8.1 Introduction

The design of distribution networks needs another approach than the design of transportation lines. While design of transportation lines is primarily aimed at meeting hydraulic boundaries, design of distribution networks has an extra dimension towards water quality, more specific towards discoloration (see also chapter 6).

Another factor that complicates the design of a distribution network is the estimation of the demand. The demand pattern of an individual house differs from the combined demand pattern of a cluster of houses. The demand pattern of a single house is ‘spiky’ and there is hardly any continuous flow. In a house with four occupants, the average daily demand would be typically 4 times 130 to 150 litre, being proximally 500 to 600 litres per day. This is typical for the Dutch situation. In other countries higher daily demands occur. In the USA this can be as high as 400 litre per person per day. The average demand in the Netherlands would be 25 litre/hour. However the actual momentary maximum demand is 1500 l/h as will be explained in paragraph 8.7.

In a cluster of 200 to 500 houses, the demand is much smoother over time and one can calculate with an average flow and factors for the maximum flow that are in the order of 2 to 3 times the average demand. This results in the typical dimensional demand pattern as shown in fig. 5.12.

In chapter 6 the influence of sediment on water quality is explained and the possibilities to control this influence. One of the steps is to prevent the sediment from settling and accumulating. If sediment doesn’t accumulate in the system, incidental resuspention cannot occur, so the problem of discoloration is limited. The ultimate solution to the accumulation problem is keeping the velocity high, so sediment will be held in suspention.

8.2 Demand in a distribution network and fire flow requirements

The most normative design criterion for distribution networks historically is the fire flow demand and not the actual drinking water demand. This fire flow demand is supplied through fire hydrants.

Fig. 8.1 - Fire hydrant

Historically a lot of water companies originate from municipalities. Fire fighting departments also originate from municipalities and in the Netherlands, as in almost all of the European countries, fire fighting still is a municipal responsibility. Combination of the fire flow requirements and the drinking water network is very obvious and probably the only viable way of supplying these large amounts of water. However this has an impact on the design of distribution systems and water quality. Although not uniformly defined the usual capacity of a fire hydrant is 30 to 60 m3/h and should be within 40 to 50 meter from every object. This results in fire hydrants every 80 to 100 meter in a distribution network. Looking at single-family houses with an average width of 4 to 5 meters, this means that for every 20 tot 25 houses a fire hydrant is needed. The maximum flow for 25 houses is 5 m3/h (see paragraph 8.7), while the needed fire flow is 30 to 60 m3/h. The fire flow requirement is dominant above the normal drinking water demand and exceeds it by a factor 6 to 12.

During the past 5 to 10 years the discussion has started to downsize the fire flow demands. Modern building and single-family homes comply with stricter fire codes than older building and the amount of water needed to perform a ‘first attack’ is less than the conventional demand of 60 m3/h. This makes it possible to downsize the network in such a way that the actual drinking water demand becomes dominant and new requirements can be set to design of distribution networks. This leads to a few steps to design a distribution network ultimately resulting in a ‘self-cleaning’ network. In fig 8.2 the principal difference between a conventional and a self-cleaning network is demonstrated.

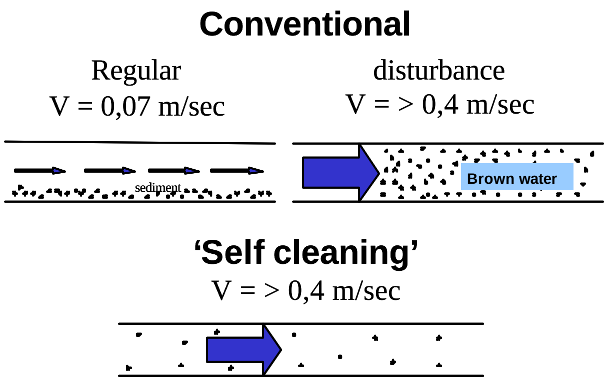

Fig. 8.2 - Conventional and self-cleaning network

In this chapter first the conventional way of designing distribution networks is demonstrated followed by the design of a modern type network.

