6.1 Introduction

Drinking water networks are designed to maximize the continuity of supply. This means that not only in the situation that all systems are operable the supply is guaranteed, but also if a foreseeable number of elements of the system fail. This can be for instance the failure of a pipe because of a burst, power failure causing pumps to stop, etcetera.

To ensure the continuity of supply water companies traditionally built in redundant elements in their system. For example a careful selection of sources, preferably as much protected as possible, storage facilities, technical lay out of pumping stations and treatment plants in separate parts, emergency power systems, water quality monitoring, alarm installations, etcetera.

Also networks are designed to function as long as possible, even during failures of part of the system. Main characteristic of networks is for that reason a looped structure. Figure 6.1 shows a typical drinking water network with a looped structure. Note that also semi directional pipes are present.

Fig. 6.1 - Typical drinking water network

If one of the pipes in between valves fails in the looped system, the supply to the other consumers stays intact. The supply ‘comes from the other side’ after isolation of the failed pipe. Also if the pumping station partly fails, supply is maintained through the next set of pumps.

Generally spoken the failure of one element of the system should not be any problem for the water company to continue supply on an acceptable level. Question is however what ‘one element’ is and what the acceptable level is.

Within the Netherlands drinking water companies a definition and a guideline for reliability of the drinking water supply is developed, which is incorporated in the Water Act of 2001.

6.2 Quantifying the reliability of a drinking water supply system

Basic function of a drinking water supply system is to satisfy the demand of customers in an area. The first requirement is that there is enough drinking water available to satisfy this demand. Following requirement is an adequate infrastructure (pumps and pipes) to transport and distribute the water. If these requirements are fulfilled customers get their demand supplied in the normal situation being that all systems are available and working properly.

Under normal operation conditions however elements of the system will be put out of service. This can be voluntary and planned for instance for maintenance or inspection reasons. Also involuntarily and unplanned elements must be taken out of service as a result of failure. Examples are power failure for the pumps or pipe breakage.

The reliability of a system is defined as the extent to which the supply system is capable of supplying the demands in a period of time given the probability of failure of elements and the effects of these failures. For failure of one element of the system the reliability can be calculated with the following formula:

$$R = \left[1 - \frac{POF * POS * ND}{OD}\right] * 100\%$$

with:

R : Reliability of the system in %
POF : Probability Of Failure per time unit
POS : Period Out of Service in time unit
ND : Not satisfied Demand in m3 per time unit
OD : Original Demand in m3 per time unit

Failure of elements can have several effects. For instance failure of one pipe in a looped system will only have limited effects, because the rest of the loop will supply water. If for instance the effect of the failure is that 20% of the demand is not satisfied, the probability of failure is once per annum and the time of failure is two days, the reliability of the system for this failure is:

$$R = \left[1 - \frac{1/365*2*0,2*OD}{OD}\right]*100\% = 99,8904\%$$

Power failure at the pumping station however can have a more dramatic effect, because the feeding of the network will stop and none of the demands is satisfied. If this happens once a week (52 times per year) and lasts for 6 hours (13 days per year) then reliability is:

$$R = \left[1 - \frac{52/365*13*OD}{OD}\right]*100\% = 85,2055\%$$

To quantify the reliability of the complete supply system, every element has to be analysed on its effect on the original demand. Moreover data should be available on the probability of failure and the period of failure.

In practise the weak point of the reliability analysis is the availability or the absence of good quality data on failures. Also the influence of these data can be enormous. If for instance the power failure in the above mentioned example only occurs once a year instead of once a week, the reliability will increase to

$$R = \left[1 - \frac{1/365*0,25*OD}{OD}\right]*100\% = 99,9315\%$$

Question however is which will have a larger effect on customers: a 6 hour non compliance during night hours on a large area or a 2 days non compliance on a smaller area. Second question that comes to mind is how to improve the reliability of the system. This can be done by decreasing the probability of failure or by limiting the period of failure through timely repair. Also the effect of the failure can be controlled.

