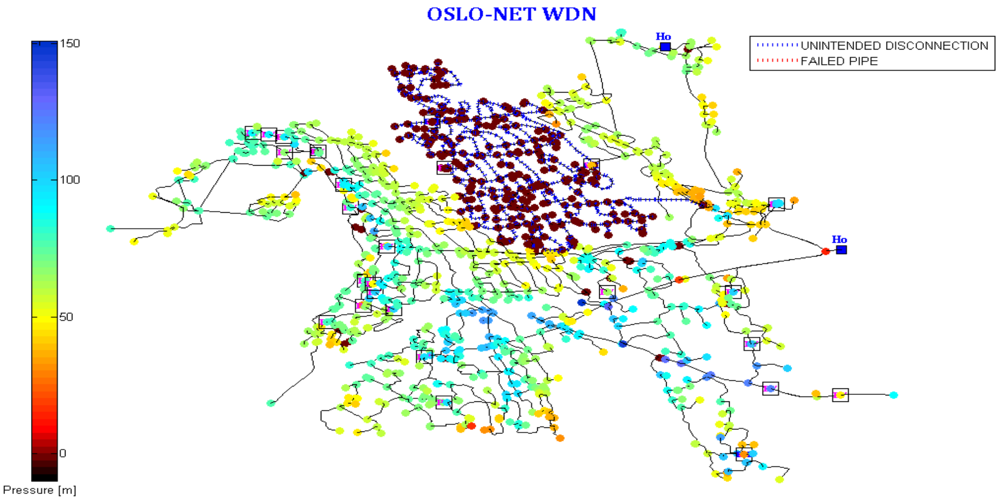


Figure 14: Failure of VSP12, PDA

Table 11: HCI values WDNetXL, Pumps

Pipe Label	Pipe ID	function	WDNetXL (DD)	WDNetXL (PD)
VP12	5296	VSP	0,2928	0,2911
VP6	5297	VSP	0,0158	0,0135
VP7	5298	VSP	0,0109	0,0085

6.2.1.3 Valves

When comparing HCI values for valves, shown in xx, it is clearly a large difference between HCI values from Relnet and the values from WDNetXL, both demand and pressure driven. The HCI values from Relnet are on average more than 3.5 times as high as those for DDA from WDNetXL. Another important finding is that the PDA indicates that most of the pipes are insignificant, in terms of failure of supply if they have a mechanical failure.

Valve	Relnet	WDNetXL (DDA)	WDNetXL (PDA)
RK138	0,0981	0,0153	0,0130
RK159	0,0353	0,0255	0,0232
RK125	0,0101	0,0039	0,0015
RK160	0,0096	0,0034	0,0010
RK163	0,0091	0,0030	0,0006
RK143B	0,0085	0,0024	0,0000
RK126	0,0084	0,0024	0,0000
RK161	0,0084	0,0024	0,0000
RK129	0,0084	0,0024	0,0000
RK132	0,0084	0,0024	0,0000
RK133	0,0084	0,0024	0,0000
RK134	0,0084	0,0024	0,0000
RK135	0,0084	0,0024	0,0000
RK136	0,0084	0,0024	0,0000
RK137	0,0084	0,0024	0,0000
RK144	0,0084	0,0024	0,0000
RK146	0,0084	0,0024	0,0000
RK147	0,0084	0,0024	0,0000
RK153	0,0084	0,0024	0,0000
RK157	0,0084	0,0024	0,0000
RK164	0,0084	0,0024	0,0000
3	0,0084	0,0023	0,0000
RK143A	0,0084	0,0024	0,0000
RK139	0,0023	0,0024	0,0000

It has not been created any figures to show the impact of valve failures.

6.2.2 Worst case scenarios

Worst case scenarios given an indication to how vulnerable the system is to specific situations. It also shows the components that are most critical for the network to function at optimal conditions. Results from the worst case scenarios, lists the links that have been disconnected either as a result of failure in nodes or pipes. We will start with worst case scenarios for DDA, before going over to PDA. WDNetXL is capable with also running the worst case scenarios for nodes also, however the results from the calculation seemed to focus on the different tanks and reservoirs, and it was therefore left out.