8.3 Minimum pressure at supply point

The supply point is the 'end' of the distribution network as far as the water company is concerned. In the Netherlands the water meter is the last part of the connection. In unmetered situations the stopcock is the last part of the connection. Then the actual house installation starts and that is where the water is consumed. For calculation reasons the pressure at the actual supply point should be at least 200 kPa, when no water is abstracted from the installation. Reason behind this is that the pressure at the highest tap point is enough to overcome the hydraulic resistance of the house installation and the tap point itself. In a typical one family house the highest tap point would be at the attic, which will be 7 to 10 meters above street level. Effective static pressure at that point will be 130 to 100 kPa and this is enough to supply water through this tap point. At the outflow of the tap the pressure is atmospheric. The hydraulic resistance of the pipes and the tap itself consumes the pressure drop of 130 kPa.

The connection to the house installation is equipped with a water meter and a non-return valve (also called check valve). The reason for the water meter is obvious. The reason for the check valve is to prevent water that entered the house installation from re-entering the distribution network. Water that entered the house installation may be slightly contaminated in the system, for instance it will warmup, copper or lead can be dissolved from the plumbing system etc. Backflow can occur when for instance the pressure in the system drops and water from bathtubs or washing machines can flow back into the pipe system. A pressure drop can be caused by a failure of the pipes (leak or total break down) or for instance a large abstraction through a fire hydrant (see paragraph 8.2). The non-return valve will prevent this water from flowing back into the network.

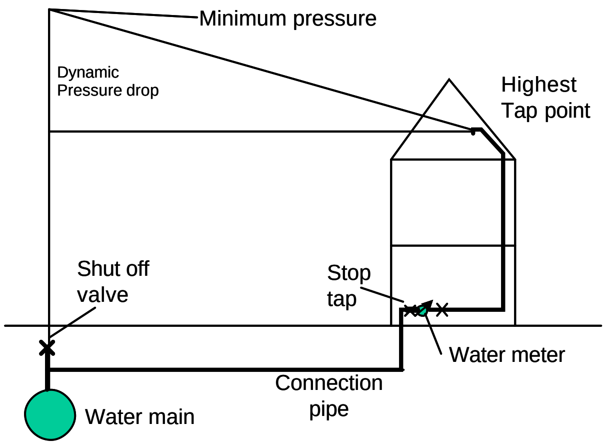

Fig. 8.3 - Schematic of a house installation

Figure 8.3 gives a schematic of a house installation.

8.4 Conventional distribution network

The structure and capacity of conventional distribution networks are determined in the Netherlands by conventional requirements for fire fighting water. The combination of drinking water supply and fire fighting, has resulted in conventional distribution networks largely consisting of pipes with diameters of 110 mm or more, arranged in a looped structure. These pipes meet the fire department's conventional requirements for fire fighting water of 60 m3/h for a hydrant, situated every 80 to 100 meters. An example of a conventional distribution network is shown in Figure 8.4.

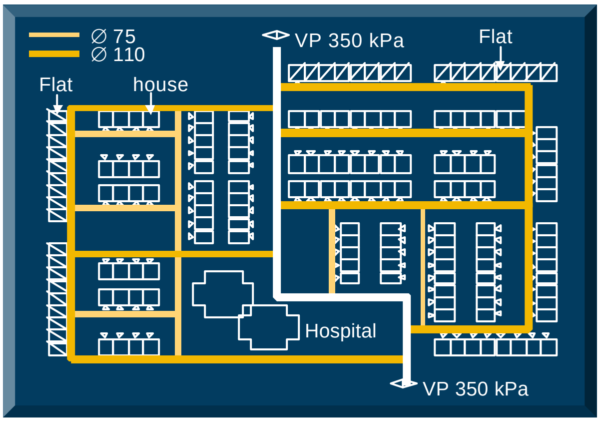

Fig. 8.4 - Conventional distribution network

In the network that serves a new building area loops can be recognized with a diameter of 110 mm. At several points the loops are closed with pipes with a diameter of 75 mm. On the 110 mm pipes the fire hydrants are located. The line connecting the two VP-points is part of the main structure of the overall network and closes the loop on a transport level.

