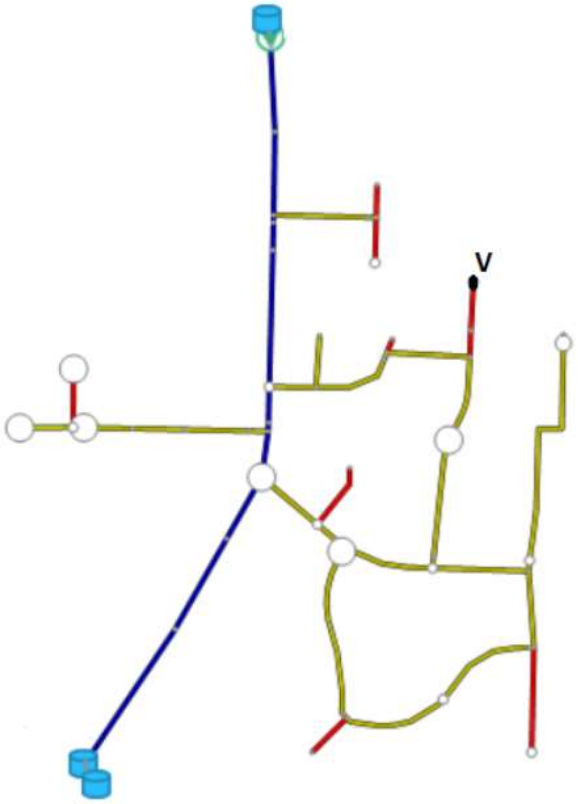

# Identification of critical pipes in a drinking water distribution system

Master's thesis in Infrastructure and Environmental Engineering

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DEPARTMENT OF ARCHITECTURE AND CIVIL ENGINEERING

CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2023
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MASTER’S THESIS ACEX30

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Cover: Visualization of used drinking water model in Mike+.

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# Abstract

The aim of this master thesis is to identify the most critical pipes in a drinking water distribution system through hydraulic modelling. The criticality of a pipe will be based on the consequences of pipe breakage including the affect on the supply of valuable users.

Reliability will be seen as the ability to supply the quantitative demand to the households and valuable users at any time and to identify the criticality of a pipe, the pipe´s contribution to the system reliability has been evaluated. The contribution are estimated by evaluating the results from hydraulic simulation of the drinking water system, without the investigated pipe. Four indices, demand, affected users, time and valuable user index as well as a gathered criticality index are used to estimate the reliability of a drinking water system.

To give more substance of the identification of critical pipes the reliability requirements of a drinking water distribution system could be further evolved. When determining the criticality of the pipes in the system, one key aspect is how pipes with different patterns should be compared between each other. Pressure driven and demand driven approach gave the same results for the majority of the pipes and a risk-based approach including probabilities would give a more in depth analysis of the criticality.

Keywords: Drinking water, Distribution system, Reliability, Critical pipes, Valuable users

# Sammanfattning

Syftet med den här masteruppsatsen är att identifiera de mest kritiska ledningarna i ett distributionssystem för drickvatten med hjälp av hydraulisk modellering. Hur kritisk en ledning är baseras på konsekvenserna av ett ledningsbrott inklusive effekterna på leveransen till känsliga brukare.

Tillförlitlighet har setts som förmågan att leverera den kvantitativa vattenefterfrågan till hushåll och känsliga brukare vid alla tidpunkter. För att identifiera hur kritisk en ledning är har ledningens bidrag till systemets tillförlitlighet utvärderats. Bidraget har uppskattats genom hydraulisk modellering av ett distributionssystem för dricksvatten, utan den undersöka ledningen. Fyra index: Efterfrågan, påverkade brukare, tid och känsliga brukare samt ett samlat index har använts för att uppskatta tillförlitligheten av ett dricksvattenledningssystem.

För att ge mer substans till att identifiera den kritiska ledningarna bör kraven på tillförlitlighet för ett distibutionssystem för dricksvatten utvecklas. Att kunna jämföra och värdera olika avbrottsmönster är en nyckelaspekt för att bestämma hur kritisk en ledning är. Resultaten av de två använda modelleringssätten (Pressure driven och demand driven) var liknande för majoriteten av ledningarna. Ett riskbaserat förhållningssätt med sannolikheter skulle ge en djupare analys än att enbart bestämma hur kritisk en ledning är utifrån konsekvensen.

Keywords: Dricksvatten, Distributionsystem, Tillförlitlighet, Kritiska ledningar, Känsliga brukare

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Jonatan Brandén, Gothenburg, March 2020

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# 1

# Introduction

The aim of a drinking water distribution system (henceforward DWDS) is to safely deliver adequate quantities of drinking water to end-users under sufficient pressures to permit or facilitate a wide range of human endeavors. A robust DWDS, with a low risk of non-deliverance of water is one of the main goals when planning and operating a drinking water distribution system. In particular socially important functions such as hospitals will need a high reliability of deliverance.

A DWDS consists of a number of components such as pumps, pipes and storage tanks. While pumps and storage tanks are regularly monitored, pipes are located under the ground and in general in a widespread area with small possibilities of inspection (Gheisi et al, 2016). In Sweden it is estimated that the renewal rate of pipes and the investment in DWDSs must increase to be able to ensure the delivery of water (Svenskt Vatten, 2017). An identification of the most critical pipes in a system would help to prioritize the measures and the renewal.

Hydraulic modelling is one important tool when developing and operating a distribution network. Simulations of different failure scenarios can give a deeper understanding about a DWDS, how it will behave during failure as well as how to mitigate the consequences. (Wright et al 2015). One example is Care-W, which is an European project where hydraulic reliability models are used as one of the tools to develop a strategy for rehabilitation planning (Eisenbeis et al 2003). The hydraulic models is used to try to quantify the hydraulic importance of a pipe since it is considered as one of the key factors when prioritizing pipes for rehabilitation.

## 1.1 Aim

The aim of this master thesis is to identify the most critical pipes in a drinking water distribution system through hydraulic modelling. The criticality of a pipe will be based on the consequences of pipe breakage including the effect on the supply of valuable users.

## 1.2 Specification of issue under investigation

The aim is supplemented by three different research questions that also will be the starting point of the theory. These questions will, when answered, help to create the basis of the analysis. The questions are stated below:

- Which requirements should a drinking water distribution system obtain?
- What indicators should be considered when identifying the criticality of a pipe?
- Which activities should be counted as valuable users?

## 1.3 Limitations

The project will not consider the probability of a failure but only the consequences of it. It is possible to argue that the criticality will be dependent of the probability of failure. However, it is hard to quantify the probability of failure since it depends on many different parameters that is pipe and site specific. Another reason that the probability is not considered is that one goal of this project is to be able to do a simplification of a model out of the pipe criticality. This implies that only the hydraulic impact can be considered.

The project will also only consider failure of a single pipe at a time. A multiple pipe failure requires both a more complex view of the criticality and to be managed in a correct way it will probably require some kind of probability estimation.

# 2

# Theory

## 2.1 Criteria of drinking water distribution system

One of the key aspects to identify critical pipes is to define which requirements a drinking water system should obtain. In Sweden the law of public water services, 2006:412, is restricting the water supply. In the law, water supply is defined as the provision of water adequate for normal household consumption.

### 2.1.1 Quality requirements

In Sweden drinking water is considered food, which means that Swedish National food agency ("Livsmedelsverket", SLV) regulates the water quality. The regulations from Swedish National food agency is an implementation of a drinking water directive (98/83/EG) from the European Union which includes minimum requirements of the drinking water quality. In the regulations from SLV it is stated that a distribution system should be designed, maintained and operated in a way that it can supply healthy and clean water to the users. Healthy and clean is defined that the water does not contain micro-organism, parasites and substances in such quantity that it could be harmful to humans. Concentration limits for not serviceable water and water that is serviceable with remark has been defined for a several number of micro-organism, parasites and chemical and physical substances.

### 2.1.2 Pressure requirements

In contrary to the quality requirements in Sweden there are no regulations according the service level of a drinking water system (VAV, 2001). Every municipality are able to set their own service goals. However, Swedish Water & Wastewater Association, SWWA, has recommendations for pressure requirements (VAV, 2001). There are three recommendations which are specified against different flows.

1. The highest pressure in connection point should not exceed 70 meters of water.
2. The lowest pressure at the highest tap in a connected household ought not to be less than 15 meters of water. At least 99 percent of the time the recommendation should be fulfilled but it does not apply to a single high building or extra high buildings.
3. The pressure in a fire hydrant should not be less than 15 meters of water during fire water outtake. The recommendation should be fulfilled at least

during maximum water demand in a normal day. During a fire water outtake the second pressure recommendation does not apply for tower block.

Most Swedish societies proceeds from these recommendations even if some changes can be seen. As an example VA SYD, which is a municipal association operating the water supply in five municipalities in the south of Sweden, uses 25 meters of water for both recommendation 2 and 3 (personal communication V.Pelin 2019-03-04). This is an experience based decision since VA SYD have found that new installations in the household give a higher pressure loss than before.

From a more international perspective the standards vary both when it comes to the pressure requirement as well as which condition the pressures are specified at (Ghorbanian, Karnei & Gou 2016). In comparison between selected countries in all over the world, guidelines for pressure varies between 10 - 35 meters of water during all conditions or maximum demand. The guidelines during fire flow are relatively equal over the investigated countries and varies between 10 - 20 meters of water. Ghorbanian et al (2016) also presents five pressure guidelines, developed by Friedman et al (2010), to create a water distribution system with low rate of water losses, pipe breaks and energy usage. The guidelines are listed below.

1. Above 0 meters of water during emergencies, as pipe main breaks and power failures
2. More than 14 meters of water during maximum day demand and fire flow conditions
3. More than 25 meters of water during normal conditions
4. Less than 70 meters of water during normal conditions
5. In greater than 95 % of the time the pressure should be within ± 7 meters of water

### 2.1.3 Reliability

SWWA states in VAV P83(VAV, 2001) that every municipality determine their own delivery reliability goals. They do not recommend any limits but give examples on how to formulate the goals. Delivery interruption in minutes per user and year is one example.