For pipes there are five event categories, with five simultaneous failures as the absolute worst. There are a total of 24 solutions given for both DDA and PDA. In interesting question about for this analysis, was if the PDA and DDA would give the same results for segments. It was expected to have some degree of variations between the two, in terms of amount supplied.

The absolute worst case is, as can be expected, the disconnection of the pipe segments connecting the supply nodes to the network shown in Figure 15.

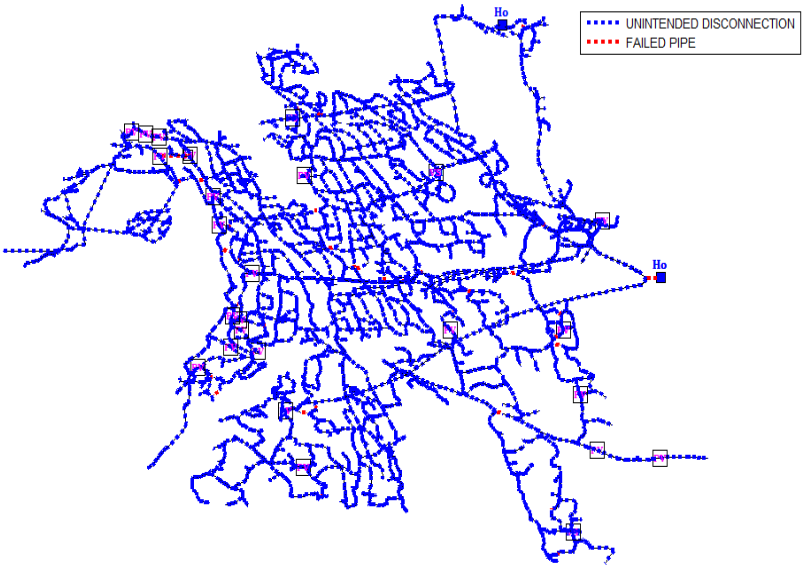


Figure 15: Total disconnection from supply

One important note with regard to the question on if the two simulations, the results were in agreement on most critical segments/pipes only in agreement on 8 out of 24 solutions. And it is therefore these 8 scenarios that are defined as worst case scenarios for their category. There will now be a brief run through of the worst case scenarios, starting with few simultaneous failures.

The first one to start with is the failure of the southbound supply pipe from the main WTP in Skullerud. Comparing the worst case found for single failure event, it shows that the PDA has a slightly lower supply than what DDA has for the exact same failure. The failure is in the failure of the supply line DDA gives the segment a HCI value of 0.319, and PDA gives a HCI value of 0.322. The result from DDA is shown in Figure 17, while result from the PDA is given in Figure 16.