The Dutch water companies developed an approach to the reliability of the drinking water supply system based on the serviceability to the customers. This approach is focussed on the limitation of the effect of failure on the original demand rather than on the probability or period of failure. Underlying philosophy is that a large impact on a large number of customers should be prevented at all times. A large calamity lasting only a short time has an uncontrollable effect on the image of the drinking water supply.

In the following paragraphs the Dutch Approach will be explained

6.3 Definitions and starting points.

Terms used within the subject of reliability should be well defined to be able to set up an analysis method and a quantitative guideline. The following definitions are developed and consequently used within the Dutch drinking water industry.

Drinking water supply system
The complete system that serves the drinking water supply, starting at the raw water source up to and including the customers tap.

Failure
Breakdown of an element of the drinking water system that can be fixed within 24 hour or has only local effects on a limited number of connections.

Calamity
Breakdown of an element of the drinking water system that cannot be fixed within 24 hours and has an effect on a larger group of connections.

Disaster
Multiple calamities.

The quantative guideline for reliability uses the following starting points

- Failures and calamities belong to the normal operation of a water company and it should be prepared to cope with it in advance;
- The drinking water system should be laid out in such a way that failures and calamities don’t disrupt the supply considerably;
- Effects of disasters can be so divers that a water company cannot be expected to be prepared in advance;
- During disasters water companies act following best practise in close co-operation with the Heath Inspectorate.

6.4 Quantative guideline for reliability

Consequence of the first starting point is that every element of a drinking water system can and will fail at one time. The second starting point states that even in case of failure or calamity the drinking water supply should be maintained at a certain level. A quantative guideline is aiming at defining this ‘certain level’.

Within the Dutch Water Act the following definition is used:

> In case of failure of one element of the drinking water supply system the remaining supply capacity in centres of demand should be at least 75% of the maximum daily demand.

The terms of this definition are explained as follows:

Failure of one element

The guideline is aimed at calamities: failure of elements that cannot be fixed within 24 hours. An element is a part of the drinking water supply system that can be isolated. This is for instance a pipe segment between valves or an element of a treatment plant that can be shortcut or completely isolated.

Centres of demand

The centre of demand is the description of the term ‘larger group of connections’ as used in the definition of a calamity. A centre of demand is a clusters of connections of which the demand equals 2000 house connections.

Remaining supply capacity

The remaining supply capacity is the amount of water that can be supplied in the most severe affected centre of demand.

75% of the maximum daily demand

In a centre of demand 75% of the maximum daily demand should be supplied. This means that during peak hours the supply can be less than 75% of the hourly demand while during lower demand hours more than 75% of that hourly demand is supplied.

This remaining supply capacity is determined using a technique called pressure dependant demand.

6.5 Pressure dependant demand

The quantative guideline for reliability aims at determining the remaining supply capacity under calamity circumstances. One of the essentials for doing this is the pressure dependant demand. Figure 6.1 gives the principle of this pressure dependant demand.

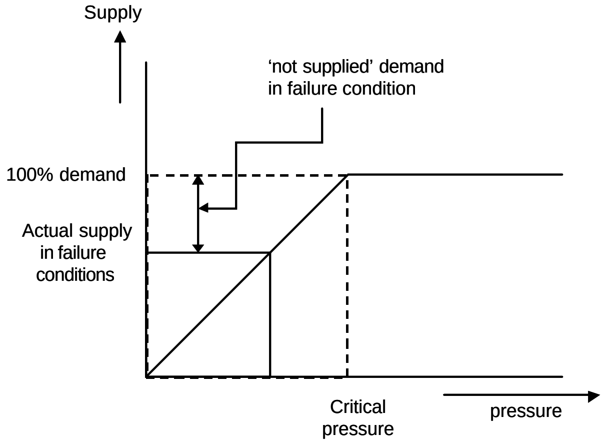

Figure 6.2 - Pressure dependant demand

The assumption is that the demand is independent from pressure if this pressure is above a certain critical threshold; usually this is set at 200 kPa. If pressure drops below this level, than the demand will drop as well. The reasoning behind this is based on the level of tapping points. Tapping points above the second floor level will not be reached anymore and the possible demand at those points will not be satisfied.