The conventional requirement for fire fighting water is much higher than the normal requirement for drinking water resulting in the relative large pipes for the loops in the network. The large diameters result in low velocities and in high residence times in the pipes during normal drinking water supply. The distribution network's ring structure causes the water to flow in alternating directions. The low velocities combined with alternating flow directions result in sediment accumulation in the pipes. Occasional higher demand, causes sediment to be resuspended and carried along. Customers then experience discolored water. Customers describe the color in different shades with red, brown and black as dominant colors. Specific color problems as white or blue water refer mostly to other problems. White water may originate from supersaturated water. The color will disappear within seconds when the water is left in a glass or other container. If a white color doesn't disappear the origin might be calcium parts. Blue water typically indicates copper corrosion problems and mostly occurs within a house plumbing system. Under certain conditions, the long residence times can also result in deterioration in bacteriological conditions.

8.5 Valves, isolation and sections

If maintenance is necessary, parts of the networks should be isolated. For instance a house connection has to be renovated or bursts in mains must be repaired. When a burst occurs the part must be isolated to stop the water from leaking out of the system. In a looped system as a conventional distribution system, at least two valves are necessary to isolate a pipe: one at each end of the pipe. If at every pipe joint valves are installed so that isolation can be reached with two valves, this results in lots of valves.

In reality not so many valves will be installed, so isolation of a part of the network will always take more than two valves. Typically it takes 4 to 5 valves to shut down a section of 30 to 40 connections.

Also for practical reasons the number of connections in one section is limited. If a large number of connections is affected with a simple isolation, this will cause a lot of questions ‘at the trench’. If ‘low pressure’ or ‘no water’ is experienced and the water company is recognisable in the neighbourhood, for instance because of cars with logos, people tend to go and ask what is happening. A few questions can be handled during work, but too much will seriously influence the work.

A more technical reason is the recharging of the network. If the repair is done and the network is closed again, the pipes will be filled with water and the house installations also. Although every connection in the Netherlands is equipped with a non-return valve, theoretically preventing the house installation from emptying, they will be drained. Recharging compresses the air in the pipes, causing temporarily sound complaints. This inconvenience is preferably restrained to as little connections as possible. Apart from the inconvenience of air in the pipes, recharging takes time, prolonging the time connections are without water.

The most obvious reason to limit the number of connections in a section is the number of people affected during repair or other maintenance.

Typically an allowed number of connections in a section is between 20 and 120. The range in this number is a result of company policy, balancing the investment in valves and the practical implications in maintenance. Ironically the investment in the network has to be done at present, while the benefits in maintenance usually will be profited by the next generation. Repair and maintenance will increase only after 30 to 40 years when the network deteriorates or when the character of the buildings changes.

8.6 Modern distribution network

The research leading to the conclusions towards sediment in a network (see Chapter 7) is of recent date. The start was in the early nineties of last century and several years later resulted in the phased approach towards sediment control in a network. As discoloured water leads to complaints at the connections, the prevention of sediment accumulation in that area is most effective for curing the problem. Simply put keeping the water in motion is the best way to prevent accumulation, or at least accelerate the water on a regular base. This asks for smaller pipes than used up till than and a dedication to a

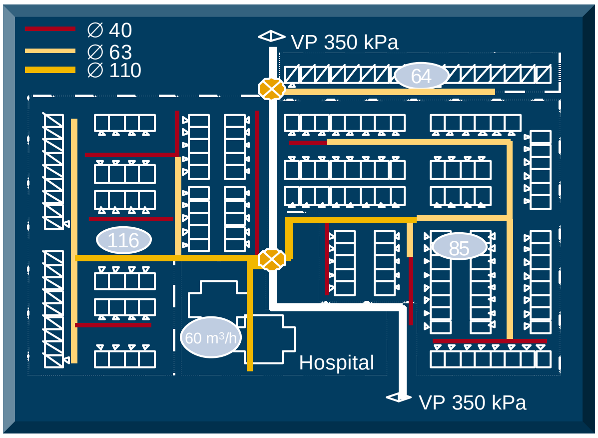

Fig. 8.5 - redesigned network

'drinking water only' concept in designing a network.

The basics of a modern distribution network are:

- o Meet the actual drinking water demand
- o Self cleaning velocities: 0,4 m/s regularly in the network
- o A unidirectional flow.

The main characteristics of a modern distribution network are a branched system with pipes with a relatively small diameter.

In the design process several steps can be recognized:

1. Determine drinking water demand
2. Arrange sections
3. Compose main structure
4. Design sections
   => check pressure drops
5. Fit in fire flows
   => check pressure drops.

