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ScienceDirect

Procedia Engineering 89 (2014) 339 – 346

Procedia Engineering

www.elsevier.com/locate/procedia

16th Conference on Water Distribution System Analysis, WDSA 2014

Robustness of the Drinking Water Distribution Network Under Changing Future Demand

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Abstract

A methodology to determine the robustness of the drinking water distribution system is proposed. The performance of three networks under ten future demand scenarios was tested, using head loss and residence time as indicators. The scenarios consider technological and demographic changes. Daily patterns were simulated with SIMDEUM for each connection. The analysis showed three robust networks, which are able to cope with extreme scenarios, though different scenarios have different consequences on the performance of the networks. The consequences on the performance are a function of the size and layout of the network. Therefore, robustness analysis is network specific.

Peer-review under responsibility of the Organizing Committee of WDSA 2014

Keywords: Network modelling; scenario approach; drinking water distribution systems; future water demand; SIMDEUM.

1. Introduction

The drinking water distribution system (DWDS) is a critical urban infrastructure and is constructed to provide service for 50 years or more. In developed countries, most of the cities have an existing DWDS which has been designed and built decades ago, probably based on forecasted residential demands and firefighting demand. In the

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Peer-review under responsibility of the Organizing Committee of WDSA 2014
doi:10.1016/j.proeng.2014.11.197

coming decades, water use and users' routines are likely to change driven by complex changes in technology, infrastructure and regulations, as well as economic and societal trends [1]. As a result, changes in the drinking water demand and in the drinking water demand pattern, more specifically in the peak demand, can be expected [2]. Therefore, it is crucial to determine the robustness of the current DWDS to cope with this future demand and guarantee a reliable water supply under these changing conditions. Robustness is defined as the ability of a system to maintain its functionality over a large range of future conditions [3]. In this article, the functionality of the system was evaluated based on two main parameters: minimal pressure and water quality presented as water age.

2. Method

Determining future demand involves large uncertainties. In this study the scenario approach was used to deal with these uncertainties. Scenarios are not predictions or forecasts of the future, but a set of alternative views of how the future might unfold [3]. Water demand is determined by users and their routines as well as the type of the water appliances [4]. In this study, instead of trying to design with uncertain parameters, the robustness of the net was tested by analyzing changes in the performance under extreme loads. This study focused on the distribution pipes that supply the customers: the pipes in the streets. Transport mains were not included. The networks were tested considering changes in demand, reflecting different life styles and technological changes, and aging infrastructure. The purpose of the DWDS is to supply water of good quality at adequate pressure and ditto flow. Therefore, the functionality of the network is evaluated, based on two main criteria: pressure in combination with flow and water quality.

In the Netherlands the customer should receive water with a pressure of at least 150 kPa after the water meter at 1 m^3/h flow [5]. To determine the minimum pressure delivered to the customer, head losses in the DWDS were quantified. In this article, the maximum head losses (m) in the network are considered, assuming sufficient pressure in the transport network. The water quality in the DWDS was quantified using maximum residence time as surrogate variable. Residence time is an important aspect of water quality in a DWDS as it influences bacterial regrowth, corrosion, sedimentation and temperature. More specifically, the maximum water age (or residence time) is most important [6]. In this study, the 99th percentile of the residence time in the network was used to analyze the different scenarios.

2.1. Simulating drinking water demand

Ten diurnal patterns with a time interval of 5 minutes were simulated for each connection and for each scenario with SIMDEUM [4]. This means that a unique stochastic drinking water demand pattern is constructed for each demand node by summation of the individual household's drinking water demand patterns. SIMDEUM uses statistical information as well as information regarding end-uses, allowing the simulation of changes in technologies and in user behavior. For the current situation the input data were based on Blokker et al. [4], for the future scenarios the input data were based on Blokker et al. [2].