In general, in Sweden there are unusual with reliability goals. However, the city of Gothenburg has formulated a goal saying that the average user should have an interruption time of less than 10 days on 100 years, which estimates to be 144 minutes per year (GR, 2014). The goal is including the whole process from raw water to tap, which implies that the distribution system should have even shorter interruption time.

### 2.1.4 Vulnerable users

National food agency, which regulates the Swedish drinking water industry, states in a report from 2007 that a user with specific need of quality and quantity is characterized by that a disturbance of supply will give more severe consequences than other users (Livsmedelsverket, 2007). Further the authors give several examples of which activities that could be categorized as a vulnerable user.

- Hospitals
- Health centres and other medical facilities
- Schools and preschools
- Food production (e.g. central kitchens)
- Users with specific need (e.g. dialysis patient)

In a guide for planning of emergency water (Livsmedelsverket, 2017), Swedish national food agency goes through how to develop a strategy for prioritising water supply during an emergency. In Swedish legislation water supply is defined as the water sufficient for household consumption. It is thereby, on basis of legislation, never wrong to prioritise household consumption over other type of water use, but it could be wrong to prioritise the opposite. It is also stated in the report that the prioritisation should be done to minimise the impact on the individual and the society level. To help prioritising the water supply two questions can be analysed.

- The impact on an activity under a drinking water disturbance.
- The importance of an activity for the individual and the society.

As an example of a measure of the impact on an activity, National food agency (Livsmedelsverket, 2017) suggests that the activities can be structured from if it needs to cease completely, partially or not at all during a disturbance of water supply. Another aspect to take into consideration could be the time aspect. It is possible that there are activities where the impact is instant while other activities are not affected until a couple of hours or even longer time period.

National food agency (Livsmedelsverket, 2017) are also presenting a grouping of different activities based of importance and a suggested prioritisation of the groups, see ranked list below. They are also stating that dependent of the conditions in a municipality individual activities could be prioritised higher than in the suggested lists.

1. Activities with great importance for life and health
2. Activities with great importance for the functionality of the society
3. Activities with great importance for the environment
4. Activities representing great economical values
5. Activities with great importance for social and cultural values
6. Other activities

In a report from the Swedish Civil Contingencies Agency, also called SCCA (MSB, 2011), they propose goals for emergency preparedness of drinking water, social important activities are defined as an activity that fulfills one of the two following terms:

- A blackout of or a major disturbance in the activity that alone or together with a corresponding event in other activities in a short time could lead to a serious crisis in the society.

- The activity is necessary or very important to be able to handle a crisis in the society with as small damage effects as possible.

Later in the report from SCCA social important activities that are dependent of a secure drinking water distribution are exemplified. Examples that are brought up are hospitals and other medical facilities, food production and retirement homes. Hospitals in general and emergency hospitals in particular are mentioned of importance to take into consideration when contingency planning. It should also be noted that the examples from SCCA are very similar compared to the examples brought up by National food agency earlier in this section.

In another report from Swedish Civil Contingencies Agency (MSB, n.d.) social important sectors dependent on technical supply from the municipality, which includes services as drinking water supply, sewer, district heating and waste disposal, are mentioned. In the report it is specifically stated that food production as well as health and social care are sectors which are critical dependent of a functioning drinking water supply.

## 2.2 System reliability

The definition of system reliability varies in different studies. Shuang et al (2014) defined system reliability in general, as the ability to under a given working state and time period completes the scheduled functions, while Gheisi and Naser (2015a) sees reliability as a measure of the ability to provide users' quantitative and qualitative demands at all circumstances. A third example is Ciaponi et al (2012) who defined system reliability as the ability to satisfy users when taking into account all the possible working conditions that may occur during a operational life.

A number of authors dived system reliability into two disciplines, topological or mechanical reliability and hydraulic reliability (Wright et al, 2015, Shuang et al, 2014, Atkinson et al, 2014, Ostfeld et al, 2002). Also, water quality reliability has been cited in the literature as a third possible class of reliability (Gheisi and Naser, 2015b)

According to Ostfeld et al, (2002) topological reliability can be referred to as the probability that a given network is connected, given that its components could fail. Connected, in the sense that the nodes are connected by operational pipes to a water source. Measures in this approach takes only into consideration if a node is connected with an operational link or not i.e. the serviceability of this link is not included. However, that a node is connected does not ensure an adequate water deliverance. Atkinson et al (2014) describes mechanical reliability slightly different as the functionality during mechanical uncertainty such as component failure (e.g., pipe breakage or pump failure).

Hydraulic reliability is described by Ostfeld et al, (2002) as the probability that a drinking water distribution system is able to supply users demand during a specified time interval and specified conditions. It will thereby refer to the basic function of a water distribution system. The ability to deliver a desired demand with a desired pressure to a desired location at a desired time. According to Atkinson et al (2014) hydraulic reliability indicates how the system can handle hydraulic uncertainties over time, such as pipe deterioration or demand changes.

Gheisi and Naser (2013) investigated which key factors that will affect the results of a reliability analysis for a drinking water distribution system. Three key factors were identified in the report: the rate of failure in pipes, pipe failure combinations, as well as the reliability measure and its criteria were identified as the most influencing factors.

### 2.2.1 Reliability index

Since the performance reliability of a drinking water distribution system are complex and depend on the interaction between a numerous of subsystems, components and external conditions, a wide range of reliability indices can be seen in the literature (Gunawan et al, 2017). One example that can be seen are the Todini's resilience index (Todini, 2000) which compares surplus hydraulic power with available hydraulic power. Hydraulic power which can be described as product of flow and pressure and the index is basically an estimation of how much of the available hydraulic power that will be lost during the distribution to the consumers. Network Resilience Index proposed by Prasad & Park (2004) is almost similar to the Todini index but will also consider the number and dimensions of pipes connected to each node. A third example is the Modified Resilience Index which compares the surplus hydraulic power to the required hydraulic power (Jayaram, 2008). There are also indices that consider heads instead of the hydraulic power such as Minimum surplus head (MSH) and Total surplus head (TSH) (Monsef et al, 2019). These two indices are both based on subtracting the nodal pressure with the required pressure at every node and while MSH is the minimum difference, TSH is the sum of all the differences. MSH will consider the node with the lowest margin of head while TSH considers the total margin of head in the system. However, Monsef et al (2019) showed that the indices presented above are not able to fully describe abnormal operation conditions such as pipe burst and major nodal demand changes.

Another commonly used index in reliability analysis of water distribution system is a ratio between supplied water, outflow, $Q^{out}$ and demand, $Q^{de}$ (Gupta & Bhave 1994, Ciaponi et al, 2012, Shang et al 2014, Gheisi & Naser 2015a). The index measures the ability to distribute the demanded water and can be expressed as:

$$RI_j = \frac{Q_j^{out}}{Q_j^{de}} \tag{2.1}$$

$$RI_{sys} = \frac{\sum_{j=1}^{J} Q_j^{out}}{\sum_{j=1}^{n} Q_j^{de}} \tag{2.2}$$

In the equations 2.1 and 2.2 $RI$ stands for the reliability index of water delivery, $J$ the number of nodes in the drinking water distribution system. The subscripts $j$ and $sys$ refers, respectively to node number and system. As can be seen in the equations above this definition can be applied on both a single node but also on a bigger scale as a whole distribution system. Another advantage with this definition is that it is simple and it is easy to refer how this will be experienced by the users (Ciaponi et al, 2012).

However, Gupta and Bhave (1994) problematised an index only defined by a quota of outflow and demand. The authors compare three different cases that will indicate the same reliability index but they argue they should be valued different. The scenarios are stated in the list below and assumes that the demand is equally distributed between the nodes and static in time.

1. 90 % of the demand will be met in 100 % of the nodes in 100 % of the time
2. 100 % of the demand will be met in 100 % of the nodes in 90 % of the time
3. 100 % of the demand will be met in 90 % of the nodes in 100 % of the time

Further Gupta and Bhave argues that the first scenario is the most preferable and that the third one is the worst. To differentiate these scenarios Gupta and Bhave introduced two factors, called time and node factors. Time factor, $F_t$, which describes the ratio between the duration of acceptable situations and the total duration. It will thereby be a measure of the mean time a user has an acceptable water delivery and is defined as:

$$F_t = \frac{\sum_s \sum_j a_{js} t_{js}}{JT} \tag{2.3}$$

To calculate this index the time period is divided into different states, $s$. In a state the demands and condition of the network are remaining constant. If any condition of the network or demand is changing a new state is started. The time length of each state is described by the variable $t_{js}$ Further $J$ is equal to the total number of demand nodes ($= \sum j$) and $T$ the time period of analysis ($= \sum t$). Variable $a_j s$ could have either value 1 or 0 depending on the outflow ratio, $Q^{out}/Q^{de}$. If discharge ratio at a node for a particular state is equal to or more than a predefined acceptable value, then $a_j s = 1$, otherwise $a_j s = 0$. As an example, if the predefined acceptable level is 0.6, $a_j s = 1$ for the nodes in a state where at least 60 % of the demand are satisfied.

Nodal factor, $F_n$,is on the other hand calculated by taking the geometric mean of nodal indices. Nodal indices, $RI_j$ (Eq. 2.1), which in this case are the ratio between volume of outflow and volume of demand, $Q^{out}/Q^{de}$, for every individual node. The equation for Nodal factor is expressed as:

$$F_n = \left[ \prod_{j=1}^{J} RI_j \right]^{1/J} \tag{2.4}$$

Since the Nodal factor is calculated by geometric mean one low nodal index could heavily influence the factor, thereby will the factor be a measure of the equality of the distribution. An index for equality to complement the outflow demand ratio has also been used by Gheisi and Naser (2015a). They calculated their equity index by comparing the deviation between each nodal index and the average of nodal indices with the average of nodal indices. By doing so they will get a index representing the amount of outflow variations i the water distribution system.