The relation describing the pressure dependency is set as a linear one. This is not the real situation, but is sufficient for the analysis we want to do. Future research will give more insight in the actual dependency.

The method of pressure dependant demand is preferred above the situation that negative pressures can occur in the network.

In figure 6.3 a simple network and the pressure line in the network is given.

The network consists of 8 pipes, joined at four nodes.

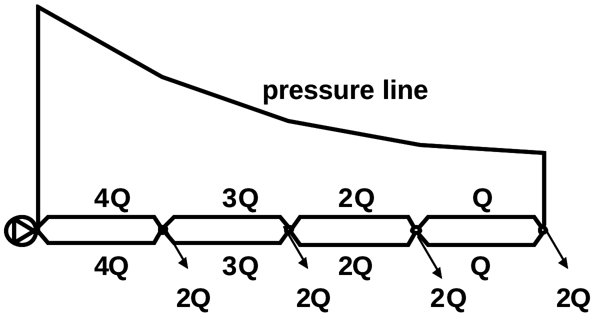

Figure 6.3 - Simple network with four identical loops and resulting pressure line

The pipes between the nodes are parallel and all have the same characteristics. At each node the demand is 2Q. In the original situation the pressure at the end node is the critical pressure, so all demand in satisfied.

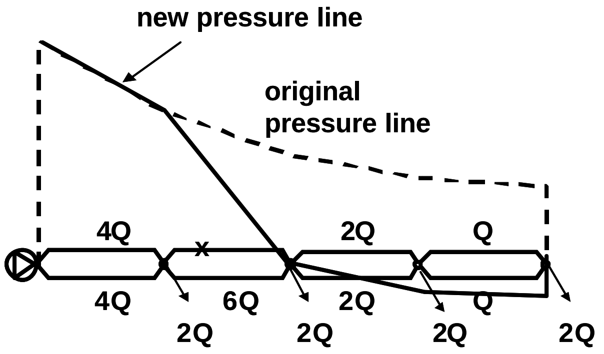

Figure 6.4 - Simple network with one loop faling

In the situation one pipe of the second loop is broken and isolated for repair. In that situation the total volume flow of 6Q is transported through one pipe resulting in a four times higher pressure loss over that loop/section.
Pressure drops for the following nodes below zero. This is a situation that is not realistic, because at negative pressure no water can be supplied.

In this way an impression of the affected area is obtained, but the impression is too pessimistic. In reality the absolute pressure in the pipes will be above atmospheric and the actual amount of supplied water will be less than demanded, because the higher tap points will not be used and due to the lesser pressure, the flow out of the tap points will be restricted.

A more realistic situation is calculated when the pressure dependant demand is applied. This will result in pressures above atmospheric but with less supply and for instance the situation of figure 6.5 will result

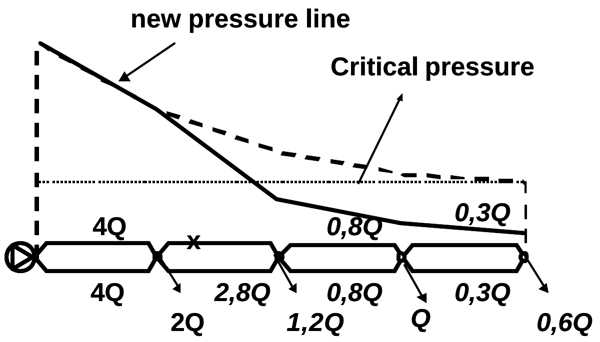

Figure 6.5 - Simple network, one loop failing, pressure dependant demand

In this picture the italic numbers are the new demands as a result of the pressure dependency. The pressure in the three nodes 'downstream' of the pipe failure is below the critical pressure and these nodes are actually affected. From the original 6Q that was demanded a 2,8Q is actually satisfied, meaning that 53% is not supplies, leaving a reliability of 47%.

6.6 Assessing the reliability of a drinking water system

The reliability of a drinking water system as meant in the guideline is not something that can be measured in practise. In case of a failure only the actual pressures and volume flows can be monitored and recorded, but not the pressures and volume flows that would have been if the failure did not occur.
This makes the analysis of reliability a verifying instrument rather than a design tool.
The methodology of the assessment of reliability is given in the flow chart of figure 6.6.