2.2. Scenario definition

First a baseline analysis was done to determine the current situation, based on data provided by the drinking water companies and statistical information of the areas. After that different demand scenarios were defined. The water demand prognosis for the Netherlands for 2025 was used [7]. Additionally, the four future scenarios for 2040 proposed by the planning agencies in the Netherlands for 2040: Regional Communities (RC), Strong Europe (SE), Global Economy (GE) and Transatlantic Markets (TM) were used as base scenarios [8]. The four scenarios emerge from variation along two axes; one is the extent to which the government stimulates free market forces, the other is the international orientation, or the extent to which the borders and economy are open for international influences. The implications of these scenarios in residential water use are described by Blokker et al. [2].

Additionally, five scenarios were defined during a workshop held with representatives of two Dutch water companies. The scenarios are a combination of different feasible factors based on the scenarios for 2040, or technological development combined with the current situation, for instance 100% of penetration of new technologies, such as vacuum toilets (1 L per flush), dual systems for non-potable demand, or luxurious high flow shower heads.

Not only technological changes influence drinking water demand. Therefore a scenario considering an increasing leakage rate due to aging of infrastructure (Leak) was analysed. The ten scenarios are briefly described in Table 1.

2.3. Networks description

Three existing networks in the Netherlands were selected, one branched design and two looped designs. The networks were simulated for a three day period, using EPANET software [9]. The characteristics of the networks are shown and described in Fig. 1 and Table 2. The demographic characteristics are described in Table 3.

Table 1. Description of the ten scenarios.

Scen.	Name	Characteristics
0	Now	Baseline: current situation
1	Pr.	Prognosis 2025
2	RC	Regional Communities: per capita demand declines because the economic downfall results in (water) saving behaviour, coupled with decreasing population. The average age of the population increases.
3	SE	Strong Europe: Despite low economic growth, mobility increases due to open borders. Personal hygiene habits have changed with an increase in shower frequency. Water pricing based on real cost drives alternative water resources to be adapted on a larger scale; e.g. rain water tanks for watering the garden.
4	TM	Transatlantic Market: Population growth causes increases in drinking water demand. Innovations aim at luxury and wellness products.
5	GE	Global Economy: Economic growth causes increases in consumption. Innovations are aimed at luxury and wellness, people shower longer and water their garden more frequently to diminish the effects of climate change.
6	Dual	Toilet, laundry machine and outside tap are not supplied by DWDS
7	Eco	Based on RC with innovative sanitation concepts. 100% adoption of 1 L flushing toilets
8	Lux	Luxury, based on current situation with 100% adoption of luxurious shower. Increase in the frequency of shower from
9	GE+	Based on “GE” but with a shower frequency of one shower per day.
10	Leak	Based on “Pr.” with leakage of 20%.

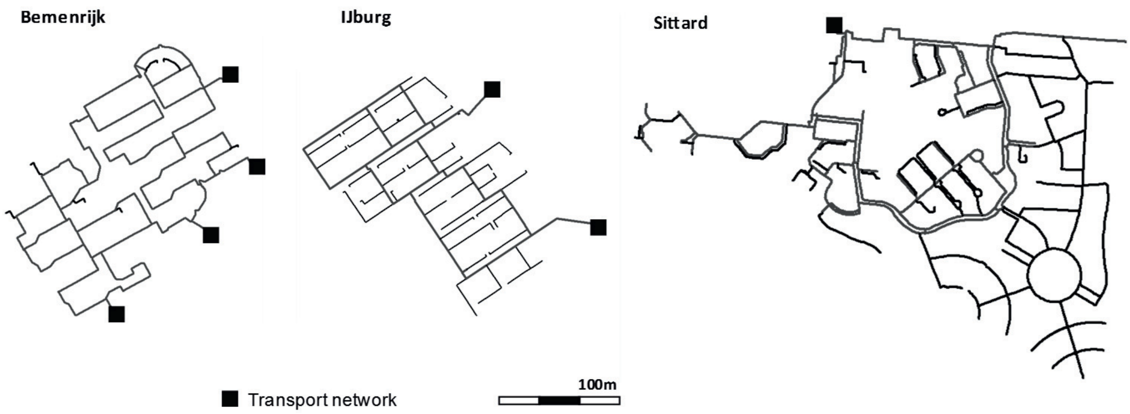

Fig. 1. Network layouts.