To gather the different indices into a single reliability index, $R_{nw}$ Gupta and Bhave (1994) uses the product of the indices.

$$R_{nw} = RI_{sys} * F_t * F_n \tag{2.5}$$

### 2.2.2 Criticality of a pipe

To identify criticality of a pipe a common way is to see which effect a single pipe has on the system reliability (Shang et al 2014, Wright et al 2015). This can be made by closing each link in succession and measuring the chosen reliability index. The links can then be sorted on basis of its effect on the system reliability.

Within the project of CARE-W three hydraulic reliability models, RelNEt, Failnet-Reliab and Aquarel, has been developed (Eisenbeis et al 2003). The models assess several indicators linked with hydraulic availability as defining pipe failure impact on demand or pressure and the hydraulic importance of a pipe, hydraulic reliability of the whole network as well as defining Hydraulic Criticality Index (HCI). HCI is basically the quota between outflow and demand and similar to the reliability index earlier called RI (Eq. 2.2).

When using RelNet the pipes in the network will be closed in succession and the HCI will be calculated for every pipe (Eisenbeis et al 2003).

Failnet-Reliab model works in two steps, hydraulic modelling followed by calculation of reliability indices (Eisenbeis et al 2003). Only one simultaneously pipe break is assumed to happen. The indices take hydraulic results, weighting of nodes (quantity and vulnerability) and probability of pipe failures into consideration. The weight of nodes is dependent on three factors, the quantity of the demand, the type of consumer connected to the node and the vulnerability of the consumers.

Aquarel, on the other hand includes two pipe failures simultaneously which creates a more complex criticality index dependent on probabilities of pipes breaking (Eisenbeis et al 2003).

## 2.3 Drinking water modelling

A drinking water model consists mainly of two types of elements, nodes and links (MIKE, 2019). Together these two types of elements can build up a network similar to the investigated distribution system. Nodes, which defines the interconnection between links, can be given water consumption (demand), storage capacity (tank nodes) or inflow. Links mainly function is to transport water between the nodes, and can also be used to restrict that transport (valve links) or increase the pressure (pump links). When a network is built, a hydraulic analysis can be performed. In this analysis flows in links and pressures in nodes will be calculated through an iterative process. There are several hydrodynamic model software's, but one commonly used software is EPANET which is the numerical engine of MikeUrban$^{+}$, the modelling software used during this thesis work.

When it comes to hydraulic analysis of a water distribution system the techniques can be categorized into two types depending on the relation between demand and outflow, Demand driven analysis (DDA) and Pressure driven analysis (PDA) (MIKE, 2019).

As stated above a node can be given a demand. The demand stipulates the outflow in every node. To avoid any misinterpretation the demand will in this report be defined as the desired amount of water while outflow is defined as the supplied amount of water.

### 2.3.1 Demand driven analysis

In a demand driven analysis the assumption that the nodal outflow is fixed and the demand is satisfied regardless of what network pressure can be achieved in a veritable system. (Tabesh et al, 2002). This assumption is a simplification of the reality since it is intuitive that if the pressure in a node drops under a critical level the outflow will be reduced. A demand driven model is thereby only valid during normal condition when the pressure can be expected in such level that it is possible to satisfy the desired demand. To get a realistic simulation result during pressure-critical conditions a relationship between pressure and outflow needs to be stated in the hydrodynamic model.

### 2.3.2 Pressure driven analysis

In similarity to the demand driven analysis a demand is determined for every node and the pressures are then calculated. In contrast to DDA, PDA will automatically adjust a node's outflow depending on the available pressure in that node (Tabesh et al, 2002). This indicates that a pressure driven analysis will be equivalent to demand driven analysis when the designated demand is fully satisfied, usually during normal operating conditions. However, if a pump fail, a pipe breaks or any other event occurs leading to insufficient pressures, the PDA can realistically simulate the outflows, whilst DDA are only able to indicate that a supply problem will arise.

How outflow ($Q_{out}$) will change from demand ($Q_{dem}$) depending of present pressure ($P_{act}$), required pressure ($P_{req}$) and minimum pressure ($P_{min}$) can be described by different equations. In the hydrodynamic model MikeUrban$^{+}$ there is a possibility to choose between three different equations, Wagner, Tucciarelli and Fuijiwara equation (MIKE, 2019).

Wagner equation (Wagner et al, 1988):

$$Q_{out} = Q_{dem}\left(\frac{P_{act} - P_{min}}{P_{req} - P_{min}}\right)^{\frac{1}{n}} \tag{2.6}$$

Tucciarelli equation (Tucciarelli et al, 1999):

$$Q_{out} = Q_{dem}\left(sin\left(\pi\frac{P_{act}}{2P_{req}}\right)^{2}\right) \tag{2.7}$$

Fuijiwara equation (Fuijiwara & Ganesharajah, 1993):

$$Q_{out} = Q_{dem}\left(\frac{(P_{act} - P_{min})^2(3P_{req} - 2P_{act} - P_{min})}{(P_{req} - P_{min})^3}\right) \tag{2.8}$$

In Wagner equation $n$ is a constant that influence the outflow and is often given a value between 1.5 - 2 (Tabesh et al, 2002). To get a grip of how the outflow will change depending on the pressure all three equations are plotted with normalized pressure and outflow in the figure below. The constant $n$ in Wagner equation is 2 in this figure. As can be seen are Tucciarelli and Fuijiwara equations very similar to each other while Wagner equation gives a higher outflow at most pressure values ($p<0.8$).

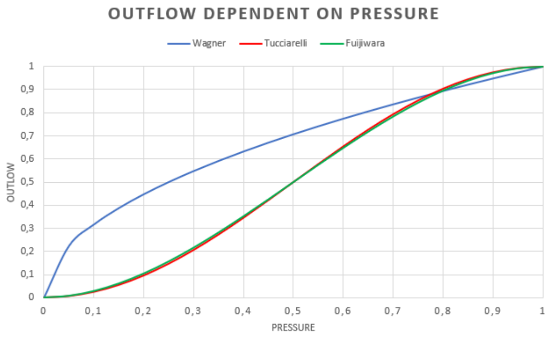

**Figure 2.1:** Wagner, Tucciarelli and Fuijiwara equations graphically drawn for normalized pressure and outflow

## 2.4 Comments of the theory

As presented in section 2.2.1 Gupta and Bhave (1994) introduced three scenarios from which they concluded that only a quota between outflow and demand are not able to fully describe the reliability. To better describe the reliability two additional indices was introduced. Gupta and Bhave ranked the scenarios in the order presented in the list below where scenario ranked as 1 is assumed to be the most preferable.

1. 90 % of the demand will be met in 100 % of the nodes in 100 % of the time
2. 100 % of the demand will be met in 100 % of the nodes in 90 % of the time
3. 100 % of the demand will be met in 90 % of the nodes in 100 % of the time

As can be interpreted from this ranking is that it is more important that the water is distributed equally (scenario 2) than the highest impact on the system (scenario 3). Scenario 2 implies that 10 % of user will be out of water during an interruption time while scenario 3 implies that all the users will be out of water during 10 % of this interruption time.

In Sweden the interruption of water supply in 2018 was estimated to be on average 6.2 minutes per user (Svenskt vatten, 2019) and of the pipe breaks in Gothenburg between November 2007 and December 2010 were 84 % reported repaired the same day as it was detected (Malm et. al, 2015). On a daily basis the interruption time will be short. Therefor a scenario where all users are affected are assumed to be worse than a scenario where only 10 % of the users are affected.

There are, however, possible to argue that in a context where the reliability of the network is low and the water resources are restricted the equality of water distribution will be important and the ranking could be as presented in the list above.

From the argumentation above the ranking of the scenarios can be changed and be as presented in list below (with the most preferable scenario first).

1. 90 % of the demand will be met in 100 % of the nodes in 100 % of the time
2. 100 % of the demand will be met in 90 % of the nodes in 100 % of the time
3. 100 % of the demand will be met in 100 % of the nodes in 90 % of the time

Even though an interruption of water to 10 % of the society will have a great negative impact on the affected households, it will from a Swedish perspective be during a limited time. Thereby it will be assumed a more preferable scenario than the whole system being out of water, even though it is during a shorter time period. It could also be assumed to be more complicated to distribute water through an alternative system to all the users than 10 % of the users although it is during a shorter time period.

# 3

# Methods

## 3.1 Reliability and methodology

As can be seen in section 2.2 there are a number of different definitions of reliability used in the literature. The definition will control which indicators and measures of the reliability that should be used. However, in this report reliability will be seen as the ability to supply the quantitative demand to the households and valuable users at any time.

To identify a pipe´s criticality the pipes contribution to the system reliability has been evaluated. The contribution is estimated by evaluating the results from hydraulic simulation of the drinking water system, with the investigated pipe taken out of operation. Four indices and a gathered criticality index, which are presented later in this chapter, are used to estimate the reliability of a drinking water system. The four indices will try to estimate the rates of supplied demand, affected users, time and the effect on valuable users. The method will be based on the approach used by Gupta and Bhave (1994), but some modification and additions have been made to the indices to better fit with the criteria of a DWDS presented in the previous chapter.

### 3.1.1 Assumptions

As presented in section 2.3 there are two different ways to model demand in a drinking water model, which comes from two different assumptions. In the case where pressure driven demand is used there are three states the node can be in, operational, failure or intermediate state. The node is operational when the pressure is higher than, or equal to, the predefined required pressure level and the demand are fully met. Failure occurs when the pressure drops under the predefined minimum level and no demand can be met. During intermediate state the demand are partly met and the pressure lays between the two predefined levels. The value of demand depends on on the estimated pressure and has been calculated with the Wagner equation(Eq 2.6).