The conventional network in figure 8.4 will result in a redesigned network as represented in figure 8.5

8.7 Determine actual drinking water demand

The demand pattern of one house is much more erratically than the demand pattern of 1000 houses. The pattern of one house will be a number of spikes over the day, while the demand pattern of a cluster of houses will have a much smoother pattern (see figure 8.1 and 5.12). The method to determine the maximum demand of a number of houses is based on the method used to determine the maximum demand for an in house installation. This is the so-called $q\sqrt{n}$ - method.

The maximum instantaneous demand of one house is determined with the $q\sqrt{n}$ - method:

$$q_{m.n} = 0{,}083\sqrt{n * TU_{house}} \text{ with}$$

$q_{m.n}$: Maximum instantaneous demand of n houses in l/s
n : Number of houses
TU_{ouse} : Number of tapping units house
0,083 : Capacity of 1 TU in l/s (300 l/h)

q√n-method

One of the effects of the fire fighting demand is that the normal drinking water demand is no real design criterion for the level of distribution networks: 'the pipe in the street'. The basic design criteria for a conventional network are more the connection between the fire hydrants and closing of the loops. The basic connection is a 100 (AC or CI internal diameter) or 110 mm (PVC, external diameter) pipe, sufficient for supply of 60 m3/hour through a hydrant.

With the modern design rules, the actual drinking water demand on a connection level is a relevant design criterion. The only estimation method available however for a 'design-demand' is the method used for the design of in house installation called the q√n-method. This method is based on the assumption that the simultaneous use of tap units is based on a square root function. The maximum simultaneous use of 4 tap units is 2, when 16 tap units are present maximal 4 of them will be used simultaneously, etcetera. The origin of the method is not traceable, but the method is widely accepted for the design of in house installations.

For the estimation of the design demand of sets of connections the method is upgraded to a number of houses. As the method is originally used for the estimation of the maximum demand with a certain safety factor, it is obvious that in reality the maximum demand will be over-estimated. In the evaluation of the new networks also the q√n-method will be evaluated and probably adjusted to get a more realistic and accurate method. For now the method is adequate for the design of modern distribution networks. New developments in both fire fighting demand and water consumption will lead to new estimation methods.

Table 8.1 - Typical house installation

Tap point per house	Number of TU
Toilet cistern tap 1	0.25
Toilet washbasin 1	0.25
Toilet cistern tap 2	0.25
Toilet washbasin 2	0.25
Kitchen sink	4
Dish washer	4
Bath/shower mixer tap	4
Washbasin mixer tap (bathroom)	1
Washbasin tap (bedroom)	4
Washing machine tap	4
Total per house	22

Every house installation will have a number of tapping points with a varying number of tapping units. A bath or shower mixer tap will have a different maximum flow as a toilet cistern tap. A toilet cistern tap for instance is equal to 0,25 TU, while a kitchen sink tap or a bath mixer tap will have 4 TU In table 8.1 a typical Dutch single-family home installation is given. This house has 10 tapping points with a total capacity of 22 tapping units.

The maximum flow for this house will be

$$q_{max} = 0{,}083\sqrt{1*22} = 0{,}389 \text{ l/s} = 1{,}4 \text{ m}^3\text{/h}$$

The maximum flow for a set of 9 of these houses will be

$$q_{max} = 0{,}083\sqrt{9*22} = 1{,}168 \text{ l/s} = 4{,}2 \text{ m}^3\text{/h}$$

and so on.

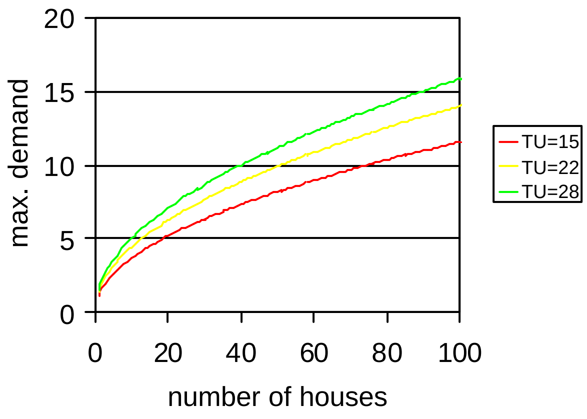

Fig. 8.6 - Maximum instantaneous demand for three types of dwelling

In figure 8.6 three maximum demand curves are given for several types of dwelling.
In the example now the demand per unit of houses can be determined by counting the number of houses and calculate the maximum instantaneous demand.