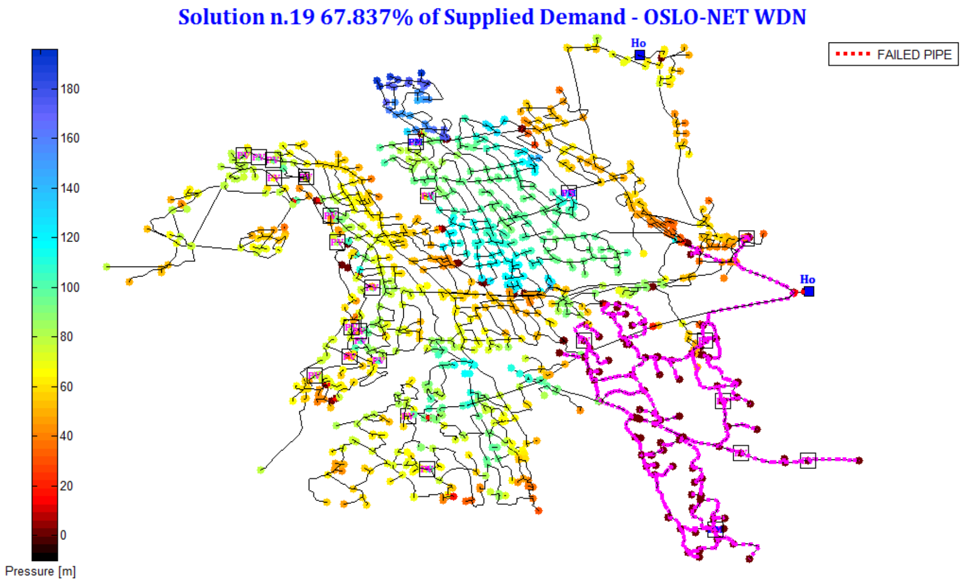


Figure 16: failure of supply pipes from Skullerud, PDA

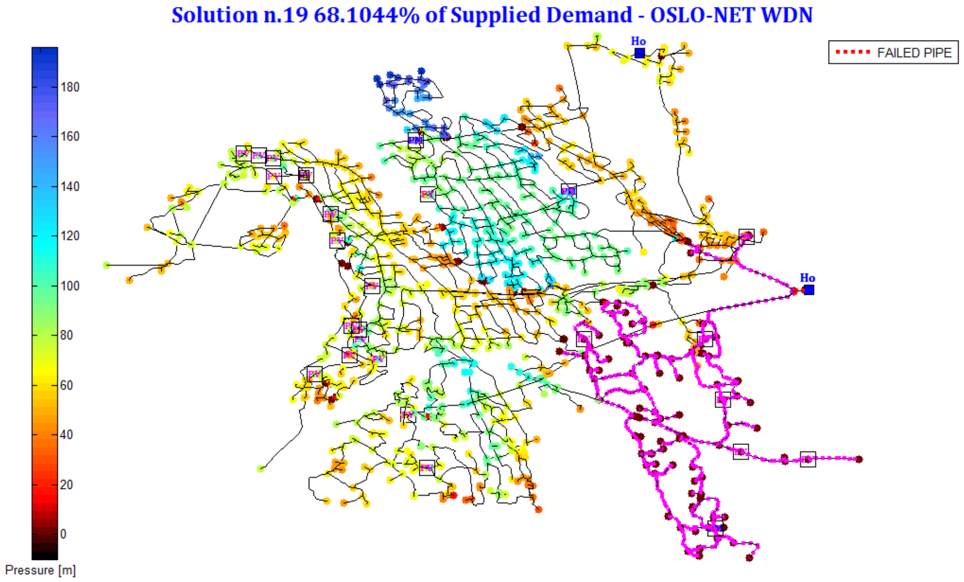


Figure 17: failure of supply pipes from Skullerud, DDA

Looking at the two figures, we see that they are as expected identical.We can also see that there are no nodes that have been disconnected, but are unsupplied as a result of insufficient pressure and quantity entering the network.

The next worst case scenario is the event, of two simultaneous failures, the loss of supply from Skullerud and the failure of the segment containing the pumping station at Lamberseter. This leads to an even higher loss of supply, with HCI values for DDA and PDA 0.609 and 0.612 respectively.

