Risk reduction in the Riga water supply by application of modeling tools, pathogen control and turbidity reduction

Colophon

Title:
Risk reduction in the Riga water supply by application of modeling tools, pathogen control and turbidity reduction

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Deliverable number: D 7.5.4

TKI Categorisation

Classification									
Supply Chain		Process Chain		Process Chain (cont'd)		Water Quality		Water Quantity (cont'd)	
Source		Raw water storage		Sludge treatment		Legislation/regulation		- Leakage	x
- Catchment	X	- Supply reservoir		- Settlement		- Raw water (source)	x	- Recycle	
- Groundwater	X	- Bankside storage		- Thickening		- Treated water			
- Surface water	X	Pretreatment		- Dewatering		Chemical		Risk Management / Consumers	
- Spring water		- Screening		- Disposal		- Organic compounds	x		
- Storm water		- Microstraining		Chemical dosing		- Inorganic compounds	x	Risk analysis	
- Brackish/seawater		Primary treatment		- pH adjustment		- Disinfection by-products	x	- Hazard identification	X
- Wastewater		- Sedimentation	x	- Coagulant		- Corrosion	x	- Risk estimation	X
Raw water storage		- Rapid filtration	x	- Polyelectrolyte		- Scaling		Risk evaluation	
- Supply reservoir		- Slow sand filtration		- Disinfectant		- Chlorine decay		- Risk tolerability decision	
- Bankside storage		- Bank filtration		- Lead/plumbosolvency		Microbiological		- Analysis of options	
Water treatment		- Dune infiltration	x	Control/instrumentation		- Viruses		Risk reduction / control	
- Pretreatment		Secondary treatment		- Flow		- Parasites		- Risk reduction options	
- Primary treatment	X	- Coagulation/flocculation	x	- Pressure		- Bacteria	x	- Decision making	
- Secondary treatment		- Sedimentation	x	- pH		- Fungi		- Implementation	
- Sludge treatment		- Filtration	x	- Chlorine		Aesthetic		- Monitoring	
Treated water storage		- Dissolved air flotation(DAF)		- Dosing		- Hardness / alkalinity		Risk Communication	
- Service reservoir		- Ion exchange		- Telemetry		- pH		- Communication strategies	
Distribution	X	- Membrane treatment		Analysis		- Turbidity	X	- Potential pitfalls	
- Pumps		- Adsorption		- Chemical	X	- Colour		- Proven techniques	
- Supply pipe / main		- Disinfection		- Microbiological	X	- Taste		Trust	
Tap (Customer)	X	- Dechlorination		- Physical	X	- Odour		- In water safety/quality	
- Supply (service) pipe		Treated water storage						- In security of supply	
- Internal plumbing		- Service reservoir				Water Quantity		- In suppliers	
- Internal storage		Distribution						- In regulations and regulators	
		- Disinfection	X			Source		Willingness-to-pay/acceptance	
		- Lead/plumbosolvency				- Source management		- For safety	
		- Manganese control				- Alternative source(s)		- For improved taste/odour	

		- Biofilm control	X			Management		- For infrastructure	
		Tap (Customer)				- Water balance		- For security of supply	
		- Point-of-entry (POE)				- Demand/supply trend(s)			
		- Point-of-use (POU)				- Demand reduction			

TKI Categorisation (continued)

Contains		Constraints		Meta data		
Report	X	Low cost		*Author(s)*	Talis Juhna, Janis Rubulis, Laura Sterna, Maris Bernats (RTU), Daniel Schumann (TZW), Luuk Rietveld (DUT)	
Database		Simple technology		*Organisation(s)*	RTU, DUT , EAWAG, BDS, BBE, S::can, KWR, TZW	
Spreadsheet		No/low skill requirement		*Contact name*	Talis Juhna	
Model		No/low energy requirement		*Contact email*	Talis.Juhna@rtu.lv	
Research	X	No/low chemical requirement		*Quality controller name*	Ian Walker	
Literature review		No/low sludge production		*Quality controller organisation*	WRc	
Trend analysis		Rural location		Source	TECHNEAU WA7	
Case study / demonstration	X	Developing world location		*Date prepared*	15/07/2009	
Financial / organizational				Date submitted (TKI)	30/08/2010	
Methodology	X			Date revised (TKI)		
Legislation / regulation						
Benchmarking						

Summary

This report provides an overview of the second part (2009-2010) of the Riga Case Study, which was designed to apply several technologies, developed within the TECHNEAU project, in mitigating risks related to drinking water quality deterioration in the Riga water supply. The risks were identified and their severity was weighted in the first part (2008-2009) of the case study. The two major risks were: (i) uncertainty about the efficacy of the surface water treatment plant for removal of anthropogenic pollution and natural organic carbon, and (ii) discoloration of drinking water in distribution networks.

To develop and recommend mitigation strategies, the following models were developed and validated in the study: (i) bacterial regrowth model, (ii) iron pipe corrosion model, and (iii) water treatment plant model (simulator). Two strategies to deal with discoloration were tested in the study.

Based on the modeling results and field studies, a number of short- and mid-term practical recommendations were proposed:

- to use a model-based chlorine dosing strategy;
- to increase the pH of water using CO_2 purging technology;
- to replace biologically active carbon filters with granular active carbon filters;
- to use unidirectional flushing starting with a clean front from large diameter transient pipes.

Other relevant conclusions and recommendations are expected to be derived in the future when more data will be acquired by the Riga Water company from using the models and technologies provided by the TECHNEAU project.

Contents

1. INTRODUCTION

In the Baltic states, like in several other European countries[1], water companies in the water sector have traditionally focused more on managing their assets to maintain serviceability and reduce costs rather than on service improvements through technical innovation. This approach has been rather successful in meeting the current Drinking Water Directive. However, it makes companies less competitive for the future, when more efficient, energy saving and reliable technologies and management strategies will be used.

Although over the last few years scientists have developed many advanced water technologies, their application by the water industry is rather limited. This is because implementation of novel solutions in the development stage requires a closer cooperation between company and scientists. Examples of successful full-scale application of innovative technologies may encourage companies to use more of them in practice. Accordingly, practical demonstration of the technologies developed within TECHNEAU in “real life situations” in case studies was one of the cornerstones of the project. Due to time and other constraints (e.g. economical, technological and social) not all of the technological solutions developed in TECHNEAU could be implemented in practice during the lifetime of the project. However, it is expected that many will be adopted and will be of benefit in the future.

Riga (the capital city of Latvia) was selected as one of the sites for a Work Area 7 case study. This region is in a period of transition from central administration (Latvia regained independence from the Soviet Union in 1991 and joined the European Union in 1994) to a free market economy, thus both social behaviour and technological solutions have had to be adapted to the new situation. In the Soviet Union, all technologies were

[1] Report from Council of Science and Technology in UK (2009) can be found at www.cst.gov.uk/reports/files/water-report.pdf

standardized (developed by state research institutes) and there was little experience in implementing innovations by companies themselves. In the current process of transformation, this activity however is insufficiently stimulated. This reluctance could be partially explained by the fact that water supply companies are municipally owned (viz. monopolies), thus they are not exposed to competition in the free market, in which innovation has an important role in survival of companies in the long term.

Innovative technologies can be used for several purposes including for data acquisition and optimization of technological processes. In the Riga Case Study they were used for obtaining data needed for risk assessment and mitigation of identified risks. In the first part of the study (2008-2009), the risk analyses were carried out in the Riga water supply system using advanced data acquisition technologies. During two years of the case study (see more detailed report D7.5.3) more than 700 possible hazards were reviewed by a group of experts. The unknown data which were needed for risk calculations were acquired using several technologies developed in TECHNEAU. This allowed identification and ranking of major risks according to their severity.

The aim of this second part of the study was to suggest how to mitigate the identified risks (from D7.5.3) by using advanced technologies and strategies developed in TECHNEAU. Although the major intention was to make strategic suggestions which the company would implement in the future, during the case study some practical recommendations were made which are presented in this report.

Background

The Riga Water company is a typical municipality-owned enterprise of a former eastern bloc country which has accessed the European Union during the last few years. The management is a top down decision-making structure with major incomes from tariffs that are set by the state-controlled agency. The involvement of the public and investment in research and innovation is minor.

Both surface water and groundwater is used for drinking water production, which is around 150 000 m^3/d. The infrastructure was mostly built using Soviet technologies. However, due to the availability of European funds most of the water (and wastewater) treatment plants have been renovated and are producing drinking water which meets current European standards with some exceptions. At groundwater sites, iron and manganese still exceed the Drinking Water Directive, therefore the construction of groundwater treatment plant is planned in the future.

Latvia is rich in water resources including well-protected groundwater. All water supplies in the country abstract groundwater for drinking water production. Riga, being historically an industrial city, experienced an increase in water demand which exceeded the available groundwater resources. To prevent a further decrease of groundwater level, it was decided to use surface waters as well. At one of the sites, groundwater is artificially recharged using lake water, whereas at the other site, surface water from the Daugava river - the largest river in the Baltic States - is being used. The intake (hydropower station dam) is located downstream of many cities in Latvia and Belarus. As the result, the river is exposed to anthropogenic pollution. Due to reformation of industry in the 1990s, the pollution load in the river has been decreasing. However, the water quality is still not good (Water Framework Directive criteria). The river crosses forest and bog soils and as a result the water contains high levels of natural organic matter (NOM). The surface water is treated at Daugava Water Treatment Plant (WTP) using coagulation and sedimentation technology, which was recently upgraded with the multiple barrier principle (including two-stage ozonation). To avoid bacterial regrowth, biologically active carbon (BAC) filtration is used before water post-chlorination.

The water distribution network was built more than 100 years ago, mostly using cast iron and metal pipes. The rate of pipe breakage is high therefore frequent network repairs and replacements take place. Due to a decrease of water consumption in the 1990s, the production of water dropped leading to slow flow and stagnant water conditions in the networks and accumulation of loose sediments.