8.8 Compose main structure/divide into sections

Composing the main structure:

- ➢ Identify design boundaries:
  - o Identify location and pressure feeding points (usually larger transport lines)
  - o Identify demand points and concentrations
  - o Identify routes for pipe lines
- ➢ Compose demand clusters of 50 to 200 houses, identify special demand points (hospitals, shopping malls, schools, etc)
- ➢ Compose looped main structure (reliable feeding points)
- ➢ Determine connection points of the demand clusters to main transport structure.

Figure 8.7 is the result of these steps for the example network

The main transport structure of the network will be the feeding of the demand clusters. This main structure has to have certain reliability and will therefore be part of a looped system with sufficient valves (see also paragraph 8.8). In the example of fig 8.7 this is the connection between the points indicated as VP 350 kPa. These are points located in the main struc-

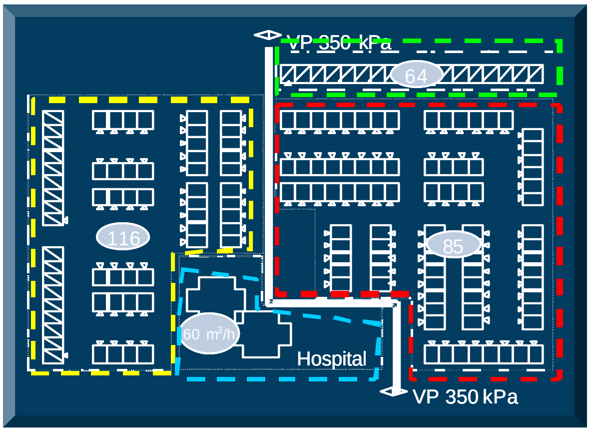

Fig. 8.7 - Redesign step 1

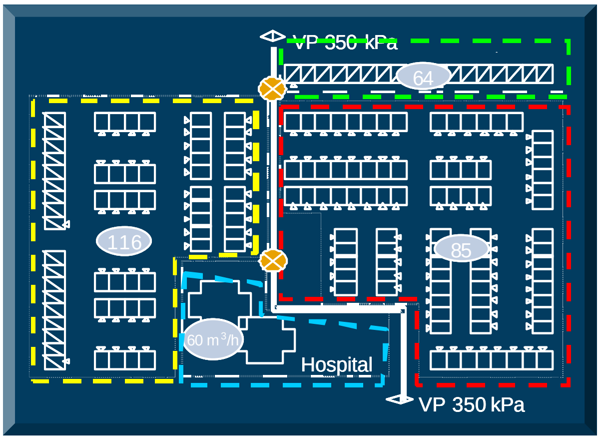

Fig. 8.8 - Section of demand points (redesign step 2)

ture with 350 kPa as minimum design pressure. The connecting line has also a transport function of the looped major system. Dimension of the pipe will be larger than 110 mm.
Onto this main structure the branched sections of houses will be connected. Normally the number of houses in a section that must be isolated in case of failure and/or repair will be limited to 50 to 200 connections. Looking at the sections that can be formed, there will be 3 large sections (fig 8.8) with 'normal' houses and one special section with a special flow requirement. In this case there is a special fire flow requirement because of a hospital.

These sections will be connected to the main structure at concentrated points indicated in figure 8.8. Reason behind this is that by concentrating the demand points on the main structure also in this structure the flow patterns will be unidirectional. Concentrating the demand points create a 'sink' in the system toward which the water will flow.