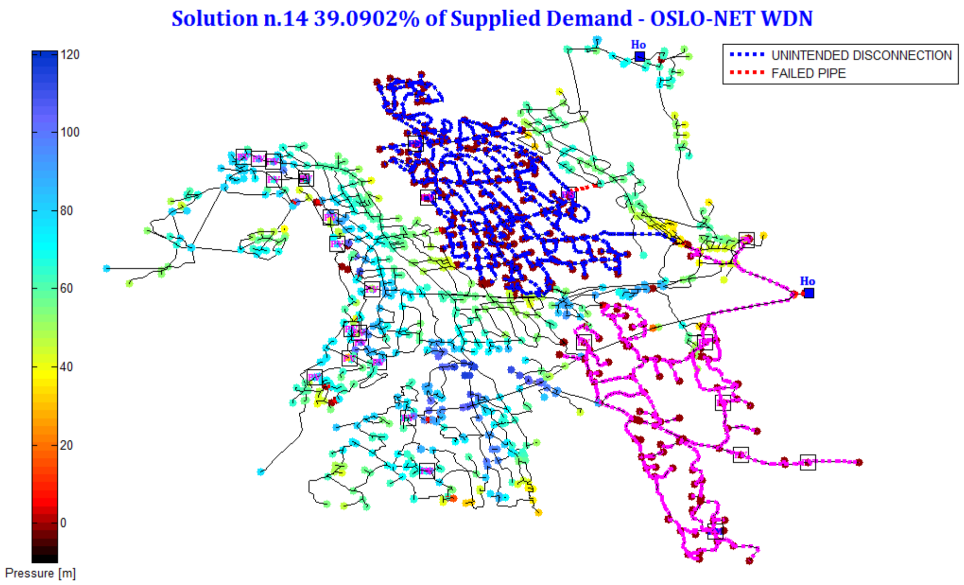


Figure 18: failure of supply pipes from Skullerud and Lamberseter pumping station,

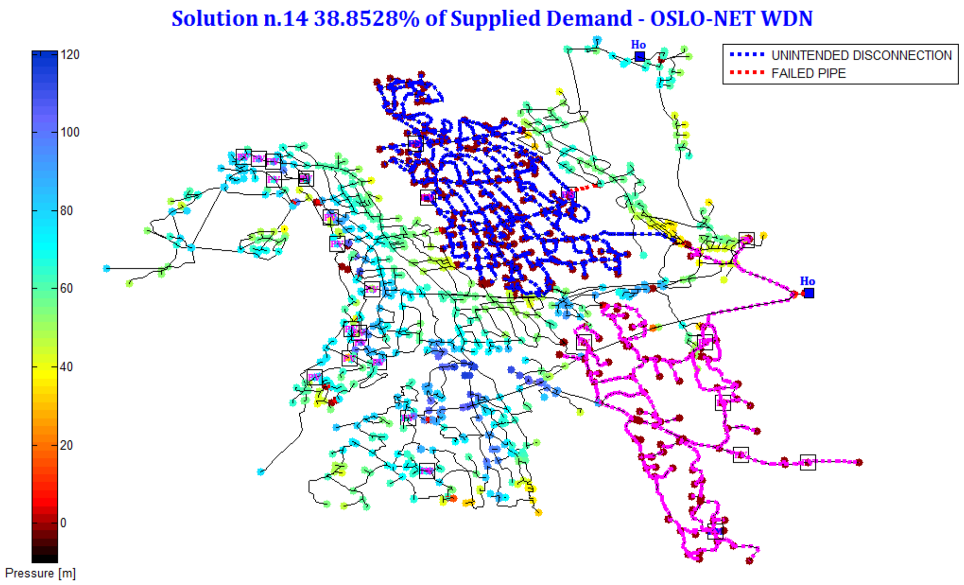


Figure 19: failure of supply pipes from Skullerud and Lamberseter pumping station,

The last worst case scenario found, is the loss of supply from all the reservoirs and the pumping station at Lamberseter. This event is estimated to supply roughly 2.1% of total demand. The HCI values are 0,9782 for DDA, and 0,9784 for PDA.