Risk assessment results

During the first two years (2008-2009) of the case study (see more detailed report D7.5.3), the major risks related to water quality in Riga were identified (Table 1, Appendix 1). One of the findings when choosing the mitigation actions was that understanding of the processes was not always sufficient. It was decided that in order to find the optimal solutions in the long term, the company could use water quality models developed in TECHNEAU for water treatment plants and networks. Thus, the following models were made available for the company: (i) the water treatment simulator (SimEau), (ii) the corrosion model of pipes in the distribution networks, and (iii) the bacterial regrowth model with option for accurate chlorine dosing. Secondly, a pathogen intrusion risk was identified at the artificial groundwater recharge site. To deal with this problem, a methodology for water sampling and rapid analyses was suggested. Based on the long-term analyses, the technological solution has to be developed by the company. Thirdly, extensive investigation of turbidity which included modeling and field trials has lead to a recommendation to start flushing the system within the next three years. It was proven that this flushing is economically feasible for large pipe networks as in Riga.

2. MITIGATION MEASURES

In this section, more detailed descriptions of the application of mitigation actions in Riga are presented. They include application of i) the water treatment plant simulator to stabilize removal of anthropogenic substances and NOM, ii) the corrosion model to predict the extent of corrosion and sensitive areas in the networks, iii) the bacteria regrowth model to predict optimal doses of chlorine, and iv) unidirectional flushing to mitigate turbidity problems in the networks. Mitigation actions for pathogen removal are not suggested yet as more studies applying the methods presented in D7.5.3 need to be carried out by the company.

2.1. Application of the water treatment plant simulator

2.1.1 Background

The Daugava river raw water source is exposed to pollution from wastewater treatment plants, agriculture and industry. In the previous studies (D7.5.3), analyses of water quality toxicity (using a fish biomonitor), and measurements of endocrine distrupting compounds (using a bioassay) and algal toxins were carried out. Overall analyses showed that the risk for sporadic contamination existed, and that information about removal efficacy of anthropogenic compounds during water treatment at Daugava WTP was needed. Moreover, analyses of the concentration and composition of NOM showed that removal of organic matter during coagulation and BAC was suboptimal. It was therefore decided to develop a water treatment simulator for Daugava WTP, which can be used later by the company to optimize the performance of the treatment processes.

2.1.2 Methodology

A model of the Daugava WTP was built in the water treatment simulator (SimEau). Within this environment, it is possible to simulate the drinking water treatment based on known raw water quality and chemical dosages applied. In Figure 1 (Appendix 2), a schematic overview is given of the

Daugava WTP in SimEau, consisting of raw water intake, pre-ozonation, coagulation/sedimentation, pH adjustment, rapid sand filtration, main-ozonation and biological filtration. The final disinfection step - chlorine addition - is not yet incorporated in SimEau and will be implemented later.

Coagulation has the objectives to maximize removal of turbidity and particles, maximize removal of pathogens, maximize removal of natural organic matter (NOM), minimize coagulant residuals (Edzwald and Tobiason, 1999). The performance of the coagulation is dependent on temperature, alkalinity, pH and NOM concentration in the water. Less coagulant dose is needed at low pH to remove NOM, however the residual dissolved coagulant is higher, which may cause poor floc separation by downstream clarification and filtration and may result in post-precipitation problems downstream of filtration. The possibilities for manipulations are change in coagulant and base/acid dose and the mixing intensity (G-value). An on-line indication of the NOM concentration is the measurement of UV absorbance at a wavelength of 254 nm (UVA254). The particle removal can be expressed by measuring on-line turbidity of the water. The controlled parameters are therefore the remaining particles and the NOM concentration and residual coagulant.

The objectives of ozonation are disinfection, the oxidation of micro pollutants and the oxidation of NOM, transforming higher molecular weight compounds into lower molecular weight compounds. Harmful disinfection by-products can be formed such as bromate, influencing the toxicity of the water produced. The ozone decomposition in water consists of an initial phase and the second phase. In the initial phase (timeframe of seconds) decomposition mainly takes place due to reactions with NOM, in the second phase (timeframe of minutes) disinfection takes place (Buffle et al., 2006). A measure for disinfection is the CT-value, which is determined by multiplying the ozone concentration in the water with the residence time. The performance of the ozonation step is dependent on temperature and NOM concentration. When the UV254 increases, indicating an increase in NOM concentration, the ozone dose should be increased to assure sufficient disinfection (Van der Helm et al., 2009a). A higher temperature gives higher decay rate constants and thus results in lower CT values (Van der Helm et al., 2007). For ozonation the possible manipulation is the ozone dose, which can be adjusted by changing the gas flow or the ozone in gas concentration. The controlled parameters are the CT value and the NOM concentration. Current measurements which can be used to estimate these values are UV254 and ozone measurements, over the height of the reactor.

The general purpose of rapid sand filtration is to clarify the water by removal of small particles, which can be measured as the turbidity (Ives, 1970). For surface water treatment plants other benefits can be possible such as nitrification (Van der Aa et al., 2002). The application of pre-oxidation enhances the biological activity in the water, resulting in the development of a biomass concentration on the grains of a filter (Van der Aa et al., 2006). During biological filtration the biodegradable compounds in the water are consumed by the bacteria present on the grains. The performance of a filter can be monitored by measuring the turbidity removal and pressure drop over the filter. Additionally during biological filtration the oxygen concentration is important, since the bacteria consume oxygen when biodegrading the compounds. If as a result the water becomes anoxic, the conditions become less optimal, and oxygen should be dosed. The manipulated parameters are the backwash frequency of the filter and the oxygen dosage.

The manipulated parameters (e.g coagulant dose, filtration rate) at the plant govern the overall performance. Based on known raw water quality, the manipulated parameters can be adjusted such that the desired drinking water quality is met. The manipulated parameters of Daugava WTP currently implemented in SimEau are as follows: flow rate, coagulant dose, lime/acid dose, ozone dose and backwash frequency of filters (see Figure 2, Appendix 2).

2.1.3 Results and recommendations

A first validation of the water quality models applied to Daugava WTP was performed using the available parameters (Table 2, Appendix 1) as input. The simulation results showed that a reasonable prediction could be made (Figure 3, Appendix 2). However, to use SimEau as a tool for process/plant optimization, controlled experiments have to be carried out to enable a complete calibration.

The model will be available for Riga Water. Calibration can be done manually. Suggestions on how to calibrate the models are given in the deliverables of WP 5.4. Probably some support from RTU and TUD are necessary to assist in the calibration process. It will also be necessary to think of a good experiment or to select relevant full-scale data for the calibration procedure.

When the model is completely calibrated, the optimal dosage settings (manipulated parameters) can be determined based on a known raw water quality, resulting in a more stable operation and more constant drinking water quality.

Based on the results of the simulator, the following conclusions regarding the efficacy of Daugava WTP for removal of NOM and pH control were derived:

- With the model it is possible to predict pH in all treatment steps, so better control of pH is possible
- With pH adjustment before coagulation it will be possible to improve the NOM removal, which influences ozone dosage and biological filtration positively.

- Pre-ozonation will probably not result in better coagulation performance with respect to NOM removal.
- Ozone dosage in main ozonation is high, probably forming high concentrations of AOC (not measured) and hampering the biological stability of the product water.
- Ozone concentrations in the influent of the biological filtration probably hampers the efficacy of the biological filtration.

Moreover, based on measurements and tests carried out at Daugava WTP so far, several practical recommendations can be made already:

- ozonation does not increase the efficacy of NOM removal;

- enhanced coagulation (by lowering pH to 6, dose to 10 mg Al/l) may be used to increase NOM removal efficacy by 10%;

- removal of NOM during biofiltration is not efficient due to slow degradation kinetics of NOM; in the short term, replacement of biofiltration with granular activated carbon is the optimal solution, in the long term, methods for increasing the biodegradability of NOM should be suggested;

- the pH of water can be adjusted by retrofitting air purging before biofiltration (BAC); this will allow pH levels to increase without increasing sludge production (e.g. if $Ca(OH)_2$ dosing was used).

2.2. Application of the corrosion model

2.2.1 Background

More then 90% of pipes in the Riga water supply system (total length 1300 km) are made of cast iron or unlined iron. The pipe breakage rate is high, about 2000 per year (Riga Water data), which leads to water supply interruption, contamination risks, traffic closures and complaints from consumers about insufficient quality or quantity of water.

The general perception of the company is that breakages are more frequent in the older pipes, therefore the replacement strategy is to start with the oldest pipes. However, there are no previous studies in Riga about the effect of water quality and hydraulics with regard to the corrosion of the pipes. Therefore a study to develop an interactive map showing the areas in Riga with high corrosion rates and risks of failure was initiated. The map was created based on the results of simulation of corrosion of iron pipes using the model which was developed specifically for Riga.

2.2.2 Methodology

The model was developed in two main stages: 1) collection of corrosion rate data in the field, using corrosion rate measurements from special test rigs at the outlets from groundwater and surface water treatment plants; the measurements were carried out over one year using iron coupons, which were exposed to various water flow regimes; 2) from the data obtained, mathematic equations were generated in relation to the time of exposure and the material loss. The equations were introduced into the hydraulic model (EPANET freeware) of the Riga water supply system. The crucial part of the model development was its validation in the field, for which a unique technology was used. Water supply pipes were removed from several locations and brought to the laboratory where material loss of pipe materials was measured using ultrasound technology (developed by the Institute of Materials and Structure at Riga Technical University). The details of the model and validation methodology will be available in an article (in preparation).

