ONLINE MEASUREMENT USAGE FOR PREDICTING WATER AGE FROM TRACER TESTS TO VALIDATE A HYDRAULIC MODEL

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Abstract

The tracer tests were performed using two approaches in the drinking water distribution network (1374 km) of Riga city, Latvia with the goal to verify and validate a hydraulic model build up in Epanet 2.0. The water is supplied for 700 000 inhabitants with average daily water demand of 1500 l/s from six different water sources. The each water source has a different electric conductivity (EC) value with the lowest numbers for deep groundwater 272±25 µS/cm (25^{O}C) and the highest for surface and artificially recharged groundwater 468±100 and 784±18 µS/cm, respectively. The significant difference for EC in sources was used as a natural tracer. The first measurement approach is based on field works during shut-down or start-up of WTP due to monthly working regime or yearly drainage of clear water tanks at stations located in the north-east of city. In total more than 20 locations in distribution network were used for measurements of EC from hydrants and/or at taps in buildings applying online conductivity meters 3400sc™ (Dr. Bruno Lange GmbH&Co, Germany) and condu::lyser™ (s::can Meßtechnik GmbH, Austria) in predictable time interval. The second approach of tracer measurements was based on EC measurements in network within close distance to track minor changes of EC due to production/consumption ratio. The hydraulic model of Riga city was validated in 8 nodes with the maximum age of 25:40 hours, while the distal nodes in model accounts for 60 hours. Results showed that in order to measure correct changes of trace element it is necessary to do it very close to transient pipes with high flow. The measurements of tracer near reservoirs in network are unpredictable due to proper mixing of water. The approach of measurements with two online instruments in close distance (up to 5 km) to track minor changes of EC can be useful for validation of hydraulic models. However, the statistical analysis (z-test) of this method showed significant difference between mean values of measurements which can be explained with too many uncertainties (cross-connections of parallel lines, loops) for water mixing in city with population of 700 000 inhabitants.

Keywords
Electric conductivity, hydraulic model, online instruments, retention time, tracer tests, water age

1. INTRODUCTION

Water quality problems that can be exacerbated by increased water age include organic and inorganic disinfection by-products formation, decreased corrosion control effectiveness, nitrification, and microbial growth/regrowth. Further the importance of stable water quality within distribution network are increased since are found increase in numbers of waterborne outbreaks related to distribution system issues (Craun and Calderon, 2001). Many cities in the 20th century experienced significant development of infrastructure which was lead by growth of industry. At the same time increased usage of drinking water, distribution networks, pipe diameters etc. While in nowadays more and more attention is paid to save water. As well in many Eastern European cities industry declined and as a result, the domestic sector became the major drinking water consumer, causing the total water flow rate from tap even below 80-120 l/per capita/day in Riga city, Latvia (Rubulis et al., 2001). Therefore current flows in the networks are too low for previously constructed pipes, thence water age increases in distribution system. The Water Industry Database indicates an average distribution system retention time of 1.3 days and a maximum retention time of 3.0 days based on a survey of more than 800 U.S. utilities (AWWA and AwwaRF, 1992).