When the model is not pressure driven, but demand driven the node will have only one state. During the simulation the model will always see the node as operational, i.e. the demand will always be met. However, during the calculation of performance index the node is assumed to have two states. If the pressure requirement is met the node counts as operational and all demand are counted as supplied. If the pressure requirement is not met the node assumes to be in failure state and no demand are assumed to be supplied.

### 3.1.2 Indices

To determine the criticality of a pipe four indices have been used: supplied demand, affected users, time and valuable users. All indices are trying to show a different aspect of a pipe's criticality and can be a number between 0 and 1, where 0 indicates low criticality and 1 high criticality. The four indices are also weighted together into a aggregated criticality index ranging from 0 to 1, where 1 is the most critical.

#### 3.1.2.1 Supplied demand

As many reports reflecting the reliability of a pipe network as mentioned in section 2.2, an indicator linked to the supplied demand has been used. To determine the demand criticality index the outflow ($Q^{out}$) for all nodes and time steps is compared to the demand ($Q^{de}$) for all nodes and time steps. The equation is then modified to use a scale where 1 is the most critical. The equation is shown below, see eq. 3.2, where $j$ refer to nodes of the total number of nodes $n$, and $t$ refers to time steps of the total number of time steps $T$.

$$CI^D = 1 - \frac{\sum\limits_{t=1}^{T} \sum\limits_{j=1}^{n} Q_{jt}^{out}}{\sum\limits_{t=1}^{T} \sum\limits_{j=1}^{n} Q_{jt}^{de}} \tag{3.1}$$

#### 3.1.2.2 Affected users

The second indicator will describe the maximum number of affected users. Even if the amount of supplied demand is known, the distribution of shortage of demand is also important. Since a small restriction of water demand at a household probably not will cause any major negative impacts, only the affected users with a major water demand loss will be counted. When modelling, the number of users connected to each node is often unknown. Therefore, the percentage of users have been estimated from the demand in each node. The sum of the demands of affected users will be compared to the total demand of the model $Q_{tot}^{de}$, for every time step $t$. The affected users criticality index will be given the maximum value (worst case) of these comparisons, see equation 3.2.

$$CI^U = \max(\frac{\sum\limits_{j=1}^{n} Q_{jt}^{de} * a_{jt}}{Q_{tot,t}^{de}}) \tag{3.2}$$

To determine the number affected users, there is a need to define what an affected user is. This can be made with the binomial variable $a_{jt}$, that can take either 0 or 1, and shows if the node fulfill the defined limit of supply or not. Further it is able to express the variable in the form of an equation by: '

$$a_{jt} = \begin{cases} 1 & \text{for} \quad \frac{Q_{jt}^{out}}{Q_{jt}^{de}} < A \\ 0 & \text{for} \quad \frac{Q_{jt}^{out}}{Q_{jt}^{de}} \geq A \end{cases} \tag{3.3}$$

Where A is the defined limit of an acceptable water outflow compared to the demand, for instance 90 % of the demand. That means that a user with a quota between outflow and demand less or equal to 90 % will be counted as an affected user. Since a demand driven model are not able to define outflow as percentage of water demand A will be 100 % in a demand driven analysis. The definition of an affected user is an outflow less than 90 % of the demand.

#### 3.1.2.3 Time

The time aspect is as well important when determine a pipe's criticality. A pipe that when out of operation generates a interruption of water delivery during a longer time period will be more critical than a pipe that generates a interruption of water delivery during a shorter period of time. In similarity to the index of affected users the time index comes from a defined limit of supply, and the index will calculate the percentage time the system manages to supply water equal or more than the limit. Equations 3.4 and 3.5 below describes how the time criticality index is calculated.

$$CI^T = \frac{\sum_{t=1}^{T} b_t}{T} \tag{3.4}$$

The binomial variable $b_t$, that can take either 0 or 1, shows if the system fulfill the defined limit of supply or not. Further it is able to express the variable in the form of an equation by:

$$b_t = \begin{cases} 1 \quad \text{for} \quad \frac{\sum_{j=1}^{n} Q_{jt}^{de} * a_{jt}}{Q_{tot,t}^{de}} \leq B \\ 0 \quad \text{for} \quad \frac{\sum_{j=1}^{n} Q_{jt}^{de} * a_{jt}}{Q_{tot,t}^{de}} > B \end{cases} \tag{3.5}$$

Where B is the defined limit of an acceptable water supply, which is the estimated percentile number of affected users with an unacceptable water outflow. The definition of an affected user is stated in the section 3.1.2.2(above). Depending on the size of the model as well as if it is a section of a distribution system the limit would probably differ since a single user will be given more or less percentile influence.

#### 3.1.2.4 Valuable users

A valuable user as for instance an emergency hospital is usually heavily dependent of a functioning water delivery. The risks when the water supply is reduced are assumed to be high and thereby will any reduction of water delivery be valued as critical. The valuable users index $CI^V$ is a binomial variable that can be calculated with the equations below, 3.6 and 3.7. If any valuable user is affected with a reduced water outflow the index will be given value 1 otherwise value 0.

$$CI^V = 1 - \prod_{t=1}^{T} \prod_{i=1}^{m} c_{it} \tag{3.6}$$

In the equation $t$ is a time variable where $T$ stands for the maximum time level and $i$ the number in a list of vulnerable users, where $m$ is the length of the list. The variable $c_{it}$ determines from equation 3.7 and describes if a node connected to a valuable user are affected with a reduction of demand (0) or not (1).

$$c_{it} = \begin{cases} 1 & \text{for} \quad \frac{Q_{it}^{out}}{Q_{it}^{de}} = 1 \\ 0 & \text{for} \quad \frac{Q_{it}^{out}}{Q_{it}^{de}} < 1 \end{cases} \tag{3.7}$$

Variable $c_{it}$ depends on the quota between outflow ($Q^{out}$) and demand ($Q^{de}$) during time step $t$ and at valuable user node $i$. If the quota is less than 1 $c_{it}$ will be given value 0 and if the quota is equal to 1 $c_{it}$ will be 1.

#### 3.1.2.5 Criticality index

To put all the indicators together into an aggregated criticality index the mean value of the above presented indices, see equation 3.8 below. It means that each index is given equal weight. There are however possibly to introduce constants for another weighting of the indices.

$$CI = \frac{CI^D + CI^U + CI^T + CI^V}{4} \tag{3.8}$$

#### 3.1.2.6 Exemplification

To get an understanding of the different indices an exemplification, similar to the problem stated in the section 2.2.1, with three different scenarios has been done. The scenarios are listed below and assumes that the demand is equally distributed between nodes and in time.

The three scenarios are again:

1. 90 % of the demand will be met in 100 % of the nodes in 100 % of the time
2. 100 % of the demand will be met in 90 % of the nodes in 100 % of the time
3. 100 % of the demand will be met in 100 % of the nodes in 90 % of the time

To calculate the indices an affected user is defined by a user with outflow less than 80 % of the demand and an acceptable water supply is defined as less than 20 % affected users. All the scenarios are also assumed to affect at least one valuable user.

**Table 3.1:** Exemplification of used criticality indices

| Criticality index (CI) | | | | | |
|---|---|---|---|---|---|
| Scen | Demand | Affected users | Time | Valuable user | Criticality |
| 1 | 0.1 | 0 | 0 | 1 | 0.275 |
| 2 | 0.1 | 0.1 | 0 | 1 | 0.30 |
| 3 | 0.1 | 1 | 0.1 | 1 | 0.55 |

As can be seen in table 3.1. all of these three scenarios have the same supplied demand ratio but differ in the other indices. Scenario 3 is estimated to be the worst case followed by scenario 2 and at last scenario 1. In scenario number one none of the users are defined as an affected user, which gives a zero when it comes to affected user and time indices. However, if the definition of an affected would be different, as for instance, outflow less or equal to 90 % of demand, the affected user index would be 1 instead of 0. Since all the users will be seen as an affected user at all time will also time index be given value 1. These changes of the values of the indices will change the aggregated criticality index to 0.775. The change of the definition of an affected user could thereby drastically change the aggregated criticality index and the ranking of the scenarios. It will thereby be of importance which definition of an affected user that is used.

## 3.2 Test of methodology

To evaluate the methodology a pipe criticality analysis has been performed on an artificial drinking water distribution system.The hydrodynamic pipe model software MikeUrban$^+$ is used for hydraulic simulations and the characteristic of the system as well as the chosen settings will be described in the following sections. MikeUrban$^+$ is a modelling software where EPANET is the numerical engine (MIKE, 2019). To reduce number of simulations the closing of the pipes is made in succession in a long simulation. Between the scenarios the tank is filled to its starting level.

### 3.2.1 Test model

For evaluation of the method a test model has been developed. It is preferable small to create a short simulation time but will also consist of different elements to give a wide evaluation of the indices. The model, like most of existing distribution systems, consist of a combination between branching and grid systems, in order to evaluate the indices for pipes of both characteristics. A reservoir is included in the test model to be able to test and assess a time varying criticality. The model also consists of a vulnerable user and a wide spread of demand applied in the nodes, which can be seen in Figure 3.1.