2.2.3 Results and recommendations

The material loss measurements in the pipe segments removed from the water distribution networks were carried out over a period of about half a year. The correlation between the data acquired in the field and obtained from the modeling is shown in Figure 4, Appendix 2. The error was about

15% which could be considered relatively low because of the complexity of the modeled system. Using results of the simulation, maps showing loss of pipe material (Figure 4, Appendix 2) due to corrosion (in mm/year) were developed. The results showed that the highest corrosion rate occurred during the first year, after which a significant decrease of pipe corrosion rate was observed. The corrosion rate was low after five years. The average corrosion rate was about 100-120 g/m^2/year or about 0.013 - 0.016 mm per year (density 7.5 t/m^3). The map can be used to predict the areas where pipe failure is most probable (indicated in red).

Notably, the corrosion rate in the long term was not very different for a pipe supplied with groundwater (east part of the networks) or chemically treated surface water (west part of the networks), even though surface water was more corrosive due to low pH. However, the measurements of the corrosion rate in the pilot scale showed that the types of corrosion were very different. In water supplied from surface water, the pitting type of corrosion was dominating (see Figure 5, Appendix 2), which means that pipe failure rate is more frequent in the part of the city supplied with this type of water. Therefore, it was recommended to increase the pH at the surface water treatment plant before the water is pumped into the city. The cheapest way for pH correction is purging out CO_2 with air. This approach was tested at the pilot plant during the TECHNEAU project. The results showed that 10 minutes of aeration was sufficient to increase pH to about the calcium carbonate saturation level, thus decreasing the damaging effect of water on the pipes.

2.3. Application of the bacterial regrowth model

2.3.1 Background

Within the TECHNEAU project, the bacterial regrowth model (to predict changes of bacterial number in water distribution networks) was developed for the Riga water supply system. However, the crucial part of any model implementation in practice is its validation to make sure that it represents the real situation in the field. Therefore the emphasis in the Riga Case Study was on finding a simple but effective way of fitting field data to the model.

The two major problems with the model validation were: 1) the lack of accurate hydraulic models of the system, and 2) an insufficient amount and quality of data used as input to the model (e.g. bacterial number, substrate concentration). This study was aiming to overcome these problems and develop a model for the company which can be continuously upgraded, thus enabling the company to choose the required degree of accuracy for the model.

During the model development, it was realized that for a water supply system with a high level of NOM, the most practical application of the model was in selection of chlorine doses, balancing the risks of byproduct formation from chlorination and high bacterial number in the water distribution networks. Therefore an additional study was started which aimed to develop a correlation between chlorine decay rate and water quality specific for Riga. As a result of the chlorine decay test, an intrinsic chlorine rate constant was derived and introduced in the model. The model can then be used to adjust chlorine doses (automatically) based on the organic carbon concentration and type which can be obtained from real-time measurements.

2.3.2. Methodology

The difficulty of developing accurate hydraulic models arises due to too many unknowns which are needed for the model calibration, e.g. actual demand at nodes, actual roughness of the pipes, etc. If the pressure head can be calibrated from measurements in the field, however, this does not provide reliable information about flow directions which is critical for water quality models. To obtain the missing information an extensive study would be needed, which would include the collection of data over a long period of time. However, companies are not usually ready to allocate resources for this type of work. Thus, in this study we decided to use an approach which can be easily accomplished by a small group of people, namely tracer studies. Using tracer studies, the actual water residence time (viz. water age) can be measured and linked to desirable parameters in the model (e.g. bacterial number, chlorine concentration, etc.). A novel method was developed using natural fluctuation of electroconductivity in water as the tracer for water residence time[2]. The results were successful for the Riga case, as a significant correlation was found between modeled and measured water residence time (see Figure 6, Appendix 2).

The second problem with calibration is insufficient input data where the bacterial number is the crucial parameter. Methods currently used to determine bacterial number are very time and resource consuming, thus large amounts of data, which are needed for the validation, are difficult to collect. Moreover, it is not clear which measurements should be used for bacterial counting. Heterotrophic plate counts represent less then 1% of total bacterial number, and are therefore unlikely to describe the actual processes taking place in the networks. In this study, it was decided to analyze total bacterial number, viable bacterial number and ATP as a measure of metabolically active cells. To increase the rate of sample processing, counting was done using a flow cytometer. This method (described in D3.3.8) allows processing of more then 50 samples per day, meaning that a large amount of data was made available which was crucial for model validation. The application of rapid detection of bacteria enables companies to continuously upgrade models to the required level of accuracy.

[2] Rubulis J., Dejus S., Mekša R. Online measurement usage for predicting water age from tracer tests to validate a hydraulic model // 12th Annual Water Distribution Systems Analysis Conference, Arizona, Tucson, 12.-15. September, 2010, - pp.1.-10

The validation of the model was carried out over a period of two weeks by taking water samples from 40 hydrants. The sampling strategy was carefully planned to make sure that sufficient pre-flushing of hydrants was done. The sampling was organized in a way such that analyses were done on the same batch of water travelling from the treatment plant to the consumers (Figure 7, Appendix 2). After samples were taken, they were analysed for the total cell and intact cell number (cell membrane not damaged) using flow cytometry as well as ATP (free and bacterial) concentration.

Software for calibration of the bacterial growth model with data acquired in field sampling was developed. The bacterial model was integrated in the hydraulic model[3] (Epanet2 MSX file) which had been developed (see D 5.5.4

Methodology of modeling bacterial growth in drinking water systems, D 5.5.9 Modeling planktonic and biofilm growth of a monoculture (P. fluorescens) in drinking water) and validated for the Riga water distribution networks The detailed results were presented at the conference [4].

2.3.3 Results and recommendations

Application of the model at full-scale showed that the bacterial number in the networks increased along with increase of water residence time (see Figure 8, Appendix 2), which is probably an indication of bacterial regrowth. More detailed analyses of bacterial size and fluorescence pattern acquired with flow cytometry, also indicted that bacterial number was due to multiplication taking place in the distribution networks. The results obtained from the model showed a reasonable correlation with data obtained during sampling (Figure 8, Appendix 2). Thus, it is speculated that the sporadic occurrence of coliform bacteria in distribution networks,

[3] T. Juhna, S. Nazarovs., J. Rubulis (2009) (in Latvian) Simulācijas metožu salīdzinājums baktēriju pieauguma modelēšana ūdens sadales sistēmās. RTU zinātniskie raksti 5 (41): 35-40

[4] F. Hammes, M. Vital, A. Briedis, J. Rubulis, T. Juhna, Tracking bacterial growth in a full-scale drinking water distribution network with flow cytometry, ATP analysis and hydraulic modelling, Water Research Conference Lisbon, Portugal, 11 – 14 April 2010, Marriott Lisbon, Portugal.

especially when chlorination is stopped for some reason, can be explained by bacterial regrowth which is due to high levels of biodegradable organic carbon. To limit bacterial regrowth, the removal efficacy of biodegrable organic carbon should be enhanced. However, because of high NOM (4-5 mgC/l) in the drinking water of Riga, the removal of the biodegradable fraction below this level is expensive and will not be accomplished in the foreseeable future. It is therefore suggested to continue to use chlorination, but to select chlorine doses more accurately using the model-based approach.

The idea of the model-based approach is to select chlorine doses to limit bacterial growth in the networks (based on the model developed) without producing trihalomethanes above the maximum allowed concentrations. Measurements of trihalomethane formation should be carried out to identify the relation between NOM and trihalomethanes. The effect of chlorine on bacterial growth can be predicted from the model developed. The problem is that chlorine decay is specific for every type of water, so generic constants may not be used for all type of waters. Thus, to find correlation with water quality and chlorine consumption, an additional study was carried out as a part of the TECHNEAU project. Chlorine decay (which was described with a first order rate constant) was determined in batch experiments for more than 40 samples from several locations in the Riga water supply system. As the result, using factoral analyses ($p = 0.05$, $R^2 = 90.34\%$) the following correlation [1] was derived:

$$k = -0.0028 + 0.001662A_{254} + 0.041177A_{700} - 0.000249\ C_{TOC} + 0.000533C_{DOC}$$

where

k – first order chlorine decay constant, min^{-1};

A_{254} - absorption of light at 254 nm, cm^{-1}

A_{700} – absorption of light at 700 nm, cm^{-1}

C_{DOC} – concentration of dissolved organic carbon, mg C/L

C_{TOC} - concentration of total organic carbon, mg C/L

This correlation shows that the chorine decay rate is dependent on concentration and composition of organic carbon in water. As all these parameters can be measured in real time, we have suggested to upgrade chlorine dosing with algorithms which link online organic carbon measurements with chlorine dosing (article in preparation).

In practice, this means that chlorine doses required to obtain residual chlorine concentrations in the networks which limit bacterial growth (given that trihalomethane concentration does not exceed the standards) will be calculated from the bacterial regrowth model. The chlorine decay constants in the models will be adjusted using equation [1] from online measurements of organic carbon (TOC, DOC, A_{254}, A_{700}). One device which can be used for the online measurements (linked to SCADA) of organic carbon is the spectrometer (s::can Meßtechnik GmbH, Vienna, Austria) which (see Figure 9, Appendix 2) which was developed in TECHNEAU.

In the long term, the company should consider strategies for increasing the removal efficacy of biodegrable organic carbon at the treatment plant.

2.4. Application of unidirectional flushing methods to reduce discoloration

2.4.1 Background

The discoloration of drinking water in the Riga water supply networks has been observed sporadically after rapid changes of water flow velocity, for example in morning peak hours and after pipe repairs. According to Riga water laboratory data, which are based on analyses of grab samples, turbidity (the main cause of discoloration) is normally within required standards (< 3 NTU). However, the sporadic discoloration of water and complaints from consumers indicate that accumulation of loose deposits takes place in water distribution networks. Notably, most of the complaints are received from the consumers living in the central part of the city where, according to hydraulic modeling results, there is a mixing zone of waters from several sources.