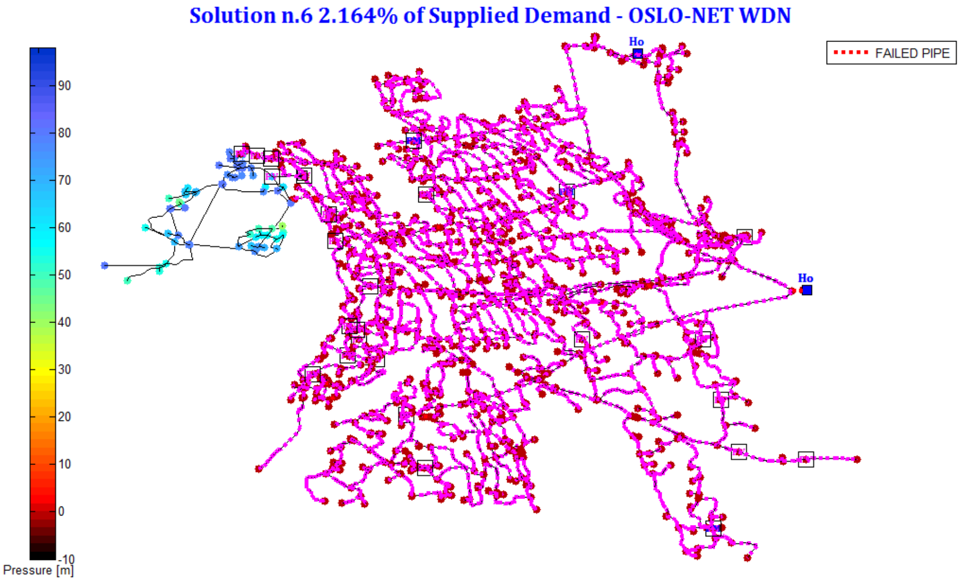


Figure 20: Loss of all reservoirs and pumping station at Lamberseter, PDA

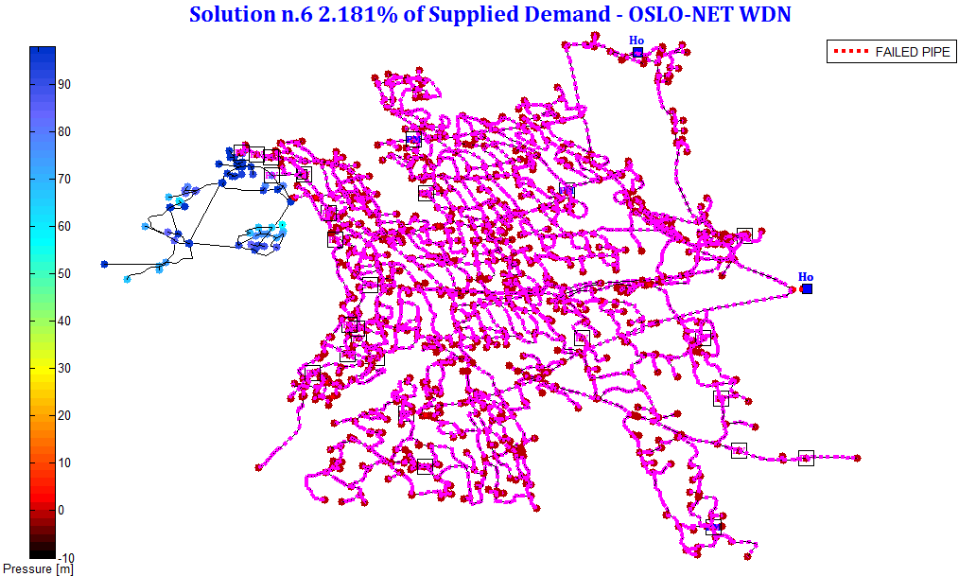


Figure 21: Loss of all reservoirs and pumping station at Lamberset, DDA

7. Discussion

In this chapter we will discus to which degree the purpose of the master project was met, and what the largest sources of difficulties and failures have been.

Method

The method that was made during the project did perform its function, and was successful in providing a way to efficiently get results for how size distribution affects a WDN's reliability. The method was more useful in providing the overall reliability of the network.

Note:

- Several of the proposed steps have not been tested and may be redundant with regard to a full reliability assessment.

Impact calculations

Relnet produced results that were easier to understand right away, for the overall network. The problem with the Relnet results, was that once one looked at the location of the more critical components using a software such as EPAnet, it became clear that some of the results could be wrong in some way, when pipes within same serial pipe had different HCI values.

WDNetXL provided more data that could be analyzed, in addition to graphically showing the impact related to a specific failure. Also there were large differences in how well the PDA and DDA related to each other for different types of links. This can be due to an inadequate use of the leakage model in WDNetXL, from the author's side, or differences based on using energy equation or not using the energy equation for the water supply.