8.9 Design branched system

The pipes connecting the houses to the main structure are branched pipes with a diameter that will decrease downstream. The maximum flow in the pipes will be determined with the $q\sqrt{n}$ -method.
A table can be composed to determine the maximum number of houses that can be supplied with a range of diameters. The table is based on the assumption that the minimum velocity in the pipe is 0,4 m/s and the maximum velocity is 1,5 m/s.

$$n = \left(\frac{v \cdot \frac{1}{4} \cdot p \cdot D^2}{0{,}083 \cdot 10^{-3} \sqrt{TU_{house}}} \right)$$

with
v : velocity, 0,4 < v < 1,5 m/s
n : number of houses
D : Diameter pipe [m]
TU : Number of tap units

Based on 22 tap units per house the following table can be composed:

Diameter pipe	# houses (TU=22)
40	1
50	3
63	7
73	15
90	32
110	68

With this table the branched system or section can easily be composed and will give a picture like figure 8.9. Normally a diameter range of maximum 3 diameters will be used. More diameters will complicate maintenance and repair too much. If for instance the range 40-63-110 is chosen, the network will be like the network in figure 8.9. Other ranges could be 40-75-90, etcetera.

Result of this exercise is a network that complies with the boundaries for a drinking water network. The challenge to comply with fire fighting demand remains.

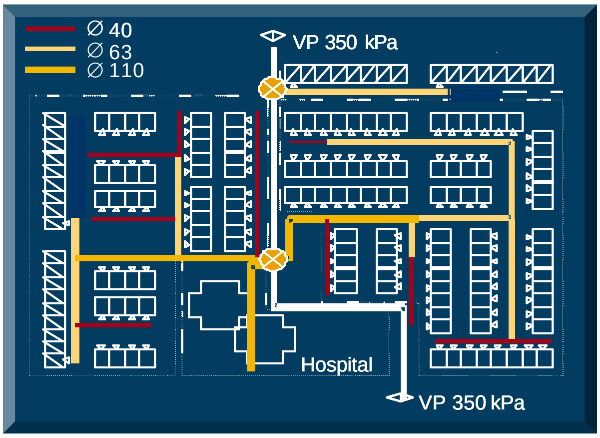

Fig. 8.9 - Branched network (redesign step 3)

8.10 Fitting the fire flow demand

The last step is to see how much fire flows can be delivered and how a network can be adjusted to accommodate the fire flows without compromising the initial boundaries. The first step is to consult the fire department on what fire flows are needed. One should bear in mind that modern houses are good equipped with fire suppressing details. A general understanding in the Netherlands is that 30 m3/h will be sufficient to cover the fire flow demand. This means that fire hydrants can be located on 63 mm pipes with a maximum length of 60 to 100 meter (12-20 mWC pressure loss). As the fire hydrant should be in the vicinity of 40 to 50 meters to any object, ‘covering circles’ with a diameter of 40 to 50 meter can be put on the network. This results in the ‘covering’ plot of the network according to figure 8.10. Obvious is that almost all the area is covered, besides a few corners.

To solve these problems the local circumstances must be examined. First step is to look for alternatives, not attached to the drinking water network. Although theoretically a number of alternatives can be mentioned, especially in the western part of the Netherlands where open surface water is in abundance, fire departments are very cautious in applying these alternatives. In the operational situation the firemen have to be able to act on routine and different situations will lead to misunderstandings.

Second step is to try to adjust the geometry of the network in such a way that routes of pipes are changed, but not the diameter. An example is in the left upper corner of the network and in the right upper corner in fig 8.11. The 63 mm pipe is prolonged so an extra hydrant can be placed in the blank area. Care must be taken towards the details of this prolonging: the connection to the building should be made after the fire hydrant and not before. If done before the pipe between the connection and the fire hydrant won’t have any supplying function and the water will be ‘dead’ with negative effects on the rest of the water. The right way of connecting is to extend the pipe even longer and feed back the pipe to the original connection point. In that way all the water passes the fire hydrant before entering the building.