The objective of this activity was to propose a simple operational method for the removal of the loose deposits from the distribution system. Two principally different approaches were tested in two districts of Riga: unidirectional flushing (UDF) and self cleaning. In addition, the OptFlush program - developed within the TECHNEAU project - was used to predict sources of loose deposits and frequency of flushing. Before flushing, the amount of loose deposits was measured using the resuspension potential method (RPM) enhanced in the project (D 5.5.1/2 Particles in relation to water quality deterioration and problems in the network) and adapted for Eastern Europe situation.[5]

2.4.2 Methodology

The first step was to assess the status of the water supply system before any activity with loose deposits removal was started. The following main tasks were performed:

- building of the equipment for unidirectional flushing, resuspension potencial measurments and online monitoring,
- analyzing the cause of the discoloration through online measurements at the water treatment plants,
- implementation of the UDF technique according to RPM measurements,
- testing of the OptFlush program for the calculation of optimized flushing intervals,

[5] Neilands K., Rubulis J., Juhna T. Application of Online Monitoring, Resuspension Potential Method and Unidirectional Flushing for Control of Drinking Water Quality in a Distribution Networks, Latvia // IWA 1st Eastern European Regional Young Water Professionals Conference, Belarus, Minska, 20.-23. May, 2009. - pp 362-371.

- calculation of the maximum daily velocities from the hydraulic model and turbidity from UDF to determine 'self-cleaning' velocities in the network by manipulating valves in the system.

For unidirectional flushing and RPM measurements, an online turbidity meter (ULTRATURB plus™ sc 100™, Dr. Bruno Lange GmbH&Co, Düsselfdorf, Germany) (Figure 10, Appendix 2) was used. The online measurements were backed up by manual measurements of turbidity using a portable turbidity meter (Hach 2100P, Dr. Bruno Lange GmbH&Co, Düsselfdorf, Germany) and a Spectro::lyser™ spectrometer (s::can Meßtechnik GmbH, Vienna, Austria).

During the application of the unidirectional flushing and RPM, the velocity was calculated from measurements of online flow meters (Siemens Sitrans FM MAG 8000, Siemens Energy & Automation Inc., Germany and ELKORA B34, Elkora Ltd., Latvia). To optimize the work in the field, a mobile cart was built equipped with an online flow meter, turbidity meter and manometer (Figure 11, Appendix 2).

The unidirectional flushing was performed in two districts of Riga city: Ziepniekkalns and Imanta (Figure 12, Appendix 2). Ziepniekkalns is located close to the Daugava water treatment plant (WTP). The network is new and has a low risk of malfunction of valves that were used during unidirectional flushing. In this study area, three-, five- and nine-storey living houses and public buildings – a kindergarten, a secondary school, shops, etc., were flushed.

The second area for flushing, Imanta is dominated by cottages and several three- and five-storey living houses. Neither of the chosen areas were indicated as having the highest risk of discoloration according to both consumer complaints and measurements of RPM. Flushed diameters ranged from 100 to 400 mm in Ziepniekkalns and 100 to 200 mm in Imanta. The whole community was flushed with eight runs within two days. The flushing routes for both communities are shown in Figure 13, Appendix 2 and an example of a flushing plan is also shown in Table 3 (Appendix 1).

2.4.3 Results and recommendations

To verify the unidirectional flushing method for removal of loose deposits from the distribution system, a demonstration in two districts of Riga city was performed. During the flushing, two TZW-Dresden experts joined (Dipl.-Ing. Sebastian Richardt and Daniel Schumann, Figure 11, Appendix 2). Within the field studies in March 2009, about 950 m of cast iron pipe with diameter 300 mm was flushed through two simultaneously opened hydrants. The activities showed several drawbacks of this method in such a large city, where the major complication was the need to stop the traffic. Some other practical problems such as finding the valves on a gravel road in a residential district and finding a sufficient capacity sewer to drain the water generated during the flushing increased the time required to complete the study. These types of problems were however solved later by more detailed planning.

In May in Ziepniekkalns, 5 km of 200-, 250-, 300- and 400-mm cast iron pipes were flushed within two days. The flushing was performed together with Riga Water staff (Figure 14, Appendix 2). Flushing started with water from a 300-mm diameter pipe assuming that it was supplied from a clean water front (route N 1 in Figure 13A, Appendix 2) from the water treatment plant. Results from the first two routes showed no discoloration problem (4 NTU) which can be explained by insufficient velocity (0.28 m/s) to resuspend the particles in the 300-mm pipe. The next three routes showed significant decreases of turbidity during the flushing (Figure 15, Appendix 2). A 400-mm pipe was cleaned where the discharge from the hydrant was too low (65 m^3/h) to withdraw deposits. The last two routes with 200-mm pipes showed turbidity decreases from approximately 100 NTU to 3 NTU. Flushing conditions in May were not optimal due to reduced pressure in the Daugava

WTP. In the period September – October 2009, the flushing was repeated in the Ziepniekkalns area. Due to increased flow in this period, the flushing was effective and it was confirmed that the conditions in the previous flushing were not optimal.

The results from flushing in spring and autumn were used to test the OptFlush program that predicts the flushing intervals (Figure 16, Appendix 2). The results of OptFlush showed that the flushing intervals in Ziepniekkalns varied between 0.5 and 4 years. The analysis of loose deposits showed that the highest iron discharge from the inner surface of the pipes was 2.26 gram per square meter (Figure 17, Appendix 2). The iron/manganese ratio of the samples indicated that the deposits resulted primarily from corrosion (Figure 18, Appendix 2). In the investigated pipes, > 98% of loose deposits was formed from the corrosion processes. This indicated that the cast iron pipes in the network have a high corrosion rate.

Using the turbidity data from flushing in the Ziepniekkalns and Imanta districts and the calculated daily maximum velocity (using the hydraulic model in EPANET) 'self-cleaning' velocities for each pipe were examined. The 'self-cleaning' velocity principle was tested with the hydraulic model for the Ziepniekkalns and Imanta districts. This principle implies that to reach velocities that must occur daily to resuspend settled sediment, water has to be forced. In order to do this, some of the valves in the system have to be closed providing that water supply interrapted. , To choose the right valves, the main indicator is velocity in the pipes and the turbidity levels. An example of areas with and without valve manipulation is shown in Figure 19 (Appendix 2).

The case study showed that to eliminate the discoloration problem, effective flushing is possible even in such a big city as Riga. Nevertheless, several technical problems were observed. In newly built areas, the boom of real estate has lead to a decline in the construction quality. Therefore closed valves in distribution loops, improperly installed hydrants and other technical problems such as a lack of storm sewers for discharge of water during the flushing have emerged. The observed technical problems are illustrated in Figures 20 – 24 (Appendix 2). The applicability of unidirectional flushing to control discoloration problems is summarized in Table 4 (Appendix 1).

If these problems are solved than unidirectional flushing appears to be an effective solution to eliminate discoloration problems in Riga, however decision about starting of this approach shall be made following Cost Benefit Analyses which is presented in another report (D 7.5.6 Cost benefit analysis of water quality improvement in Riga water distribution).

3. CONCLUSIONS

In the Riga Case Study the following strategic solutions to mitigate water quality problems in Riga water supply have been generated:

- removal efficacy of natural organic matter should be increased at surface water treatment plant (Daugava);
- efficacy of water treatment plant (Daugava) for removal of emerging pollutants should be assessed;
- bacterial regrowth in the networks shall be controlled using more accurate chlorine dosing;
- water quality problems in the networks can be solved using unidirectional flushing methods when cost benefit analyses shows that this strategy is economically feasible.

In addition, several models were developed to deal with the water quality problems in the Riga water supply. This application demonstrated a range of practical solutions which can be implemented now:

- the use of a model-based chlorine dosing system;
- the increase of water pH by using CO_2 purging technology;
- the replacement of biologically active carbon filters with granular active carbon filters;
- the application of unidirectional flushing starting with a clean front from large diameter transient pipes.

For other solutions, more studies should be carried out by the Riga Water company using models and tools developed in the TECHNEAU project.

References

Gruškeviča K., Juhna T., Østerhus S., Tihomirova K. Influence of water velocity and NOM composition on corrosion of iron pipes . In: Cost action 637 METEAU materials and related substances in drinking water, Portugal, Lisbon, 29.-31. October, 2008. - 24-25.

Neilands K., Rubulis J. and Juhna T. (2009) Application of Online Monitoring, Resuspension Potential Method and Unidirectional Flushing for Control of Drinking Water Quality in a Distribution Networks, Latvia. IWA 1st Eastern European Regional Young Water Professionals Conference proceedings, Minsk, 362-371

Riga Water Ltd., (2008) personal communication with Rigas Udens Ltd. representatives

Rubulis J., Verberk J.Q.J.C, Vreeburg J.H.G, Gruškeviča K. and Juhna T. (2008). Chemical and microbial composition of loose deposits in drinking water distribution systems, p.695-702. In proceedings: 7th International Conference Environmental Engineering, Vilnius Gediminas Technical University, Lithuania.

Vreeburg J.H.G. (2007) Discolouration in drinking water systems: a particular approach, Academic dissertation, Delft University of Technology, Delft, 183.

Antoun E. N., Dyksen J. E. and Hiltebrand D. J. (1999) Unidirectional flushing: a powerful tool, J.AWWA, 91(7), 62-71.

http://www.hach.com, Internet – webpage of Hach Company which manufactures and distributes analytical instruments and reagents used to test the quality of water and other aqueous solutions

http://www.elkora.lv, Internet – webpage of Elkora Company which manufactures and distributes analytical instruments for measuring flowrates etc.

http://www.appliedinstrumentsco.nz, Internet – webpage of distributors of analytical instruments for measuring flowrates etc.

Matsui Y, Yamagishi T., Terada Y., Matsushita T. and Inoue T. (2007) Suspended particles and their characteristics in water mains: development of sampling methods, J.Water Supply: Research and Technology-AQUA, 56(1), 13-24.