The average HCI value of the links were higher than expected, which is likely due to a lower redundancy in the network of Skullerud than in the overall network of Oslo. There is a high degree of correlation between impacts in pressure and supply, which is due to supply's dependency on pressure. The use of supply as the category to measure reliability is therefore justified.

Demand and Pressure driven analysis

With regards to pressure driven and demand driven analysis there were small differences in the results. It was not produced enough results too truly to say with high degree of accuracy what the difference between pressure and demand driven analysis. When regarding result for valves and pumps, the results indicate that using DDA will have higher HCI values than PDA. However when looking at the worst case scenarios, the PDA has a slightly higher impact than the DDA. This is also true for the HCI comparison the 50 pipes defined as most critical by Relnet.

The difference in which form of analysis has the higher impact on HCI value, with regards to pipes, valves and pumps can be due to that failures in the valves and pumps will lead to situations where the pressure in downstream nodes is below the minimum limit of the PDA, while PDA model the nodes as partly supplied. While for pipe failures the network may be able to support the minimum pressure in the nodes, and DDA assumes that the nodes are fully supplied while PDA assumes partly supplied for the same nodes.

Comparing Relnet and WDNetXL

One of the secondary purposes was to compare Relnet and WDNetXL with each other. After having used both software solutions, there are some important remarks to be made.

- Relnet is more useful to quickly find the overall criticality for the network connected to each link, with regards to total loss of supply and number of nodes with lower than required pressure. It is therefore advised to start any reliability analysis with a Relnet or similar software solution, to get an overview.

  On the other hand Relnet assigns different HCI values for pipes belonging to the same pipe segment, as was shown by the 25 most critical pipes with regard to HCI values. And Relnet does not indicate where in the system the affected nodes are located. Also Relnet only runs simulations for single failure events.

- WDNetXL is requires a little more manual input than Relnet, but in return provides a better view of the impact related to failures showing which nodes and areas of the network that are affected by a given failure scenario. Also WDNetXL can run simulations on scenarios with several simultaneous failures. The failure scenarios which one wants analyzed is manually input into the event matrix. This is both a good thing, as one can check impact for common scenarios. And a drawback as it requires more manual input. The drawback is in some senesce minimized by the assessment feature, which finds the most critical scenarios for both singular failures and simultaneous failures.

Reliability of the network in Skullerud

Based on the HCI values for the Relnet analysis, it is arguable that the distribution network of Skullerud has a high reliability is terms of supply. The reason for this high reliability is due to a high level of redundancy in the system, in ring connections in areas with high node concentration and that there are three reservoirs and a tank in the system.

Mechanical reliability assessment

When considering mechanical reliability for the WDN of Skullerud, we have used the failure rates in 5.3. It is clear that the pipes in the network can be considered mechanically reliable due to the average low probability of failure for the pipes. When using segments, the probability of failure goes up by a factor of 3.5-4.8 when compared to individual pipe failure, which is due to the average number of pipes in a segment.

If we are considering the total amount of expected failures, for the given time intervals we see that the network on a whole is relatively reliable, and that there are few expected failures per week. Summarizing the number of expected failures, for all size categories, indicates that the network is mechanically reliable. To points to note here:

The percentage of network failed is based on the assumption that all pipes that fail only fail once within the year.

The percentage of failure is considered by the author to be low, using assumption in point 1. It has not been found indicative figures describing what is considered as low percentage of failure for a network. Nor has the author contacted the municipality for information on their goals for the network.

Table 12: Expected failures in Skullerud per year

	Year	Month	Week	Day
Total expected failures in:	47,80	3,98	0,92	0,13
Percentage of network failed:	0,9019 %	0,0752 %	0,0173 %	0,0025 %

Hydraulic Reliability

For Hydraulic reliability, there will first be given a general assessment, primarily based on result for HCI and RP1 from Relnet and worst case scenarios from WDNetXL. Then the estimation of the networks average hydraulic reliability, using HCI values from Relnet. The estimation is based on impact from individual, using network states. The reason the term estimation is used, is due to the use of estimated mechanical reliability, and use of averaged values. It is possible to estimate the reliability of the network, since both probability of failure and the impacts of individual pipes and average impact of diameter categories have been obtained.