Before the analysis can start, a few steps have to be taken:
The first step that has to be made is the modelling of the complete drinking water system. The effects that will be considered will be on the level of centres of demand of 2000 connections or 5000 inhabitants. With an average demand of 150 l per person per day, the average daily demand of a centre of demand is 750 m3. With maximum day and maximum hour factors of 1,5 respectively 1,8 the maximum hourly demand is 84 m3/hour. With an average pressure slope of 0,01 and a λ factor of 0,02 this takes a 150 mm pipe. The hydraulic relevant pipes are in the order of magnitude of 100 mm. Basically this comes

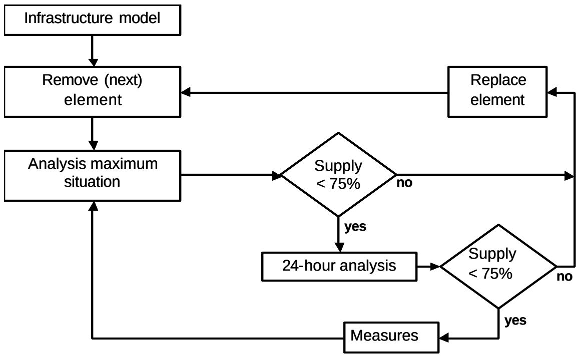

Figure 6.6 - Flow chart reliability assessment

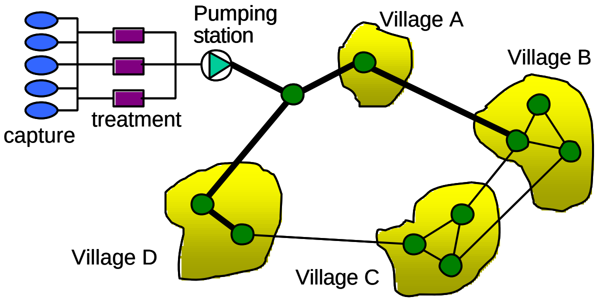

Figure 6.7 - Schematic of a drinking water supply system

down to an all pipe model

The second step is to identify the relevant calamities to consider. This first asks for a rough estimation of elements that, when failing, will have a considerable effect. Secondly the isolation possibilities must be analysed. This analysis results in a set of elements that are possibly critical. The criticality of these elements is tested systematically.

An example of a simplified model of a drinking water supply system is given in figure 6.7.

The system consists of a capture of for instance ground water with five abstraction points. A treatment has 3 isolatable parts and the pumping station is one pump cellar, meaning that failure of the pumping station will result in isolation of the entire storage. The network is divided in a number of centres of demand and connecting pipes. Recognisable is the looped structure, but also that the pipes in the periphery are smaller giving an 'unbalanced' ring.

Following the flow chart an element is taken out, e.g. the pipe to Village D. Using the pressure dependant demand the supply in the most critical point is as shown in figure 6.8.

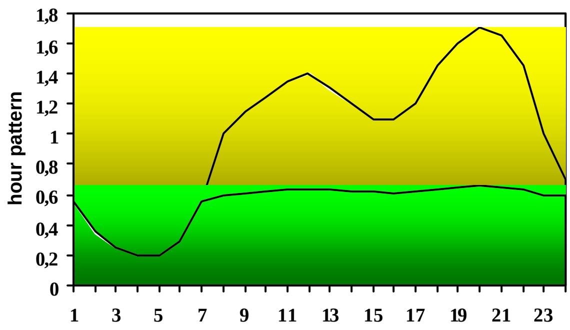

Figure 6.8 - Demand and supply in village D

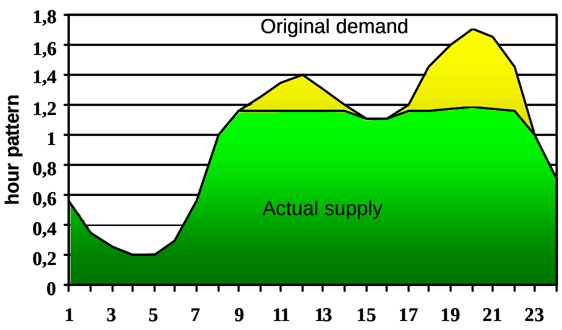

Figure 6.9 - Demand and supply in village D after connection to adjacent area/pumping stations