Mays L.W. (2000) Water Distribution Systems Handbook. 1st edn, American Water Works Association, New York, USA, 523

Neilands K., Rubulis J. and Juhna T. (2009) Application of Online Monitoring, Resuspension Potential Method and Unidirectional Flushing for Control of Drinking Water Quality in a Distribution Networks, Latvia. IWA 1st Eastern European Regional Young Water Professionals Conference proceedings, Minsk, 362-371

Polychronopolous M., Dudley K., Ryan G. and Hearn J. (2003) Investigation of factors contributing to dirty water events in reticulation systems and evaluation of flushing methods to remove deposited particles: A review, Water Science and Technology: Water Supply, 3(1-2), 295–306.

Riga Water Ltd., (2008) personal communication with Rigas Udens Ltd. representatives

Vreeburg J.H.G. (2007) Discolouration in drinking water systems: a particular approach, Academic dissertation, Delft University of Technology, Delft, 183.

Vreeburg J.H.G. and Boxall J.B. (2007) Discolouration in potable water distribution systems: A review, Water Res, 41(3), 519-529

Vreeburg J. H. G., Schaap P. and van Dijk J.C (2004) Measuring Discoloration Risk: Resuspention Potential Method. IWA Leading Edge Conference, Prague.

Appendix 1

Table 1: Major risks and mitigation actions for the water supply of Riga

Risk	Possible consequnces	Mittigation action
R1. Pollution of surface water sources from industry and treated sewerage upstream pollution	Presence of emerging pollutant e.g EDS (pharmaceuticals) new type of algal toxins	More information about efficacy of treatment process isneeded. For this water treatment plant simulator is being developed.
	Breakthrough of protozoa	More data about pathogens removal at artifical groundwater recharge plans is needed. Novel sampling and analyses methods was developed.
R2. High level of natural organic carbon and inefficient removal of NOM in biofilters.	Chlorine consumption Risk of cancernogenic substances formation in drinking water	Replacement of BAC filter with granual activated carbon filters.
R3. Deterioration of water quality in the networks	Corrosion of water pipes and leakages	Adjustment of pH at surface water treatment plant with CO_2 purging
	Accumulation of sediments and turbidity in peak flows (e.g morning hours, during repair)	Flushing of water supply system with unidirectional method
	Bacterial regrowth in the networks: chlorine consumption, small animals, smell and taste problems protozoa and viruses intrusion	Modelled based dosing of chlorine.

Table 2: Parameters Daugava WTP

Water quality	Flow	Raw water	MC	RSF	OZ	BAC	Chlorination
	DOC, mg/l	15.76±3.97	16.46±4.39	6.33±3.25	6.18±2.11	4.99±1.90	
	UV254	4.74±0.14	0.72±0.12	0.14±0.03	0.07±0.02	0.066±0.016	0.05±0.007
	pH (25°C)	7.81±0.20					6.83±0.08
	Conductivity, µS/cm	298±45					336±35
	Alkalinity, mmol/l	3.10±1.58					1.82±0.40
	Hardness,mmol/l	1.71±0.058					1.76±0.09
	Turbidity, NTU	2.18±0.76					0.11±0.03
	Suspended solids,mg/l	3.49±1.94					
	Coliforms, VIS/100ml	29.71±23.77					
	Tot Cl, mg/l						0.40±0.08
Manupulation		Ozone dose	Coagulant dose	Backwash	Ozone dose	Backwash	Chlorine doze
Design		1-3 mg/l	15-20 mg Al_2O_3/l		2-8 mg/l		0.5-1 mg/l
		Number of units 2	Number of units 16	Number of units 14	Number of units 4	Number of units 14	
		Heigh reactor	Volume of reactor	Filter surface	Height reactor	Filter surface area	

Table 3: Individual flushing plan

	Nr. of hydrant	Valves to be closed	Valves to be opened	diameter	the adress of hydrant
1	5625/3693	9313, 9545		300	Ozolciema 56-1
2	6014	9313, 9545		300	Ozolciema 26
3	3510	9545, 9314,	9313	200	Ozolciema 56/4
4	2472	9545, 9618, Nr.X	9314	300/200	Valdeķu 54/8
5	2904	9545, 9618, 9614	Nr.X	200	Valdeķu 52/2
6	4915	9618, 9616, 9311	9614	400	Valdeķu iela 53
7	1465/ in map hydrant without nr are located in the same manhole as valve nr. 9530	9618, 9616, 9309, 9310, 9523 or 9527	9311	400/200	Ozolciema 44
8	1465/ in map hydrant without nr are located in the same manhole as valve nr. 9531	9618, 9616, 9309, 9310, 9531	9531, 9523 or 9527	200	Ozolciema 44
9	6014	9618,9544, 9309, 9531, 9313, the valve without Nr. (in the same manhole as hydrant nr. 5625)	9545, 9310, 9616 (??? FOR CONSUMPTI ON),	400/300	Ozolciema 26

Table 4: The summary of practical recommendations from flushing in the Riga Case Study

N	Observation
1	Registration of complains
2	insufficient pressure from WTP to perfume UDF
3	complicated distribution network
4	≥ 400 mm pipelines, which cannot be cleared with UDF
5	Accessible storm water drainage (Figure 20)
6	no possibilities to release the flushing water because house basements are located below the street level
7	traffic jams due to flushing
8	missing or damaged tablet with hydrant connection data (Figure 21)
9	flooded *Riga* type hydrant (2 m in deep) due to raised groundwater level and dirt's (Figure 22) which cannot be used for UDF and RPM without cleaning
10	malfunctioning hydrants due to rare usage
11	broken hydrant by third person (Figure 20)
12	buried, asphalted hydrant by third person (Figure 24)
13	closed valves in distribution loops of new residential areas
14	broken valves
15	Aggressive reaction of consumers due to waste water in flushing

Appendix 2

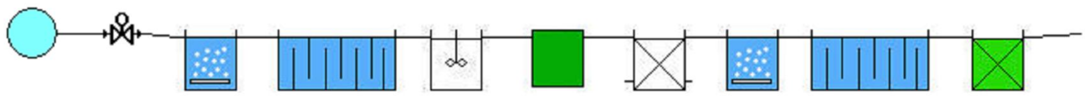

Figure 1: Flowsheet Daugava WTP in SimEau

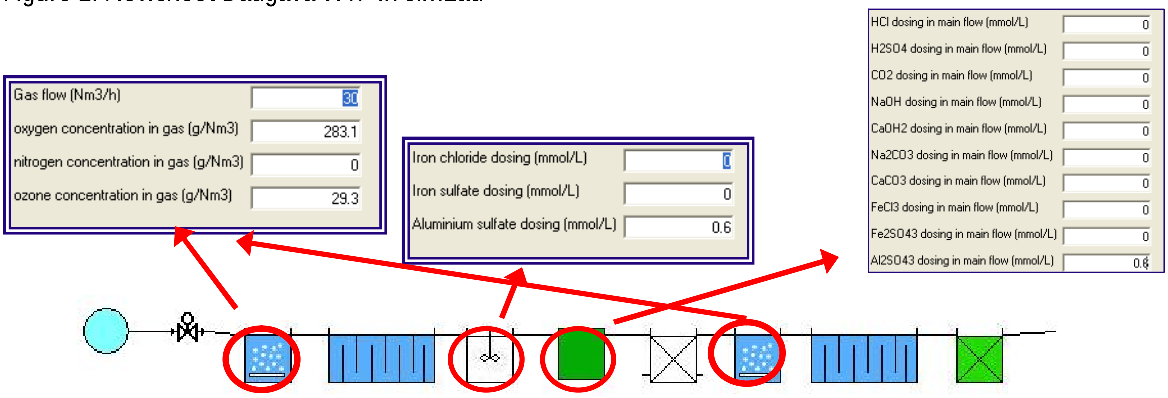

Figure 2: Possible manipulations Daugava WTP

		Raw water	MC	RSF	OZ	BAC	chlorination
Water quality	Flow						
	Temperature						
	DOC, mg/l	15.76±3.97	16.46±4.39	6.33±3.25	6.18±2.11	4.99±1.90	
	UV254	4.74±0.14	0.72±0.12	0.14±0.03	0.07±0.02	0.066±0.016	0.05±0.007