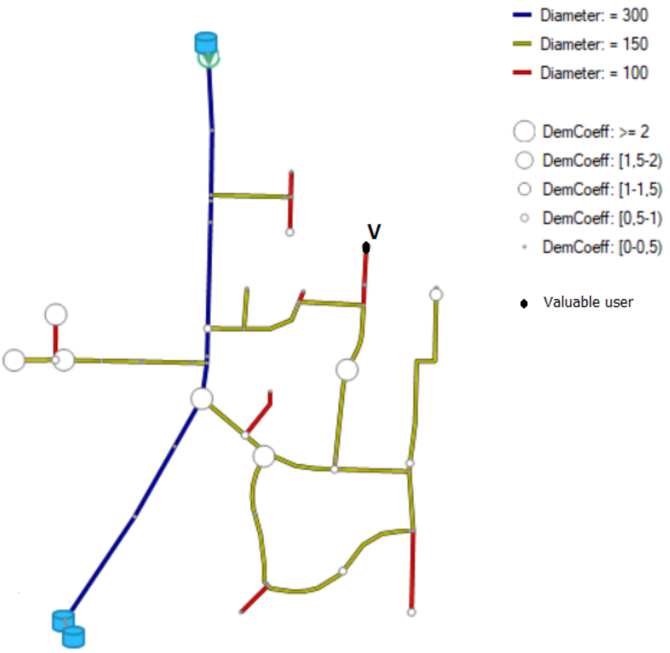

**Figure 3.1:** Test model with pipe dimensions, demands and the location of a valuable user

The model is supplied from the upper part where a pumping station with appurtenant water supply is located. The pumping station is linked to the tank in the lower part by a main distribution system of pipes with diameters of 300 mm. All the pipes in the model are assumed to have a roughness of 0.1 mm. The tank allows a water level between 35 and 42 meters, has a volume of 200 cubic meter and is designed to be able to have a water volume of 7 hours of average demand. To test the criticality of pipes instead of the pumps, the pumping station is designed to provide maximum demand with negligible change of pressure. Except earlier reason a system is usually designed to work even with a tank out of order since they regularly needs to be cleaned. To ease simulation all the pumps in parallel are assumed to be up and running, which creates a flat pumping curve. Thereby are the pumps assumed to be able to provide 50 l/s with a water head of 40 meter of water and to have a maximum head of 42 meter of water.

#### 3.2.1.1 Demand

All the nodes are located at level 0 m and the nodes contains demand between 0 to over 3 liters per second. The total demand of the model varies between 5 and 49 litres per second with an average of 27 litres per second. How the demand varies over time can be seen in the figure 3.2 below.

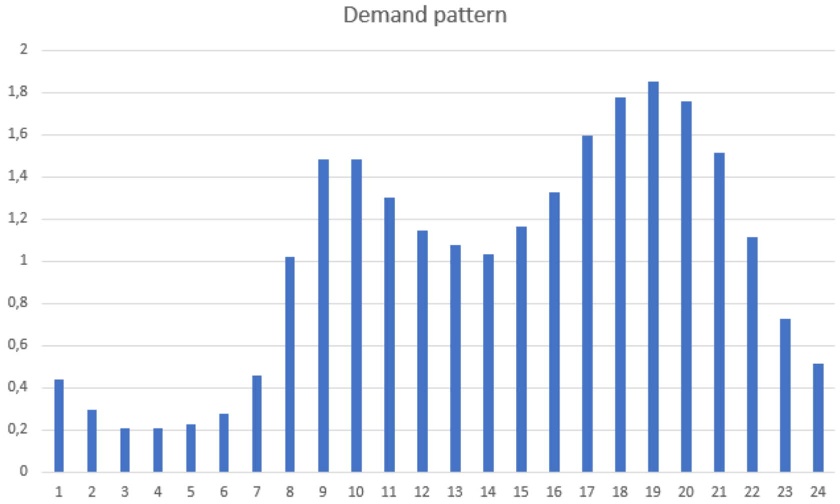

**Figure 3.2:** Demand pattern used during simulation

When modelling with pressure driven demand the demand is assumed to be fully delivered at a node pressure of 30 meters of water or more. The minimum pressure of delivery are 10 meters of water and the outflow between these pressures are calculated with the Wagner equation(Eq 2.6) with $n = 2$. During demand driven approach 30 meters of water is the required pressure in the nodes. If the pressure is below this limit, outflow is counted as 0.

### 3.2.2 Choice of testing scenarios

Since the model is fictional and not taken from a real distribution system it is hard to talk about average day or maximum day consumption. But the model can be considered to have some marginal of the load of the water distribution system, which can in most cases be comparable with an average day consumption.

#### 3.2.2.1 Time scenario

To determine the time period of the simulation there are two key questions to answer. When should the simulation start and for how long should the simulation last. In Gothenburg, the pipe breaks between November 2007 and December 2010 were 84 % reported repaired the same day as it was detected (Malm et. al, 2015). Therefore will the simulation period progress during 24 hours. The analysis will start at midnight since it is assumed that the influence of starting time is negligible as long it is the same for every simulation. The hydraulic calculations will be performed every 30 minutes of the simulation while the analysis will be performed with the time step of one hour.

# 4

# Results

The results from the hydraulic calculations will be presented in this chapter.

## 4.1 Supplied demand

First, the criticality index of supplied demand (Eq. 3.1) is presented. During the test period of 24 hours 60-80 % of the demand are dependent on the operation of the most critical pipes, which are the pipes close to the pumping station. In the circular fed part of the system many pipes do not implicate any loss of outflow if they are removed. It can also be seen that the pump are able to supply the whole system without the tank since the pipes closest to the tank has index value 0.

**Figure 4.1:** Criticality index of supplied demand is presented for the pipe network

## 4.2 Affected users

In figure 4.2 the maximum affected users of each pipe (Eq. 3.2) is displayed. An affected user is defined as the user with an outflow less than 90 % of the demand. As can be seen in the figure, almost everyone of the users will be affected if the pipe closest to the pump will fail. The south pipe supplying right part of the system is also of importance since approximately half of the users are dependent on this pipe. The north pipe supplying right part is however not showing any affected users if it is removed.

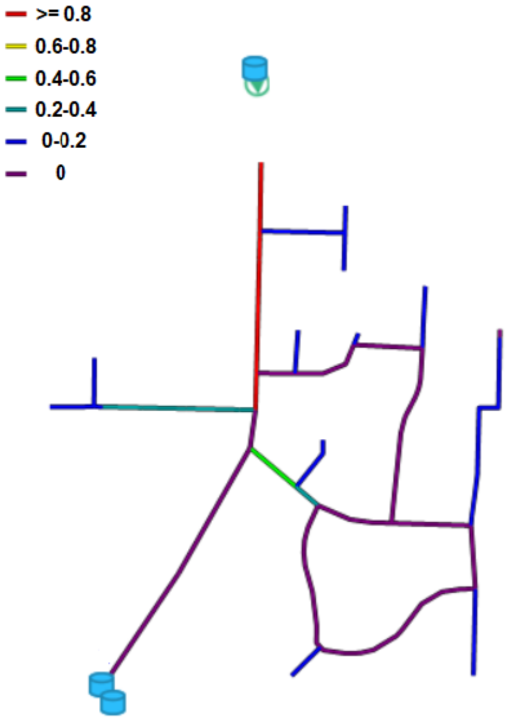

**Figure 4.2:** Criticality index of affected users is presented for the pipe network

## 4.3 Time

Time criticality index shows the percentile time that a system has a supply rate of more than a define limit(Eq. 3.4). In this case the limit is 20 % affected users of the whole system. A low time criticality index are indicating that the system are working acceptably for a high proportion of the simulated period, while a high indicates a badly functioning system(20 % of the users in the system are counted as an affected user) during a high proportion of the simulated period. The results of the simulations can be seen in figure 4.3. The pipes supplying the left part of the model has a time criticality index of 1 which corresponds well with that this part is single fed and that over 20 % of the demand is distributed in to this area, through this pipe. Other pipes with a high time criticality index are the system supplying pipes close to the pump which are under the limit approximate 50 % of the simulated time. This indicates that the tank is able to supply the system during the first half of the simulated period. Also, the lower pipe supplying the right part of the system can be seen to affect more than 20 % of the users during approximately 30 % of the time.

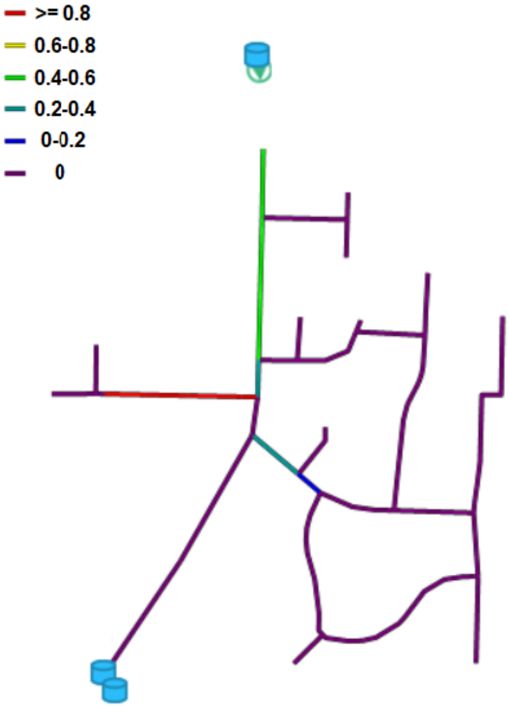

**Figure 4.3:** Criticality index of time

## 4.4 Valuable users

A valuable user is situated in the upper right part of the system. Since this index are binomial every pipe affecting the valuable user in any time of the simulation will thereby be given value 1 and the rest 0 (Eq. 3.6). The pipes affecting the valuable user can be seen in figure 4.4, below. Pipe that affecting the distribution of this node are the pipes closest to the pump, lower pipe supplying the right part of the system as well as the end pipe supplying the valuable user.