In this picture the effect of the pressure dependant demand is clearly shown: during the day hours the supply doesn't come above a certain level. The 'missed' supply is larger than the required 75%, so measures are necessary. In this case a connection of village C to an adjacent system is performed, because this will serve other calamities as well. This results in a demand and supply pattern as shown in figure 6.9.

It is clear that village D still is affected by the failure of the transportation line, but that according to the standard the effect is acceptable.

As can be seen in the picture the pumping station itself and the connecting pipe to the main loop in the system are most critical. If they fail, the whole system will collapse. This is why the connection to the other system is chosen as a remedy for the failure of the transportation line.

6.7 Use of the Reliability assessment

The method for assessing the reliability according to the guideline for quantative reliability is an evaluation tool. It makes clear what the weak points are in the system. During normal operation these weak points will not show, but in failure situations the criticality of these points are evident.

To improve the critical points a few strategies can be developed. First the vulnerability of the critical element can be limited. For instance by inspecting the critical element on a regular base. One example of this is the regular visual inspection of large transportation lines with helicopters. There are only a few very large pipes and failure of them is very crucial. This will identify activity around the pipe (build up of ram installation or other drilling activity) and prevent damage to the pipe.

Another strategy is to limit the time needed for repair of the element. For instance through stand-by contracts with building companies or by storing (emergency) repair elements. Limiting the effect is also possible with more isolation possibilities. One can imagine that more connections between parallel pipes (more loops) with adequate valves will limit the effect of failure.

6.8 Designing a reliable network

Reliability assessment as described in the previous paragraphs is an evaluation and optimisation tool. In industrialised countries where the primary requirements for a drinking water supply system are fulfilled (enough production capacity for clean water and enough transport and distribution infrastructure) this is a valid approach. In new situations the reliability has to be taken into account with the design of the network. Actually the approach isn't that much different. Instead of an actual network, the designed network can be optimised towards the reliability. In a few steps this can be demonstrated:

The first step in designing a network is to connect the (future) demand points to the network with sufficient diameter pipes. The cheapest way in doing so is to connect all demand points with as short lines as possible. An example of such an economic first design is given in fig 6.10.

When all elements of this network function well, water is supplied to all demand points sufficiently. Reliability analysis however is based on the assumption that every element of this system can and will fail and that in case of failure a level of service is maintained. In the network of figure 6.10 a failure of a pipe will cause the complete shut down of the system. For repair purposes the pipes should be empty or at least relieved from pressure.