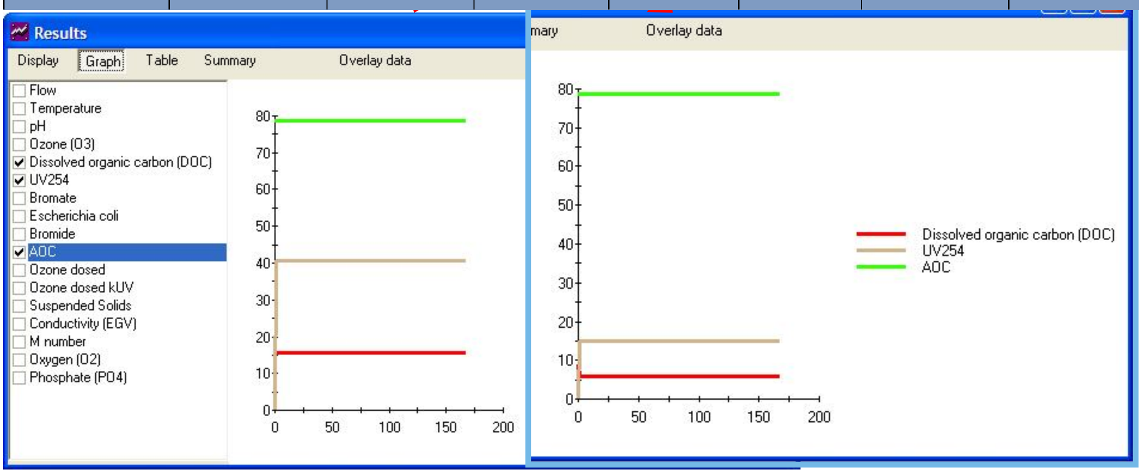

Figure 3: Simulation results for removal of organic matter at Daugava WTP

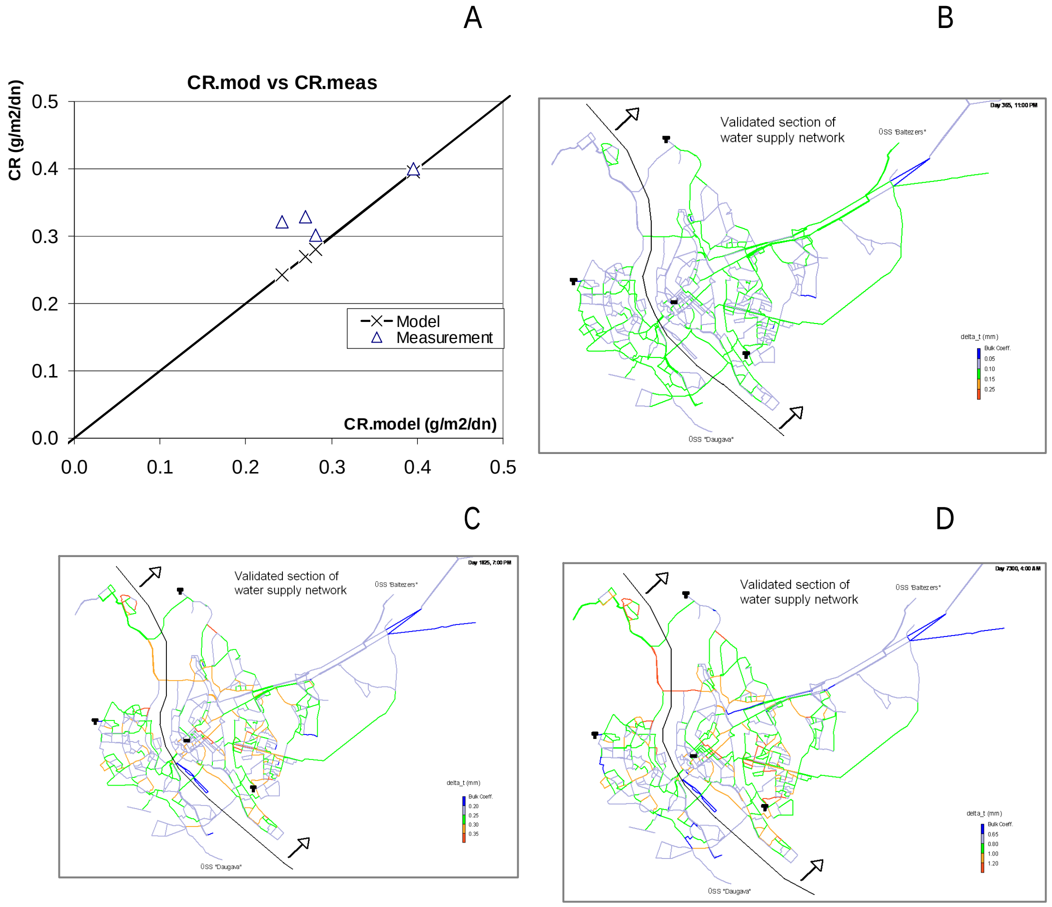

Figure 4: A) correlation between modeled and measure data in Riga; B) situation after first year of exploitation, where colors in legend indicates: blue ≤0.05 mm, gray 0.05 - 0.10 mm, green 0.10 - 0.15 mm, orange 0.15 - 0.25 mm, red >0.25 mm; C) situation after 5 years, with legend: blue ≤0.20 mm, gray 0.20 - 0.25 mm, green 0.25 - 0.30 mm, orange 0.30 - 0.35 mm, red >0.35 mm; D) shows situation after 20 years, with legend: blue ≤0.65 mm, gray 0.65 - 0.80 mm, green 0.80 - 1.00 mm, orange 1.00 - 1.20 mm, red >1.20 mm

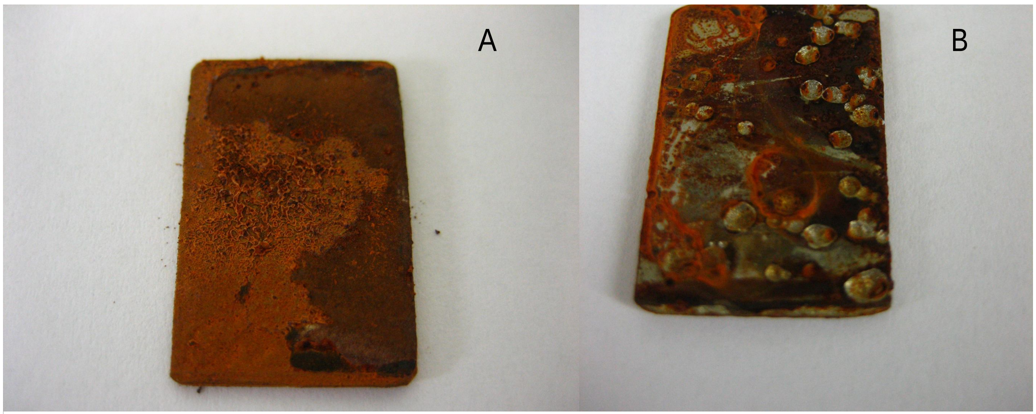

Fig. 5: Corroded iron coupons after exposure to A) groundwater and B) chemically treated surface water. Pitting due to low pH is clearly seen.

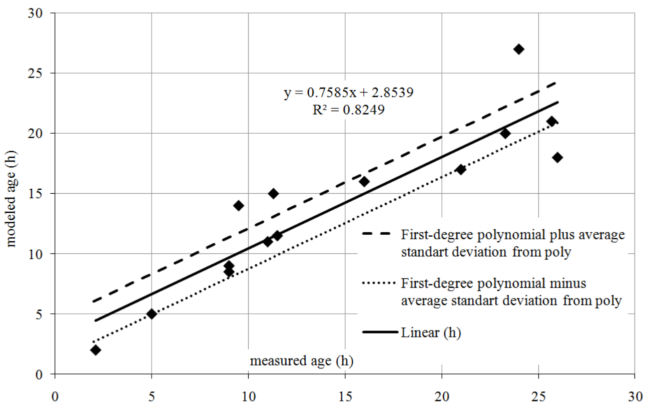

Fig. 6: Correlation between modeled and measured water residence time

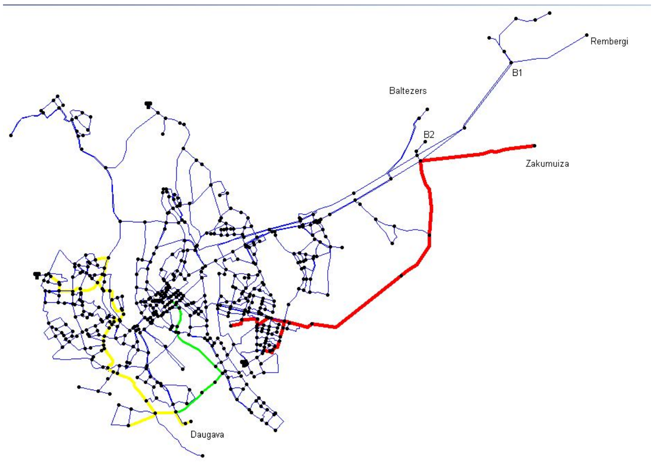

Fig. 7: Routes on water on which water sampled were taken for validation of bacterial regrowth

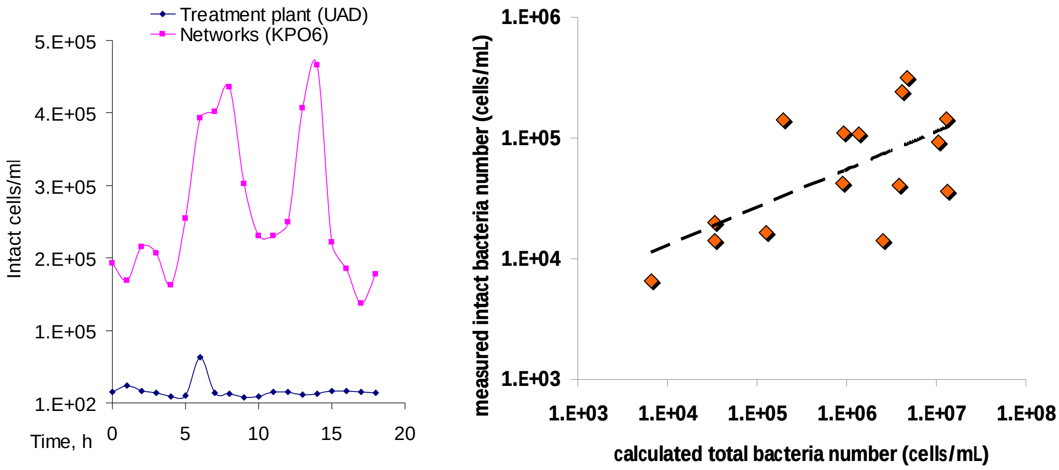

Fig. 8: A) Concentration of intact cell number at the treatment plant and in distribution networks after 15 hours of travel in the networks; measurement made over period of 19 hours; B) Correlation between measured and modeled results.

Figure 10. The photometer ULTRATURB plus ™ with controller sc100™ used for online turbidity measurements (http://www.hach.com)

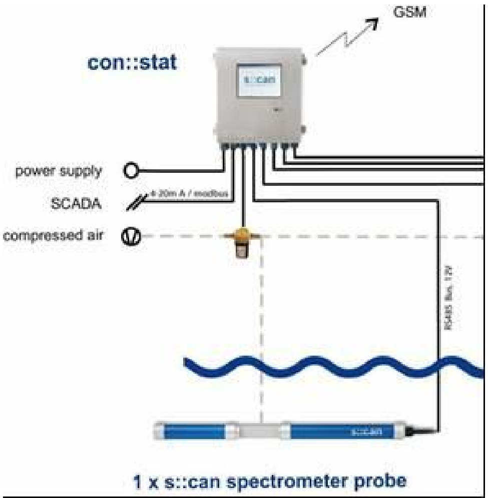

Figure 9. Spectro::lyser™ sensor and data loggin device con::stat™ (http://www.s-can.at/)

Figure 11. The UDF in case study Riga were supported by experts from TZW-Dresden. In March 2009 in field works assisted Sebastian Richardt (in the middle of A) while in Autumn joined Daniel Schumann, next to mobile cart (B).