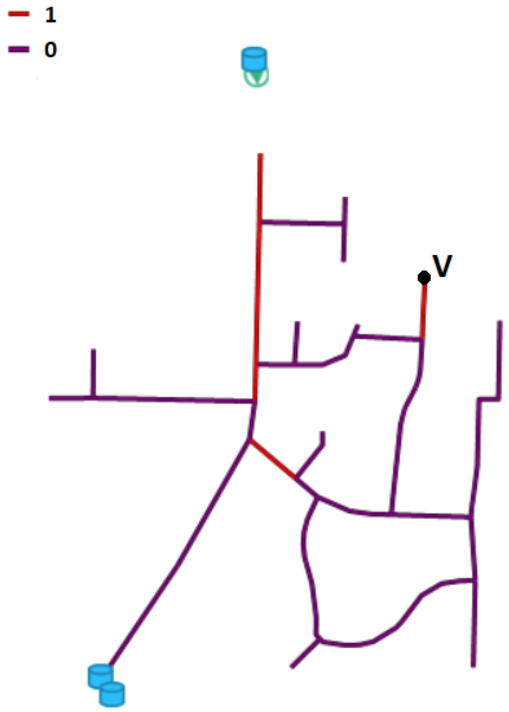

**Figure 4.4:** Criticality index of valuable users (here marked with a V in the figure).

## 4.5 Criticality index

In this section the aggregated criticality index based on the four earlier presented indices is presented. In figure 4.5 the aggregated criticality index is presented and as can be seen in figure the criticality varies between 0 to over 0.8. The most critical pipes are close to the pump and the supply of the system. It is also possible to distinguish pipes in the system with none-existing criticality, for instance the pipes close to the tank. Another thing to highlight is the pipe close to the valuable user which shows a higher criticality than comparable end pipes. One last interesting observation is that the south pipe connecting the southeast part of the system to the main pipes, between pump and tank, shows a relatively high criticality while the north pipe has a criticality index of 0 even though they have the same dimension.

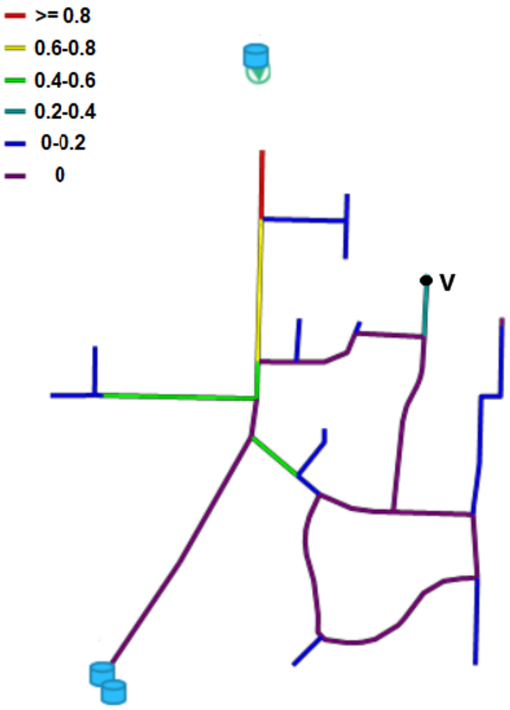

**Figure 4.5:** The aggregated criticality index

## 4.6 Time dependency

Three main types of patterns can be seen for parameters of demand and affected users. These patterns are represented by three pipes and are illustrated in the figure 4.7, below.

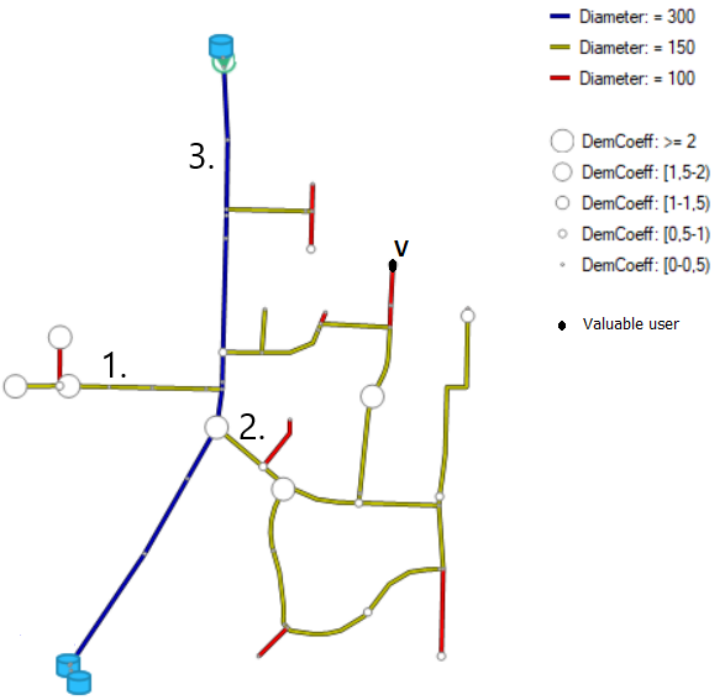

**Figure 4.6:** The three pipes used in the comparison

The index for pipe one, which is supplying a single fed part of the system, is constant 0.3 over time. The only affected users in the model are in this case the 30 % of the users that are in the end of the single fed part of the system. Since the pipe will be closed during all its test period the affected users will be constant 0.3 over time. In comparison, the index of pipe two shows a time varying pattern where the peaks can be linked to the chosen demand pattern of the supplied nodes. This type of pattern is seen in the pipes included in the circular fed part of a system and the maximum would probably be dependent on the design of the investigated system. The third index pattern is similar to index of pipe one with the exception of a delay. The delay comes from the connected tank which are able to supply the system for certain amount of time. When the tank is emptied, in this case after 11 hours, the index will stabilise at a value, in this case value 1. Value 1 entails that all the users in the model will be counted as affected users.

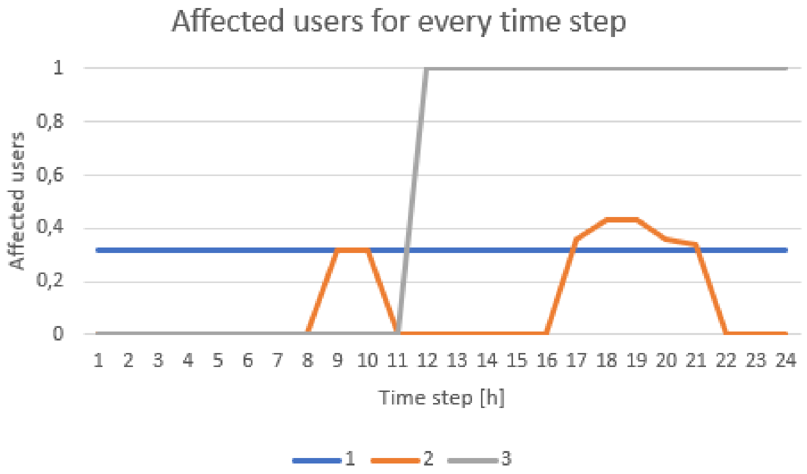

**Figure 4.7:** Affected users for every time step for the three pipes

## 4.7 Comparison between two pipes

To get an understanding about the method two pipes with almost similar gathered criticality index has been compared. Although the criticality indices are approximately the same, the pipes differ in many ways. Pipe one is in the beginning of a single fed part of the system, while pipe two is included in the circular fed part of the system. See figure 4.6 for the location of the pipes. There results in the different indices can be seen in table 4.1 below.

**Table 4.1:** Comparison between two pipes criticality index

| Criticality index | | | | | |
|---|---|---|---|---|---|
| Pipe | Demand | Affected users | Time | Valuable user | Criticality |
| 1 | 0.31 | 0.31 | 1 | 0 | 0.41 |
| 2 | 0.04 | 0.43 | 0.29 | 1 | 0.44 |

As can be seen in the table above these two pipes performs different in the most of the indices but approximately the same in the gathered criticality index. Approximately one third of the users as well as the demand are dependent on pipe one. Since the area is single fed the effect of the users will be constant over time, which can also be seen by the Time index as well as the similar value of Demand index and Affected user index. Pipe two are on the other hand important for 4 % of the demand and 43 % of the users will be affected with an available water outflow less than 90 % of the demand during a pipe failure. At 29 % of the time more than 20 % of the users are counted as an affected user. Pipe two is also important for the supply of the valuable user.

## 4.8 Pressure driven demand vs Demand driven

Two modelling approaches has been used during simulations of the model. The results from the two modelling approaches will be compared in this section. As can be seen in figure 4.8 below the majority of the pipes has a similar criticality for both the different types of modelling. Only for a few pipes a difference can be seen, where demand driven approach gives a higher criticality. However, if you compare the ranking of the pipes there is only one pipe where the ranking drastically changes if you change between the two modelling approaches. Most of the change for that pipe can be explained by the difference in valuable user index. Demand driven modelling implied that the valuable user would be affected whilst pressure driven demand modelling implied no affect.

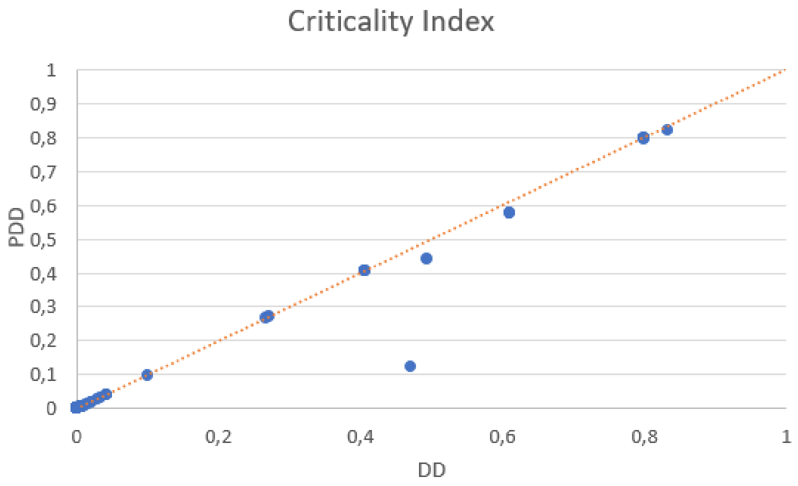

**Figure 4.8:** Comparison of the Criticality index between the two modelling approaches pressure driven demand(PDD) and demand driven(DD)

When compared the same pipes as in the section above on basis of demand or pressure driven modelling the pipes shows different results, see table 4.2. Pipe one does not have any difference depending on the modelling method while pipe two has mainly a difference demand but also affected users. The demand driven approach gives a higher criticality than the pressure driven approach does. For this pipe the loss of outflow is estimated to be 5 times higher and the affected users as well as the gathered criticality index is increased with over 10 % with DD compared to PDD.