Table 2. Network characteristics.

Connections (Current situation)	Bemenrijk	IJburg	Sittard
Volume (m³)	682	334	1019
Length (Km)	107	39	111
Q mean (m³/h)	5	5	15
Mean Residence time (h) (present situation: scenario “Now”)	8.5	5	15
Number of loops*	12.6	7.8	7.4
Connections (Current situation)	14	5	48
Volume (m³)	682	334	1019

* Number of loops = Number of pipes – number of junctions + 1

Table 3 Input data for SIMDEUM based on CBS (2013) and (Blokker et al. 2010).

				One person households			**Two person households**			**Families with children (average)**		
				Bem.	**IJb.**	**Sit.**	**Bem.**	**IJb.**	**Sit.**	**Bem.**	**IJb.**	**Sit.**
Number of people per household				1			2			3.7	3.7	3.6
Number of households (%)				34	30	24	30	18	29	36	52	47
Gender division: Male / Female (%)							50 / 50			50 / 50		
Age division (%)	Children (0-12 years old)						0			25	46	31
	Teens (13 – 18 years old)						0			17	9	18
	Adults (19 – 64 years old)			70	92	82	70	92	82	50	44	51
		Subdivision: % of adults with out-of-home job	Both persons				49	49	49	39	39	39
			Only male adult	68			26			52		
			Only female adult	52			6			3		
			Neither person				18			5		
	Seniors (> 65 years old)			30	8	18	30	8	18	0		

3. Results and discussion

Based on demographic information Table 3 and information from the drinking water companies, the end use demand per capita is determined, Table 4. Additionally, the household size per scenario is also shown.

3.1. Peak demand and Head loss

Peak demands can be related to head losses in the net. Fig. 2a shows the peak demand versus the maximum head losses per scenario. The peak demand is the 90th percentile of the maximum demand of each of the ten scenarios. Although the scenarios are the same, the inherent variability of residential water use shows that the effect of the scenarios varies per network. The maximum head loss was 4 meters for Bemenrijk, ca. twice the current head loss. The maximum head loss was 1.1 m for IJburg and 0.95 m for Sittard. The most extreme scenarios, with highest head losses were “Lux” and “GE+”.

The scenario with smaller head losses was the “Dual”. Direct comparison of the networks is not possible due to the difference in size of the networks. To compare the networks, the peak demand was recalculated per capita and the head losses were recalculated per m³ of network – dividing the head losses by the volume of the network, Fig. 2b. The maximum head losses were from 2.8 cm per m³ network for IJburg, the smallest but branched network; 3.9 cm per m³ for Bemenrijk, a looped network, and 0.86 cm per m³ network for Sittard, the largest and looped network. Bemenrijk and Sittard showed a relationship between 90th percentile peak and head losses, this relationship is not found for IJburg.

Table 4 Daily average water consumption in liters per person per network and per scenario