Assessment

The general assessment of the network of Skullerud is that the network is resilient with regard to singular failure events. There are few pipes that can impact the network in a very large way, and the majority of links in the system have a HCI value of below 0.02, for single failure events. There are four links according to the Relnet results that can cause the network to completely fail, all of which are pipes. These pipes are connected to the main WTP of Skullerud. The hydraulic consequence related to failure in one of these pipes, is mitigated by the fact that there are two supply lines coming from the WTP.

Most of the pipes have a higher impact on pressure than on water supply, which indicates that the network is better a sustaining water supply than pressure levels for single pipe failure events

With regard to multiple failure events, the system is more vulnerable. However due to the low probability of simultaneous failure, the threat of large impact on the network is not that large. However considering segments, the probability increases.

When regarding the reliability of the network, it is important to note that impacts have been calculated for the peak hour, in terms of nodal demand, but they are still considered as good indicators for impact on the network for the different links.

Estimation

For the estimating the reliability of the network, it is important to define the time span, state of the network considered and number of simultaneous failures.

Network states

There will here be given estimates of probability for the 5 defined network states, for the time interval of one day and disjointed probability. After the day based estimates, there will be given table showing the probability for all different network states in the different time intervals.

Network state 1

Network state 1, is as stated in Table 2, the state in which the network is performing within <100-90% of the required function. The average HCI value for the network is 0.0157, meaning that the network is expected to be in state one, for a singular event using the Relnet results.

There are 5154 pipes that can result in network state 1, the estimated probability for a HCI value between 0< to 10, for within one day is 12.53%.

Network state 2

Network state 2, is that the network performs 89-80% of it required function. There are 65 different links that individually can cause the network to go into a state 2, situation. The majority (45/60) of these pipes are in the medium3 size category with 8.52E-06 as probability of failure per day. The remaining 15 pipes are large diameter pipes, with probability of failure 6.0E-05. The summarized probability for the network to attain state 2, is 0,137 %.

Network state 3

There are in total 46 pipes, which can cause the network to go into state 3. The average probability for these pipes is 0.005%. The total probability for network state 3, is 0.240%

Network state 4

There are 26 pipes, which may lead to network state 4. The average probability is 0.0046% and the total probability of state 4 is 0.120%.

Network state 5

There are according to the Relnet results for HCI, 4 pipes that will result in a loss of more than 50% loss of supply. Leading to a scenario defined as complete network failure. All the pipes that can individually lead to network failure are large diameter pipes. And the probability of failure is then defined by the large diameter category in Table 5, which gives the probability of network failure as shown in

All time intervals

The probabilities for the network states using individual pipes, for all time intervals are given in Table 13. It is clear the network is expected to reach state 1, at least three within the time interval of a month. Considering the network state 3 to 5, which are the more critical once, they have a relatively low probability (<10%) of occurring within a month. For state 5, the network failure, Table 13 gives a very low probability (<1%) of occurring within a month.

Table 13: Probabilities of network states, pipes

Probability:	Day	Week	Month	Year
State1	12,533 %	87,732 %	350,929 %	4574,604 %
State2	0,176 %	1,232 %	4,929 %	64,258 %
State3	0,240 %	1,682 %	6,728 %	87,705 %
State4	0,11999 %	0,83992 %	3,35970 %	43,79609 %
State5	0,026 %	0,185 %	0,739 %	9,632 %

When using segments, instead of pipes the probabilities for each network state increases. And the probability of network failure is no longer considered relatively low.