**Table 4.2:** Comparison between two pipes criticality index with PDD and DD

| Criticality index | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Pipe | Demand | | Affected users | | Time | | Valuable user | | Criticality | |
| | DD | PDD | DD | PDD | DD | PDD | DD | PDD | DD | PDD |
| 1 | 0.31 | 0.31 | 0.31 | 0.31 | 1 | 1 | 0 | 0 | 0.41 | 0.41 |
| 2 | 0.21 | 0.04 | 0.48 | 0.43 | 0.29 | 0.29 | 1 | 1 | 0.49 | 0.44 |

# 5

# Discussion

## 5.1 Criteria of drinking water distribution system

As can be seen in section 2.1 the quality and pressure requirements are quite distinct. When it comes to reliability there are few examples of distinct requirements, but SWWA refers to that every society needs to set their own goals. As stated in section 2.1.3 the City of Gothenburg uses the goal that an average user should not be without water more than 144 minutes per year. This means that there is no difference if few users are affected during a longer time span or many users during a short period of time. It is therefore room for additional goals. As an example, the maximum numbers of users dependent on a single pipe can be a reliability goal to analyse or in any other way determine the maximum impact of a single pipe. This type of goal would also define the limit used in time index.

## 5.2 Definition of valuable user

Since the effect on a valuable user is assumed to have a significant influence on the criticality of a pipe the definition of a valuable user will be important. As presented in section 2.2.4 there is no definitely definition of which users that could be viewed as valuable. However, Swedish National Food Agency defines how to establish a prioritisation of activities from two issues: The impact on an activity under a drinking water disturbance and the importance of an activity for the individual and the society. Activities that either are of great importance for life and health or of great importance for the functionality of the society and that are affected during a drinking water disturbance is one definition of a valuable user that can be made from the theory. The definition will include a number of the activities exemplified in section 2.2.4 by Swedish National Food Agency and Swedish Civil Contingencies Agency, such as hospitals, medical facilities and dialysis patients. There are however up to every society to determine which users that should be accounted as valuable users.

## 5.3 Criticality Index

As presented in the results, pipes close to the tank shows a none-existing criticality. It means that the system will be functioning without these pipes. However, these pipes will be important since they will minimise the criticality of the other pipes. For instance will the pipes closest to the pump have a higher criticality if not the tank are able to support the system during some time. This type of support to the system will not be valued with this methodology. Another example that can be made is that if the pipe closest to the pump is doubled, the criticality of these two pipes will be zero since both of the pipes separately are able to supply the whole system. It means that an end pipe supplying only a few households would be valued more critical than these two pipes. It is obviously true that the end pipe will affect more people if it breaks than if one of the supplying pipes does but the pipes are however of importance for the functioning of the system. The ability of a pipe to increase the redundancy of the system is not valued with this type of methodology, but will need either other indices or simulations where multiple pipes can be considered nonoperational at the same time. It can also be seen from the perspective that the indices are only reflecting hydraulic reliability during a pipe failure. An index reflecting the mechanical reliability (e.g., entropy) could complement the indices to also include a higher value for pipes like these.

On the other hand, the cause of doubling the supply pipe is probably to decrease the criticality. To estimate how much the criticality will be decreased would probably best be described by means of the probability of the pipes failing. If the probability of multiple pipes failing at the same time is negligible this type of methodology will describe well which pipes that are critical, while if the probability is not negligible the methodology will have deficits describing the criticality.

This issue corresponds well to the literature where Gheisi and Naser (2013) identified three key factors that will have the most influence on a reliability analysis of a DWDS. Pipe failure combinations, rate of pipe failures as well as the chosen reliability indices are identified as the factors. The uncertainty of this method discussed in the previous paragraphs, as indices not reflecting all reliabilities as well as the assumption of only one simultaneous pipe failure can be linked to this key factors.

## 5.4 Comparison of two pipes

As presented in the results, in Section 4.7, the gathered criticality index could be almost equal for diverse types of pipes. When introducing the indices three scenarios where used for exemplification (see Section 3.1.2.6). These three scenarios where in a way extremes. Scenarios in between these extremes, such as different combinations of affected users and interruption times, exist. How these scenarios should be compared to each other is in the end a question of valuation and can not be evaluated by only ranking the extremes. It would therefore be of importance to develop the reliability guidelines of a DWDS.

The indices, however, could describe what type of interruption a pipe will cause if breaking. There is also possible to introduce constants to change the weights of the different indices.

## 5.5 Pressure driven vs Demand driven

Majority of the pipes that shows a criticality in the test model are either end pipes or single feeding pipes. These types of pipes are easy to determine a criticality of since they are constant over time and the affected users will have zero outflow of water. They do not show any difference in criticality between DD or PDD modelling. However, there are also pipes that a tank can cover for a certain amount of time and pipes in circular fed parts of the system where the criticality correlates with the demand pattern. These pipes can differ depending on modelling approach.

In this model the outflow depending of a pipe was decreased with up to 80 % using PDD, even though the gathered criticality index was decreased with approximately 10 %. In the gathered criticality index only one pipe had a significant difference between the modelling approaches. The difference was due to the difference in valuable user index. During PDD simulation no effect on the valuable user was seen while during DD simulation the valuable user was affected. A small difference in the simulation results creates a more significant difference due to it is a valuable user and that the valuable user index is binomial.

There are however hard to draw any strong conclusions about the difference between the modelling approaches, since it would differ a lot depending of the characteristics of the DWDS. There is also an aspect that even though the PDD is more mathematical correct, it requires valid assumptions, for instance the relation between pressure and outflow, to be accurate.

## 5.6 Assumptions and limitations of the method

During the work with this thesis a number of assumptions and limitations has been made. The most important assumptions and limitations and there influence on the results are discussed in the following sections.

### 5.6.1 Indices coming from demand

To estimate the number of affected users, an assumption that every user is using the same amount of water is made. This assumption is probably a good estimation when it comes to a model with high proportion of households. If a user, as for instance an industry, is using more water than an average household it would be valued higher than a household. A better but more complex estimation would have been to link the number of users to every node and thereby count the number of affected users. Industries, schools etc would as well be linked to nodes and valued compared the households. A valuation linked to the demand will be showing the same results as in this thesis, but since mentioned in section 4.1.4 it could be wrong to prioritise activities over households there are other ways to value these type of businesses and institutions compared to the households. However, the valuable user index is introduced to pinpoint the activities with a highly prioritised water demand.

### 5.6.2 Time scenario

During simulation every pipe in the system has been closed for a period of 24 hours since it would include a majority of the repair times of a pipe break. As presented in the section 4.6 three patterns are identified.

First pattern mentioned is a single fed pipe which has constant criticality. The chosen time scenario would thereby not affect the criticality indices on these types of pipes.

Second pattern that is presented is from pipes in circular fed part of the model. The criticality of these pipes varies over time depending on the demand pattern of the supplied nodes. When the simulation period starts and how long it proceeds would affect the criticality indices. As mentioned in chapter 4.6 the affected user index for the exemplified pipe differ between 0 to 40 % depending on the time. A short testing scenario during demand peaks will give a distinct higher criticality compared to a test during a longer time span.

Third types of pipes are in a branching system with a tank. These pipes criticality has two levels, one during the time the tank is able to supply the system and one after the tank is emptied. The time it takes to empty the tank would differ depending on how much of the system that is separated from the pump as well as the water volume in the tank. The choice of time scenario would have an effect on the criticality since the longer time period, the higher criticality index.

As discussed above the choice of time scenario would affect the criticality indices of the different types of pipes in different ways. How much the influence will be depends on the specific circumstances of a system. However, since the choice of time scenario will have an influence there is favorable to choose testing period depending on what type of criticality that would be tested. If it is criticality linked to pipe breaks, time period preferable should be coming from interruption times during pipe breaks.

### 5.6.3 Validity of the model

Since a hypothetical model is used there has been no need of calibration of the model. However, there are things to discuss of the validation of these types of models. Since pipes are closed in this methodology and different flow patterns will occur, the models would need to be well calibrated. In a grid system, closed pipes will lead to increased flows in other pipes, and increased flows in a pipe would require a more accurate diameter and roughness to stay in the same margin of error. It is thereby of importance to have a well calibrated model while investigating the criticality of the pipes.

### 5.6.4 Limitations

As presented in the limitations the thesis no probability of pipe errors are taken into account, but only looking for the consequences. To deeper analyse the most critical pipe a risk based approach would probably be preferable. Risk is often defined as the probability times the consequence. Thereby would a probability distribution of pipes interruptions complete the consequence to a deeper analysis of pipes criticality.

Care-W (Eisenbeis et al., 2002) is one example where the risk based approach has been used to identify critical pipes and by extension a rehabilitation program. As discussed in the earlier section 5.3.5, probability would also help to decide how many pipe failures that can occur at the same time and also how the consequences during multiple pipe failures should be compared to the consequences during single failure.

Qualitative aspects, aesthetic or health related aspects, are not taken into consideration when determine the criticality even though there are some including qualitative aspects into reliability definition (Gheisi and Naser, 2015b). There are however qualitative aspects that could be initiated by changed flow patterns in the system such as discoloring.

# 6

# Conclusion and further research

## 6.1 Conclusions

The conclusions of this thesis can be itemised into the points below.

To better identify critical pipes the reliability requirements of a DWDS could be further evolved. The consequences of a pipe breakage can be measured in different ways, but in the end it will be a question of valuation between different consequences. This valuation would be given more substance if there are goals and requirements regarding reliability.

When determine the criticality of the pipes in the system, one key aspect is how pipes with different patterns should be compared between each other. Especially pipes in circular fed parts of the system, where the criticality can vary over time, are complicated to determine criticality of.