	Bemenrijk			**IJburg**			**Sittard**			**General scenarios for the three networks**							
	Now	**Dual**	**Lux**	**Now**	**Dual**	**Lux**	**Now**	**Dual**	**Lux**	**Pr.**	**Eco**	**GE**	**GE+**	**RC**	**SE**	**TM**	**Leak**
Bath	3.5	3.5	3.5	4.1	4.1	4.1	4.1	4.1	4.1	2.7	3.1	2.7	2.7	2.7	2.7	2.7	2.7
Bath room tap	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
Dish washer	1.6	1.6	1.6	1.7	1.6	1.6	1.7	1.7	1.7	2.6	2.8	2.6	2.6	2.6	2.6	2.6	2.6
Kitchen tap	14.8	14.8	14.8	13	13	13	13.6	13.6	13.6	16.3	11.7	17.2	17.2	14.8	15.4	16.8	16.3
Outside tap	13.4	13.4	13.4	13.4	13.4	13.4	23.1	0	23.1	15.2	2.6	21.7	21.7	2.6	4.6	17.1	15.2
Shower	45.9	45.9	71.4	45.9	45.9	71.4	45.9	45.9	71.4	55.4	49.8	69.5	97.8	48.3	55.9	65.9	55.4
WC	35.4	0	35.4	35.4	0	35.4	35.4	0	35.4	21.1	6	22.4	22.4	20.7	20.7	20.8	21.1
Wash machine	14.2	0	14.2	14.2	0	14.2	14.2	0	14.2	14	12.2	15.6	15.6	12.7	14	13.8	14
Leak																	26.3
Daily total	**132.8**	**83.2**	**158.3**	**131.7**	**82**	**157.1**	**142**	**69.3**	**167.5**	**131.3**	**92.2**	**155.7**	**184**	**108.4**	**119.9**	**143.7**	**131.3**
household size	**2.3**	**2.3**	**2.3**	**2.6**	**2.6**	**2.6**	**2.5**	**2.5**	**2.5**	**2.1**	**2.9**	**2**	**2**	**2.3**	**2.2**	**2**	**2.1**

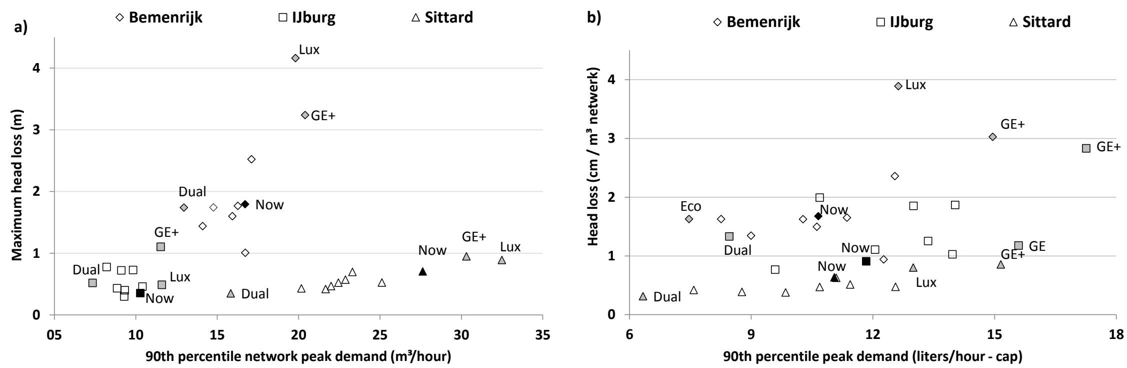

Fig. 2 a) Daily peak versus head losses per scenario for the three networks, b) daily peak per capita versus head losses per volume of network. Now: markers in black, extreme values markers in grey.

An advantage of this approach, with detailed network calculations, is that with the network model the node(s) with the minimum head on the network can be easily identified, as well as the time during the day when the maximum head losses are most likely to occur. This provides additional information about variation of the network performance on location and time, which is relevant for network management. Additionally, the maximum losses per connection can be identified for the complete network for the different scenarios. Fig. 3 shows the comparison of the three networks. Although Bemenrijk is the network with highest head losses, this maximum head loss only affects 4% of the connections. In general, for Bemenrijk and IJburg 80% of the connections have head losses lower than 5cm. While in Sittard the effect of the different scenarios is more distributed over the network.