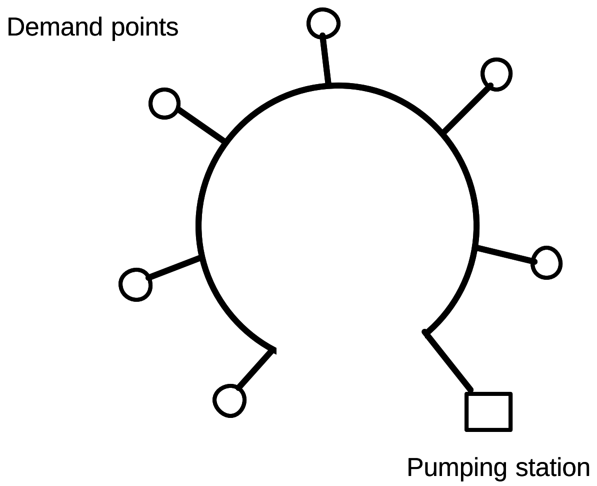

Figure 6.10 - Economic single design of a network

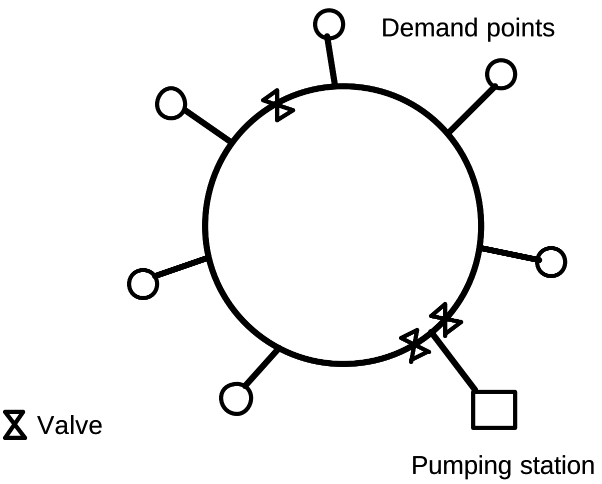

Figure 6.11 - First improvement towards reliability

A first improvement of the design of the system is to make a loop of the central supply route and to put in a few isolating valves. This enables the system to be shut down partly (see fig 6.11).

If for instance a failure occurs in the left side of the system, closing the top valve and the left valve at the pumping station can isolate this part. The right hand side of the system will still be operational.

A further enhancement of the reliability can be to install more isolating valves. Smaller parts of the system will be isolated, reducing the effect of failure of the main system (fig. 6.12)..

Ultimately, the system relies on one pumping station.

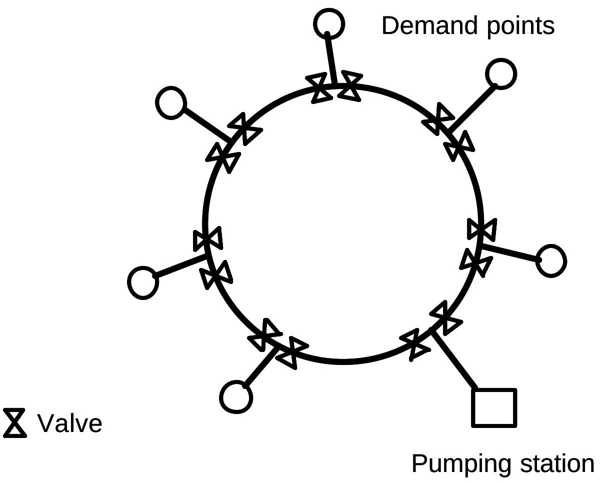

Figure 6.12 - More valves to enhance reliability and continuity of supply

If this station fails, or the connecting pipe for that matter, the total system will be down as well. Either segmenting the pumping station so it will always be partly available or otherwise by connecting the system to an alternative pumping station can solve this. A. schematic of this is given fig. 6.13. The alternative pumping station is not a dedicated station, but a station that serves another area. In case of failure of the original pumping station, the redundant capacity of the alternative pumping station will be applied to the original system. This will have also an effect of the service area of the alternative station. However this cannot be helped and the choice has to be made to either affect a large area, but maintaining some pressure and supply or to limit the effect to the original area with no supply and full supply to the alternative area: A perfect managers

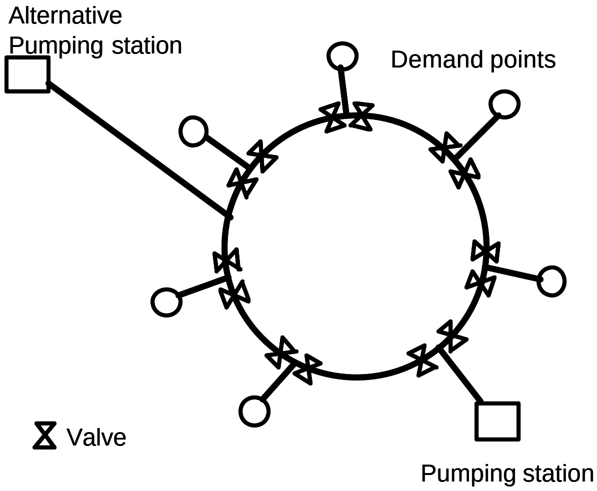

Fig. 6.13 - System interconnected to adjacent pumping station