Pressure driven and demand driven approach gave the same results for the majority of the pipes. Only one major difference of gathered criticality index could be seen, depending on the difference of the effect on the valuable user.

A risk based approach including the probability would give a deeper analysis of the criticality. Even though it is assumed that the probability of a pipe failure will be equal for all the pipes, probabilities of two or more pipe failures simultaneously will be needed to improve the strength of the analysis.

## 6.2 Further research

During this thesis work has a few areas, where there is room for further research, been identified.

First area to further investigate is how to evaluate different types of demand shortage as for instance, how should many affected users in a short time be compared to few affected users in a longer period of time. In section 2.4 it is argued that water shortage for 10 % of the users during 100 % of the time would be less critical than 100 % of the users during 10 % of the time. This statement could be investigated further and there are also gray areas in between these two scenarios that could better be evaluated. How should a criticality that varies over time be compared to a constant one?

Another area to investigate is probabilities linked to pipe failures. What is the probability of more than one pipe failure at the same time? This research would test and evaluate the influence of the assumption made in this report and several other studies (see section 2.2.2) that only one pipe can fail at a time. If using an assumption with two or more simultaneous pipe breaks the probability would also help to value the consequences during scenario with one pipe break against scenarios with two or more pipe breaks.

A third area is to implement this methodology on more DWDSs and real drinking water distribution systems. More and bigger systems will give further understanding about the methodology´s deficits and benefits.

# 7

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# A

# Appendix 1

**Table A.1:** Criticality indices with Demand driven modelling

| Pipe | Demand | Affected users | Time | Valuable user | Criticality |
|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 |
| 10 | 0 | 0 | 0 | 0 | 0 |
| 11 | 0 | 0 | 0 | 0 | 0 |
| 12 | 0 | 0 | 0 | 0 | 0 |
| 13 | 0 | 0 | 0 | 0 | 0 |
| 14 | 0 | 0 | 0 | 0 | 0 |
| 15 | 0,016474 | 0,016474 | 0 | 0 | 0,0082372 |
| 16 | 0,032949 | 0,032949 | 0 | 0 | 0,0164745 |
| 17 | 0 | 0 | 0 | 0 | 0 |
| 18 | 0 | 0 | 0 | 0 | 0 |
| 19 | 0,041186 | 0,041186 | 0 | 0 | 0,0205931 |
| 20 | 0 | 0 | 0 | 0 | 0 |
| 21 | 0,065898 | 0,065898 | 0 | 0 | 0,0329489 |
| 22 | 0 | 0 | 0 | 0 | 0 |
| 23 | 0 | 0 | 0 | 0 | 0 |
| 24 | 0 | 0 | 0 | 0 | 0 |
| 25 | 0 | 0 | 0 | 0 | 0 |
| 26 | 0 | 0 | 0 | 0 | 0 |
| 27 | 0,009061 | 0,009061 | 0 | 0 | 0,0045305 |
| 28 | 0 | 0 | 0 | 0 | 0 |
| 29 | 0 | 0 | 0 | 0 | 0 |
| 30 | 0 | 0 | 0 | 0 | 0 |
| 31 | 0,016474 | 0,016474 | 0 | 0 | 0,0082372 |
| 32 | 0,199341 | 0,199341 | 0 | 0 | 0,0996705 |
| 33 | 0,314662 | 0,314662 | 1 | 0 | 0,4073312 |
| 34 | 0,314662 | 0,314662 | 1 | 0 | 0,4073312 |
| 35 | 0,314662 | 0,314662 | 1 | 0 | 0,4073312 |
| 36 | 0,314662 | 0,314662 | 1 | 0 | 0,4073312 |
| 37 | 0,082372 | 0,082372 | 0 | 0 | 0,0411862 |
| 38 | 0,08402 | 0,08402 | 0 | 0 | 0,0420099 |
| 39 | 0,041186 | 0,041186 | 0 | 0 | 0,0205931 |

**Table A.2:** Criticality indices with Demand driven modelling

| Pipe | Demand | Affected users | Time | Valuable user | Criticality |
|---|---|---|---|---|---|
| 40 | 0,057661 | 0,057661 | 0 | 0 | 0,0288303 |
| 41 | 0,745951 | 1 | 0,583333 | 1 | 0,832321 |
| 42 | 0,669198 | 0,942339 | 0,583333 | 1 | 0,7987176 |
| 43 | 0,669198 | 0,942339 | 0,583333 | 1 | 0,7987176 |
| 44 | 0,669198 | 0,942339 | 0,583333 | 1 | 0,7987176 |
| 45 | 0,304213 | 0,884679 | 0,25 | 1 | 0,609723 |
| 46 | 0,304213 | 0,884679 | 0,25 | 1 | 0,609723 |
| 47 | 0 | 0 | 0 | 0 | 0 |
| 48 | 0 | 0 | 0 | 0 | 0 |
| 49 | 0 | 0 | 0 | 0 | 0 |
| 50 | 0 | 0 | 0 | 0 | 0 |
| 51 | 0,032949 | 0,032949 | 0 | 1 | 0,2664745 |
| 52 | 0,041186 | 0,041186 | 0 | 1 | 0,2705931 |
| 53 | 0,016474 | 0,016474 | 0 | 0 | 0,0082372 |
| 54 | 0,024712 | 0,024712 | 0 | 0 | 0,0123559 |
| 55 | 0,207211 | 0,475288 | 0,291667 | 1 | 0,4935416 |
| 56 | 0,009885 | 0,009885 | 0 | 0 | 0,0049423 |
| 57 | 0,16541 | 0,425041 | 0,291667 | 1 | 0,4705294 |
| 58 | 0 | 0 | 0 | 0 | 0 |
| 59 | 0 | 0 | 0 | 0 | 0 |

**Table A.3:** Criticality indices with Pressure driven demand modelling

| Pipe | Demand | Affected users | Time | Valuable user | Criticality |
|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 |
| 10 | 0 | 0 | 0 | 0 | 0 |
| 11 | 0 | 0 | 0 | 0 | 0 |
| 12 | 0 | 0 | 0 | 0 | 0 |
| 13 | 0 | 0 | 0 | 0 | 0 |
| 14 | 0 | 0 | 0 | 0 | 0 |
| 15 | 0,016474 | 0,016474 | 0 | 0 | 0,008237 |
| 16 | 0,032949 | 0,032949 | 0 | 0 | 0,016474 |
| 17 | 0 | 0 | 0 | 0 | 0 |
| 18 | 0 | 0 | 0 | 0 | 0 |
| 19 | 0,041186 | 0,041186 | 0 | 0 | 0,020593 |
| 20 | 0 | 0 | 0 | 0 | 0 |
| 21 | 0,065898 | 0,065898 | 0 | 0 | 0,032949 |
| 22 | 0 | 0 | 0 | 0 | 0 |
| 23 | 0 | 0 | 0 | 0 | 0 |
| 24 | 0 | 0 | 0 | 0 | 0 |
| 25 | 0 | 0 | 0 | 0 | 0 |
| 26 | 0 | 0 | 0 | 0 | 0 |
| 27 | 0,009061 | 0,009061 | 0 | 0 | 0,00453 |
| 28 | 0 | 0 | 0 | 0 | 0 |
| 29 | 0 | 0 | 0 | 0 | 0 |
| 30 | 0 | 0 | 0 | 0 | 0 |
| 31 | 0,016474 | 0,016474 | 0 | 0 | 0,008237 |
| 32 | 0,199341 | 0,199341 | 0 | 0 | 0,099671 |
| 33 | 0,314662 | 0,314662 | 1 | 0 | 0,407331 |
| 34 | 0,314662 | 0,314662 | 1 | 0 | 0,407331 |
| 35 | 0,314662 | 0,314662 | 1 | 0 | 0,407331 |
| 36 | 0,314662 | 0,314662 | 1 | 0 | 0,407331 |
| 37 | 0,082372 | 0,082372 | 0 | 0 | 0,041186 |
| 38 | 0,08402 | 0,08402 | 0 | 0 | 0,04201 |
| 39 | 0,041186 | 0,041186 | 0 | 0 | 0,020593 |

**Table A.4:** Criticality indices with Pressure driven demand modelling

| Pipe | Demand | Affected users | Time | Valuable user | Criticality |
|---|---|---|---|---|---|
| 40 | 0,057661 | 0,057661 | 0 | 0 | 0,02883 |
| 41 | 0,691816 | 1 | 0,583333 | 1 | 0,818787 |
| 42 | 0,651925 | 0,942339 | 0,583333 | 1 | 0,7944 |
| 43 | 0,669198 | 0,942339 | 0,583333 | 1 | 0,798718 |
| 44 | 0,669198 | 0,942339 | 0,583333 | 1 | 0,798718 |
| 45 | 0,230262 | 0,864086 | 0,208333 | 1 | 0,57567 |
| 46 | 0,230265 | 0,864086 | 0,208333 | 1 | 0,575671 |
| 47 | 0 | 0 | 0 | 0 | 0 |
| 48 | 0 | 0 | 0 | 0 | 0 |
| 49 | 0 | 0 | 0 | 0 | 0 |
| 50 | 0 | 0 | 0 | 0 | 0 |
| 51 | 0,032949 | 0,032949 | 0 | 1 | 0,266474 |
| 52 | 0,041186 | 0,041186 | 0 | 1 | 0,270593 |
| 53 | 0,016474 | 0,016474 | 0 | 0 | 0,008237 |
| 54 | 0,024712 | 0,024712 | 0 | 0 | 0,012356 |
| 55 | 0,040992 | 0,434102 | 0,291667 | 1 | 0,44169 |
| 56 | 0,009885 | 0,009885 | 0 | 0 | 0,004942 |
| 57 | 0,021916 | 0,315486 | 0,166667 | 0 | 0,126017 |
| 58 | 0 | 0 | 0 | 0 | 0 |
| 59 | 0 | 0 | 0 | 0 | 0 |

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