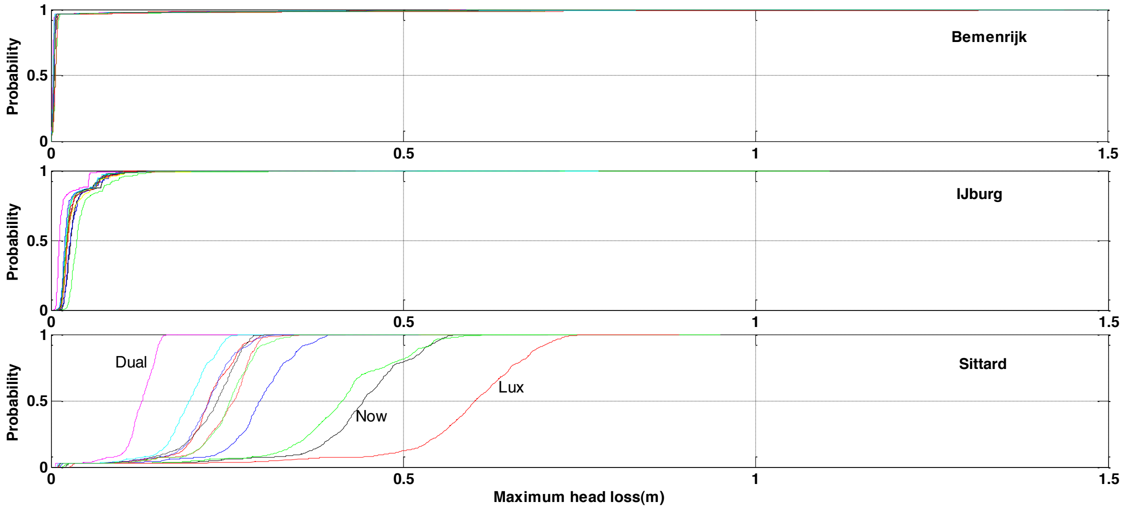

Fig. 3 Cumulative frequency distribution of head losses per network for the 10 scenarios.

3.2. Water quality

The medium residence time (□mean) in the networks varies from 5 – 15 hours, (Table 2). However, from the network analysis, the 99th percentile of the residence time in the networks varies from 36 to 72 hours, (Fig. 4). The "Dual" and "RC" scenarios had the maximum residence time, but in all cases the maximum residence time was above 36 hours. Bemenrijk showed the largest residence time. Additionally, the cumulative distribution of the residence time in the network shows that the "Dual" scenario has a large influence in the residence time in the complete network for the three studied cases. Note that the residence time is not from pumping station but from transport main at the entrance of the network.

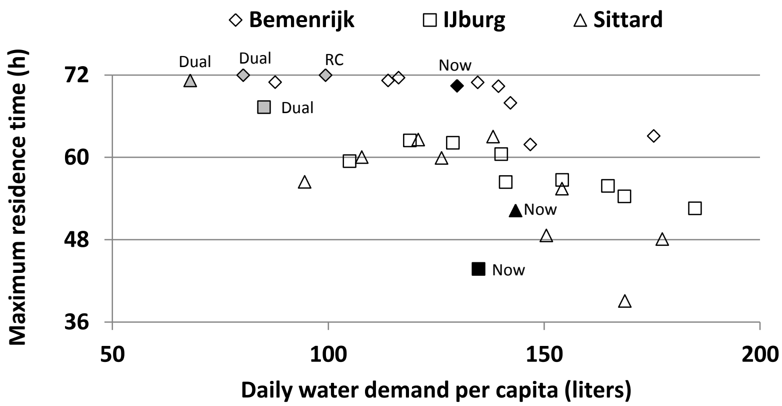

Fig. 4 Daily water demand per capita versus maximum residence time per scenario for the three networks.