Table 14: Probabilities of network states, segments

Probability:	Day	Week	Month	Year
State1	12,480 %	87,358 %	349,433 %	4555,109 %
State2	0,270 %	1,890 %	7,561 %	98,558 %
State3	0,194 %	1,356 %	5,424 %	70,699 %
State4	0,155 %	1,087 %	4,350 %	56,705 %
State5	0,038 %	0,266 %	1,065 %	13,889 %

8. Conclusions

There will here be given short conclusions on the most important aspects of the master thesis.

Reliability of a network

The best way of assessing the overall reliability of a water distribution network, is by using the expected fraction of unsupplied water. This is because supplied water is based on both fraction of connected nodes and available pressure. Assessment should be done graphically if possible, as impact on certain sections or specific recipients can be measured.

Reliability of a water distribution network must be estimated, specific time intervals, since the probability of failure increases within a time interval. It is necessary to obtain good quality failure rates or failure prediction models for the reliability estimation to be reliable. The best way to estimate the overall reliability of a network is by using segments, since they account for failure in one or more pipes within a segment.

Reservoirs are likely to be the most critical components in any network, with pipes coming second. The location of a component will influence its impact on the overall network.

Oslo

The water reliability situation in Oslo, is assessed to be reliable, with regard to for single events and normal situation, based on the SINTEF rapport. With an average HCI value of roughly 0.026, and mechanical failure rates as given in 5.3. It has not been obtained more information than the SINTEF report and failure rates from the municipality of Oslo to support this claim. However using the case network of Skullerud as an indicator, this assessment is not unreasonable.

Skullerud

The case network of Skullerud can be defined as reliable, since the probability of large failures occurring is low for both single failure events and simultaneous failures. And the average impact on supply for a single failure is 2% of demand being unsupplied. The reason the network has a high reliability is due to, redundancy in form of supply from ore then one pipe for most of the network, 3 reservoirs and 1 tank.

The expected state of the system is for any day state 0, with a probability of 86.9%, meaning the network is expected to function at optimum levels, 24 days per month (month=28days). This is however only regarding single failure events, normal operation and maintenance on the network has not been regarded.

The main treatment plant of Skullerud is the most critical components of the network, with supply lines from the treatment plant being the second most critical components. The pumping station on Lamberseter is the third most critical link in the network, affecting a major area if failure occurs.

Software solutions

Relnet is suggested as the primary software to use for reliability assessment and estimation, as it is more useful in finding impact values for all components, requiring little manual input. WDNetXL should be used to analyze components of special interests, based on location, nearby recipients or based on impact results from Relnet. The worst case scenario function in WDNetXL is very useful in finding the most critical simultaneous failure events, and should be run in the beginning of a reliability assessment.

Types of analyses

It has not been found large differences between PDA and DDA, during the master thesis. This may be due to the fact that the leakage constants in WDNetXL were not experimented with. They were not experimented with due to focus on HCI values, and general time-constraints. One should use pressure-demand equations as those in Relnet, as water barely coming out of the tap cannot constitute water supply from a municipal-customer perspective.

Expectations

The most critical events are as expected the simultaneous failure of all reservoirs and tanks. Supply lines from the Skullerud WTP was the most critical links, and most of the critical pipes are supply pipes.

Most pipes had a low HCI value as expected. While the average HCI value for components is lower than for the network of Oslo. The single highest impact was 0.7, which is much higher than was expected. This is probably due to the overall water distribution networks in Oslo having more tanks and reservoirs.

Pump VP12, at Lambersseter has a much higher impact on the total network than the two other pumps in the network. The impact on the network was higher than expected. And valves have a low impact on the network, as was expected due to their locations.

It has not been checked hydraulic impact in more concentrated areas specifically, however none of the 25 most critical pumps were located in areas with high concentration of nodes.

Recommendations

One of the tasks for the master thesis was to make recommendations to the municipality of Oslo, regarding improvement of the network. It was intended to test out some proposed links, however Relnet was unable to accept a file that had either been run a simulation on or added any components to. This task has therefore been discarded.

Literature

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Appendix

Due to size of tables the appendix is submitted electronically.