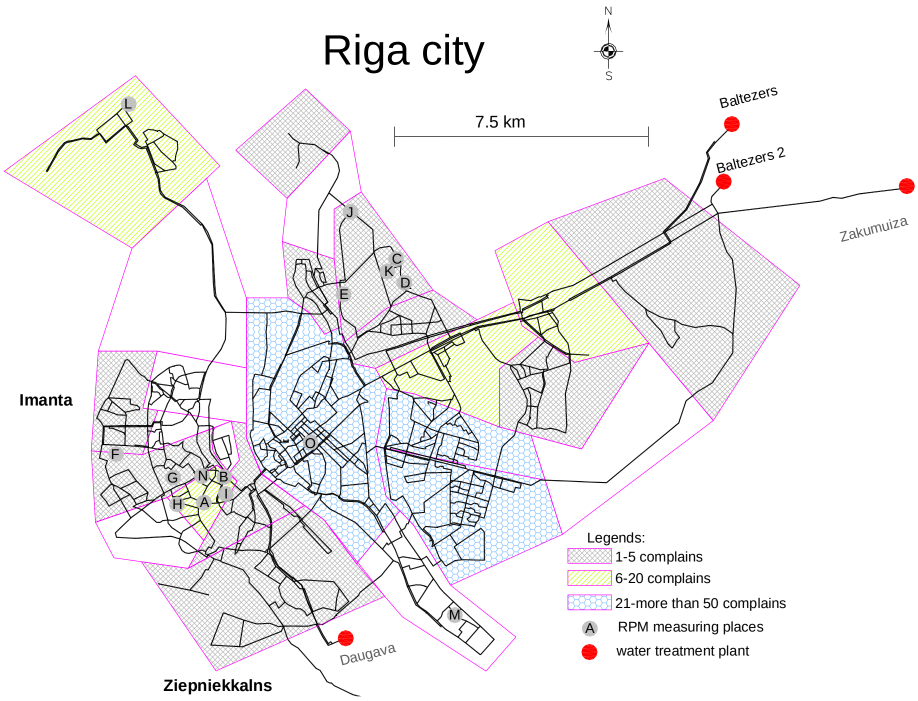

Figure 12. The map of the drinking water distribution network of Riga city with indicated communities of Imanta and Ziepniekkalns. With hatched areas indicated number of complains of discoloration for years 2005-2007 are shown, with red points - location of WTP, with grey points – measurements of RPM in the year 2008. (adapted from Neilands et al., 2009).

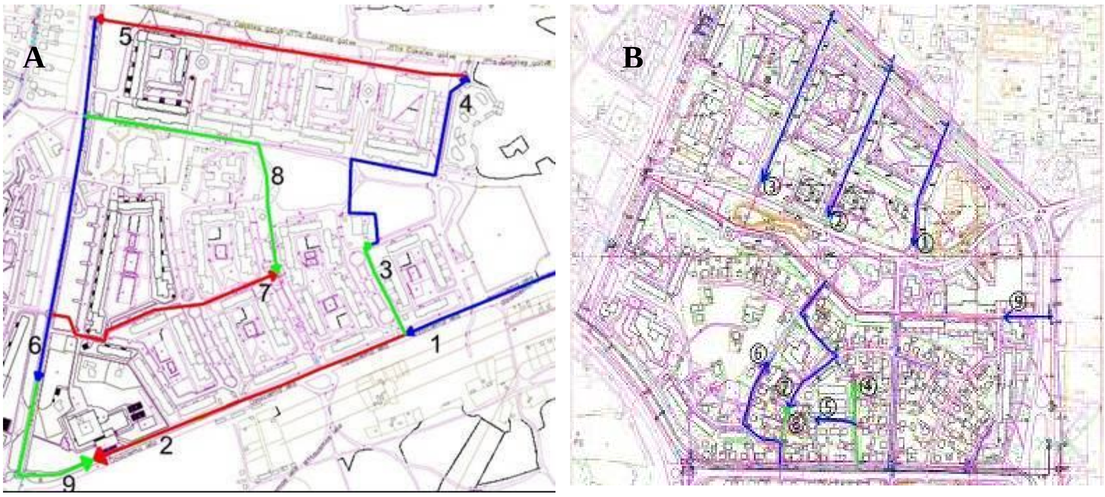

Figure 13. Overview of flushing routs in Ziepniekkalns (A) and Imanta (B) communities, Riga case study. With arrows showed location of hydrants used for UDF and with numbers in circles – sequence of flushing (created with AutoCAD 2005)

Figure 14. Training of Riga Water Ltd. staff for UDF

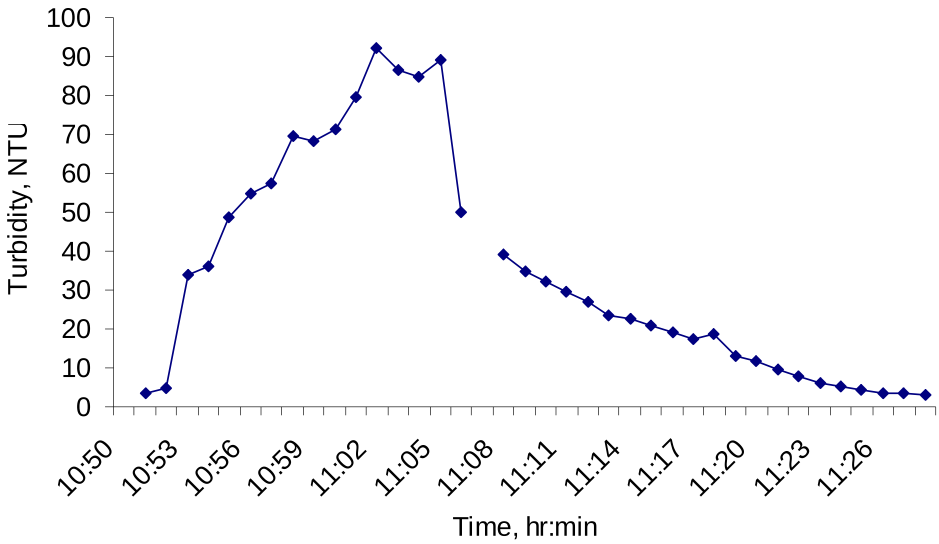

Figure 15. The turbidity measurements within UDF in route 4 for 200/300 mm CI pipe

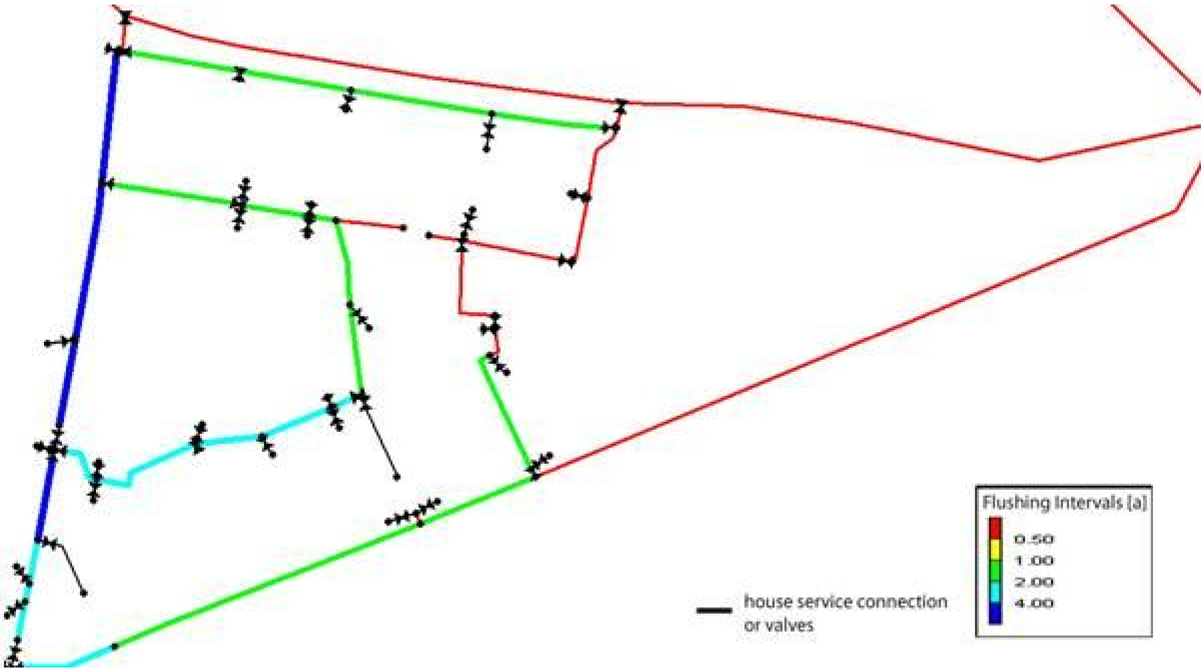

Figure 16. Predicted flushing intervals, visualized with EPANET2. The calculated flushing intervals are shown using a safety factor of 1.5.