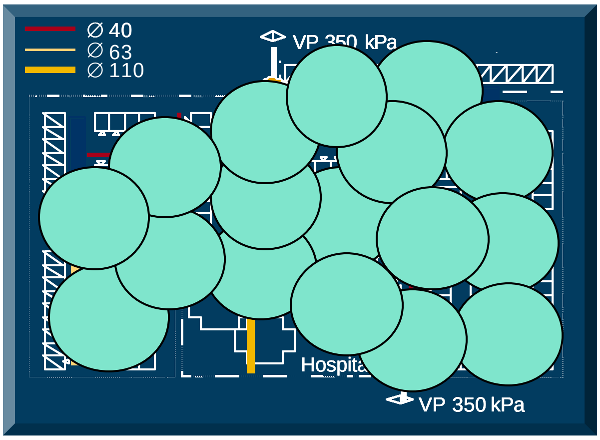

Fig. 8.10 - “Covering plot” of fire hydrants

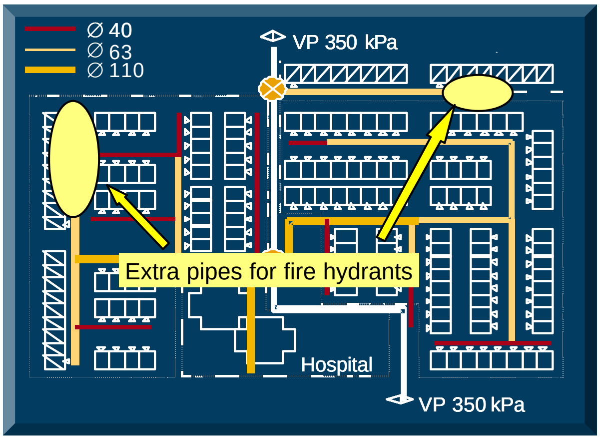

Fig. 8.11 - Adjustments to the network as a result of fire flow requirements (redesign step 4)

Final possibility is to enlarge the diameters of the pipes. This will have a negative effect on the water quality because the velocity now will be lower than desirable and maybe some regular cleaning actions are necessary.

When all the fire hydrants are located the pressure drop should be checked. During fire extinguishing the pressure in the network may drop below the minimum pressure of 200 kPa (See paragraph XX). The probability that the fire hydrant will be used is very low, less than once per twenty years. The risk introduced by lowering the pressure is back flow from the house installations with possible contaminations. The barrier for prevention of this happening is the check-valve in the house connection.

Requirement is that the fire fighters use flexible hoses from the hydrant on. (see fig 7.9).

Using the flexible hose will prevent the pressure to drop below the atmospheric pressure. If this is about to happen the hose will collapse and no water can be transported. Because of the hydraulic resistance in the hydrant itself, the pressure in the underlying pipe will always be above the atmospheric pressure.

8.11 Valves and reliability of shut down in a modern distribution network

As stated in paragraph 8.5, valves are mainly used to isolate sections in a network for any reason. In a modern distribution network, the sections are connected to the main structure with one pipe, which will have a valve. Closing this one valve is sufficient to shut down the section. This has the advantage that the time necessary for closing down is now limited to closing only one valve instead of for to five valves in a conventional system. The reliability of the closure itself is enlarged as well. Assume the reliability of a valve is 90%, meaning that 90% of all valve are actually working i.e. closing and shutting off the water flow. When 4 valves are used to isolate a section, the reliability of the closure is $0.9^4 = 0.656$. When only one valve is used to close down a section the reliability of closure is 90%.
To assess the reliability of closure the experimental valve cluster index is introduced. The valve cluster index (VCI) is defined as the number of pipes in a joint minus the number of valves in that joint. Figure 8.12 shows the implications of the definition.

The reliability of the closing of a joint is characterised with VCI. The closure is maximal if the VCI equals zero. Assume the reliability of a valve (actually closing) of x% and the probability of failure (100-x)/100%.
If the VCI equals zero in a joint with n legs and n valves the reliability of closure is

$$\text{Reliability of closure} = \frac{x}{100} + \left(1-\frac{100-x}{x}\right)\left(\frac{x}{100}\right)^{(n-1)}$$

If the VCI is more than zero (more legs than valves) the reliability of closure is limited to the x% of the single valve. If the valves fails, then adjacent joint have to be closed, leading to a less reliable closure which affects more connections.

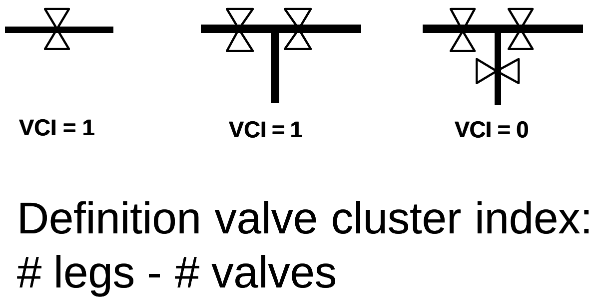

Figure 8.12 Definition of the Valve Cluster Index