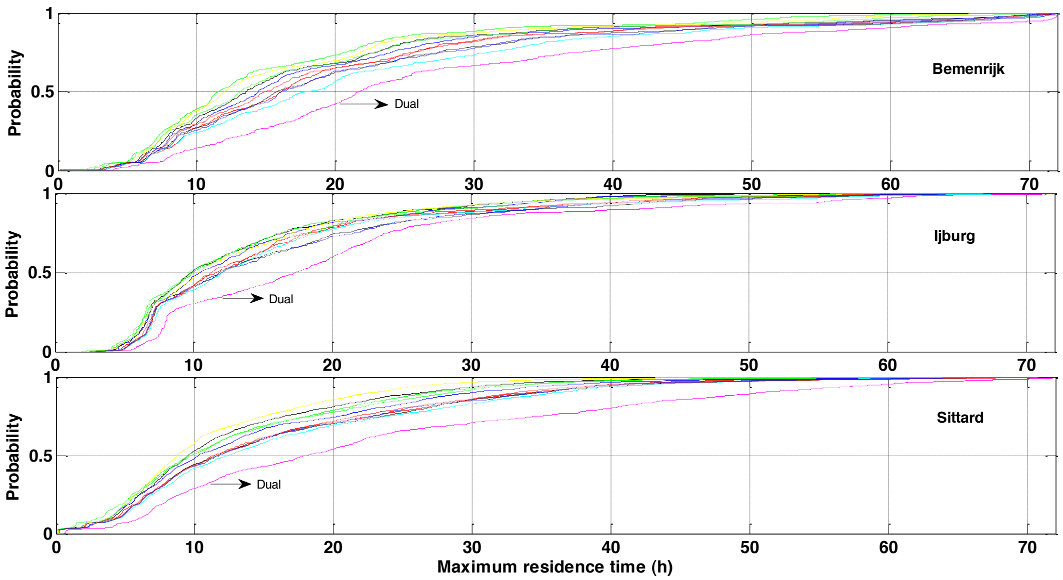

Fig. 5 Maximum residence time in the network for the three networks per scenario.

Table 5 shows the overview of the results for the three networks. The current situation is compared with the minimum and maximum values obtain with the simulation of the future scenarios. Results show that the same future scenario can have different effects on the performance of different DWDS systems. Although comparison of different networks provides an insight into the effect of a given scenario, the consequences for head losses and water quality cannot be generalized. These consequences have to be quantified per network due to variations in size (connections, length and volume), number of loops and demand.

Table 5 Overview of the results for the three networks

	Now	Min	Max	Max % increase	Max % reduction
Bemenrijk					
Demand (m^3/day)	203.6	126.0	239.2	17	-38
peak (m^3/h)	16.7	13.0	20.4	22	-22
Age (days)	2.9	2.6	3.0	2	-12
head loss (m)	1.8	4.2	1.0	132	-44
IJburg					
Demand (m^3/day)	117.0	73.9	123.5	6	-37
peak (m^3/h)	10.3	7.3	11.6	13	-29
Age (days)	1.8	1.8	2.8	54	0
head loss (m)	0.4	1.1	0.3	212	-16
Sittard					
Demand (m^3/day)	358.4	170.1	421.8	18	-53
peak (m^3/h)	27.6	15.8	32.5	18	-43
Age (days)	2.2	1.6	3.0	36	-25
head loss (m)	0.7	1.0	0.3	35	-50

Since pressure can be controlled and adjusted in the piped network for different demands, and reservoirs can be designed to allow fluctuations in demand, quality remains the most critical performance factor, especially in the Netherlands where water is distributed without residual disinfectant. Results showed robust networks, which maintain their functionality under variable demand by adapting operation and management of the system. For instance, by adjusting the pressure of the transport system, it is possible to cope with rather extreme changes on the water demand, while maintaining its functionality. For these specific cases, the maximum head losses can be compensated by increasing the pressure in the network. Peak demand needs adjustments in the operation of the treatment and storage in the production facilities.

However, special attention should be given to the lack of boundaries and limits for the appropriate functioning of DWDS. Further research should focus on determining the maximum head losses or retention times allowed in DWDS. Head losses should consider the energy and costs to guarantee a sustainable supply. In the special case of non-chlorinated water more research is needed to determine limits for maximum retention times.

The scenario approach presented in this article represents a robust approach to determine the performance levels of networks under different operating conditions. Moreover this approach can also be used during the design phase of DWDS to achieve more efficient DWDS.

4. Conclusion

This scenario approach combined with detailed network calculations is a powerful approach to assess the robustness of DWDS to deal with extreme scenarios for the drinking water demand. This approach showed that it is not necessary to forecast each change in drinking water demand in detail.

The general observation is that the current drinking water distribution infrastructure is robust enough for the future drinking water demands of most scenarios. This methodology shows to be useful to quantify the range of variation of key variables that describe network performance like head loss and water age.

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