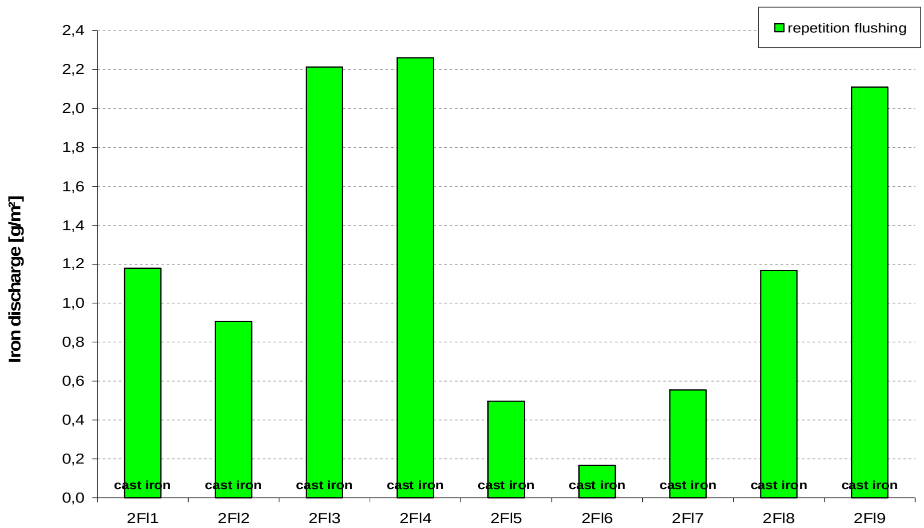

Figure 17. Iron discharge in grams per square meter

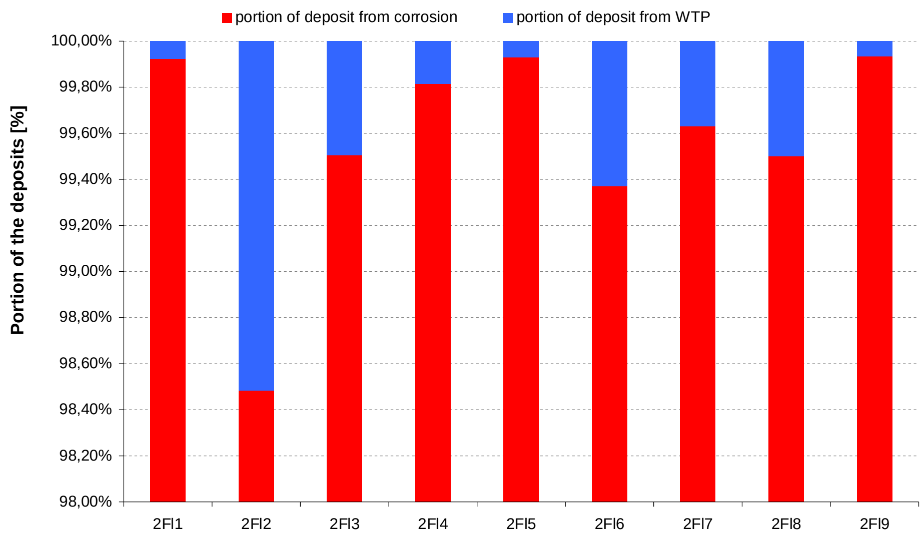

Figure 18. Portion of deposits in the pipes resulting from corrosion

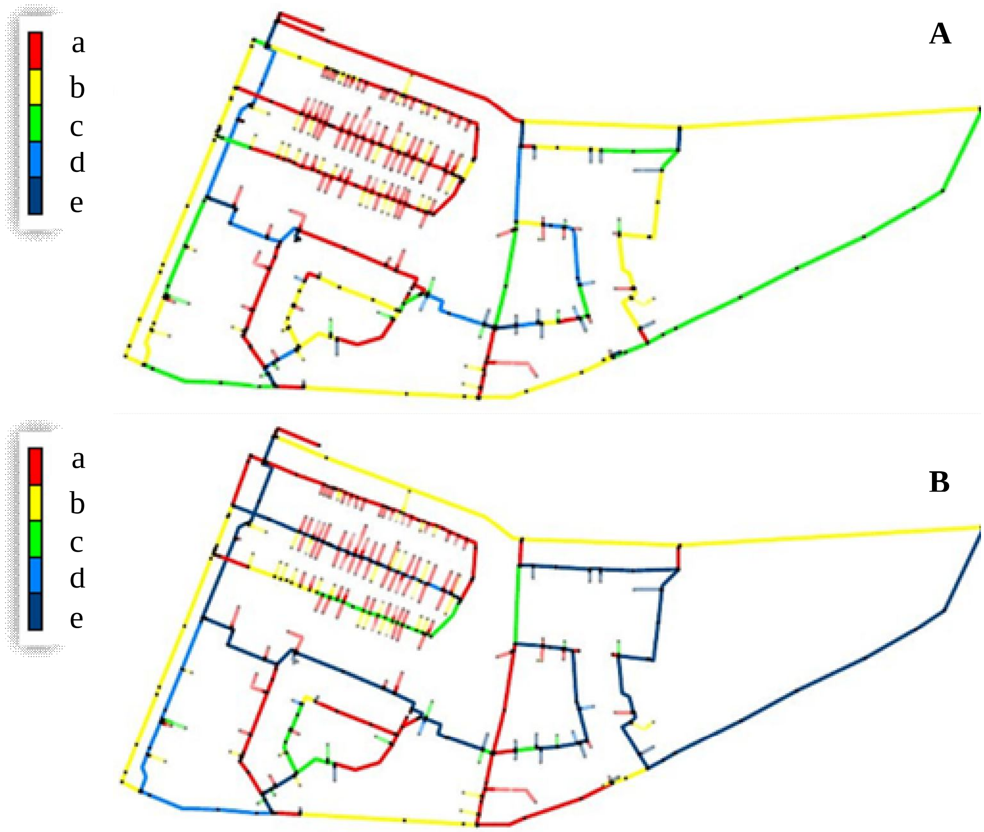

Figure 19. Maximum velocities during 24 hour period, without and with (B) valve manipulations (A)

Figure 20. Flooded streets (A, B) during Riga case study illustrate a problem of flushed water drainage in the green area and the storm water inlets

Figure 21. Damaged tablet with hydrant connection data

Figure 22. Riga type hydrant flooded and filed with sand (2 m in deep) due to raised groundwater level

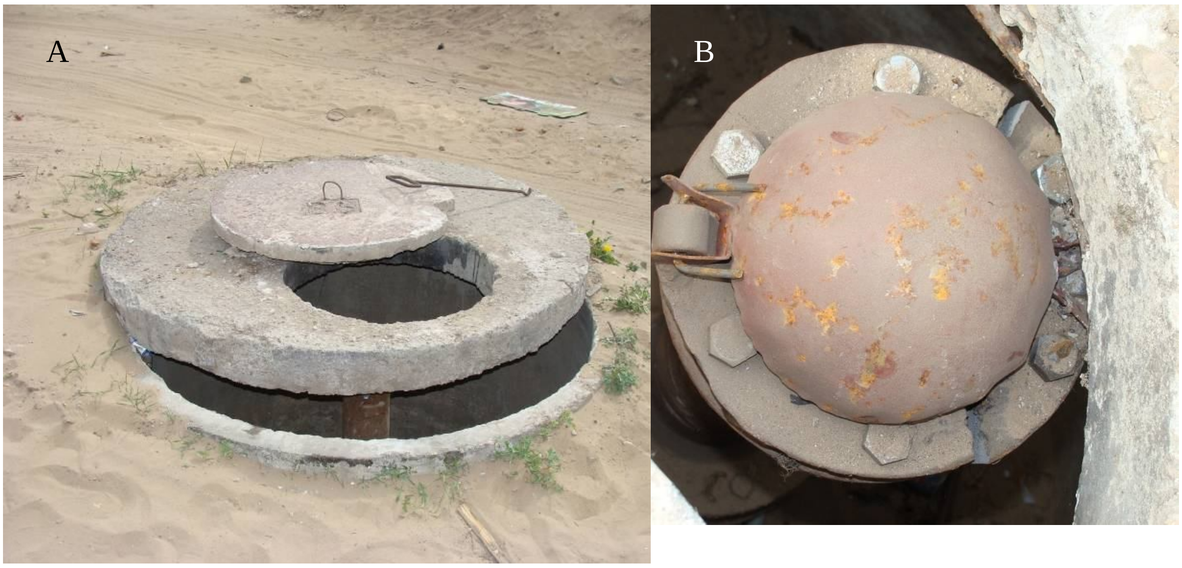

Figure 23. A damaged manhole of hydrant (A) and a broken hydrant (B) (by unknown person) in Riga case study

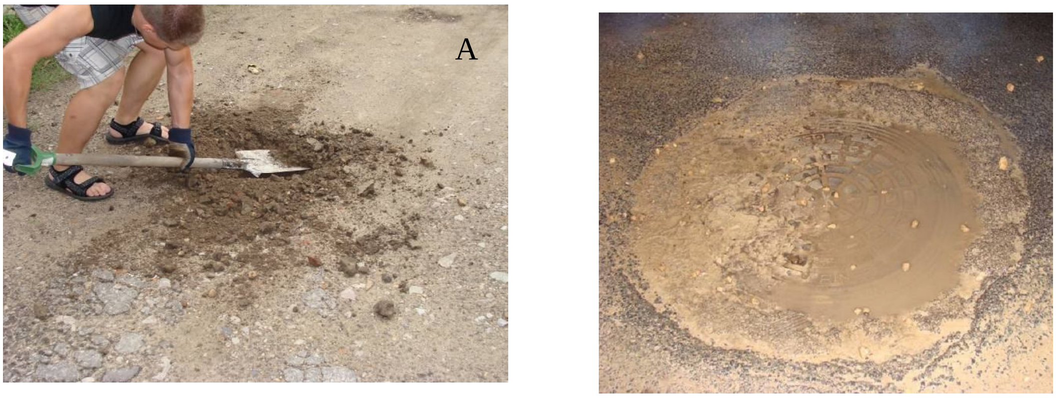

Figure 24. Buried hydrants - with a gravel layer (A) and covered with asphalt (B) on road (by unknown persons)