Tools for evaluating water age include hydraulic models, tracer studies, and monitoring programs (AWWA, 2002). Currently, to determine the water age in water distribution system widely is used chemical tracers, such as fluoride, calcium chloride, lithium chloride or other elements. The maximum amount of the chemicals used for tracer tests in distribution system is regulated. Lithium chloride is the chemical which is used for distribution system tracer studies in the United Kingdom; however, the United States water consumers have not accepted this method so it is not widely used by United States water utilities (AWWA and EES, 2002). The amount of fluoride in water is determined by the maximum allowable concentration in European Union by 1.5 mg/l (including Latvia), in USA depending on annual average of maximum daily air temperatures is suggested optimal fluoride concentration – in the State of California it is from 0.7 mg/l to 1.2 mg/l. If fluoride is used as a tracer, it may be preferential to discontinue fluoride feed so that interference with fluoride uptake on pipe walls for newly-fluoridated systems can be avoided, consequently state health departments may not allow for the purposeful discontinuation of fluoridation (AWWA and EES, 2002). However, tracer tests in Fort Collins, Colorado distribution system (Simon et al, 2006) were performed with fluoride to produce a positive step with a goal concentration of 1.0 mg/l with the background fluoride concentrations. If other tracers are used such as calcium chloride or sodium chloride, State environmental agencies may require that food grade chemicals are used or that other assurances are made concerning the safety of the tracer (EPA, 2003). Usually substances served as a trace are added to the water, but in the distribution systems composed from several sources with different water quality it is possible to use only natural water parameters such as high electric conductivity, hardness or organic matter measured as total organic carbon for tracing a distribution system (Daley, 2007) and they are effective with systems which have more than one source water treatment plant with varying water qualities (DiGiano et al., 2005).

Tracer concentrations should be measured frequently in order to determine parameters accurately. To facilitate the trace measurement in the distribution system and to reduce the costs of experiments and human resources, it is suitable to use online instruments. Skadsen et al (2008) shows that chlorine, dissolved oxygen, electric conductivity (EC) and UV_{254} values observed of the system were almost accurate with the grab samples. On-line instruments exhibited greater variability than the results of grab samples, because of instrument`s impressibility to flow and grab samples lower obtaining frequency (Skadsen et al, 2008).

Careful calibration of both hydraulic and water quality models is needed to generate an accurate prediction of water age and water quality conditions under varying demand scenarios (AWWA, 2002). Steady-state travel time models were first introduced in the mid-1980s (Males et al, 1985). According to the Balci (1997) model, verification is substantiating that the model is transformed from one form into another, as intended, with sufficient accuracy. Model verification deals with forming the model correctly. In turn Hillston (2003) stated that validation is the task of demonstrating that the model is a reasonable representation of the actual system, i.e., it reproduces a system behavior with enough fidelity to satisfy analysis objectives.

This paper presents the results of the EC tracer tests, performed with online instruments. The data obtained at distribution network were used to validate a hydraulic model.

2. MATERIALS AND METHODS

2.1 The Network

The total length of distribution network is 1 374 km, serves for 700 000 consumers and average daily demand is 1500 l/s. The 76% of all pipe length consists of cast and ductile iron, 19% of steel and all other of reinforced concrete and polyethylene. The diameters of pipes ranged from 100 to 1200 mm.

The city is supplied from six water treatment plants (WTP). Five of them are located in the north-east where naturally and artificially recharged groundwater is abstracted periodically according to demands. The chlorination is used to provide residual disinfection. Two of the WTP - Baltezers and Baltezers-2 had high EC due to usage of surface waters from the Lake Mazais Baltezers as artificial recharge. While in the WTP Zakumuiza, Baltezers-1 and Rembergi water is abstracted from deep wells and has low EC values. One of the WTP Daugava is located in the south and produces drinking water from the River Daugava where ozone, Alum, lime and chlorine are used for treatment. To level fluctuations of daily demand into the distribution network three reservoirs are operated.

2.2 Electric Conductivity Tests

Using measurements of EC, series of tracer tests were performed to verify and validate hydraulic model of distribution network of Riga city (Latvia). Fortunately, this distribution network has different stations where the water is taken from and each station has a different EC value, therefore nothing was put to the water. Field measurements were compared to the water retention time modeled in EPANET 2.0 (Rossman, 2000).

The tracer study was conducted in two ways. The first approach of measurements is based on measurements during yearly drainage of clear water tanks at WTP located in the north-east (Figure 1) and/or monthly operation regime of these WTP-s depending on the water consumption/production base. In both cases, procedure foresees the shut-down of WTP pumps for several days which provide remarkable changes of EC for several hundreds of µS/cm in distribution network and possibility to measure them with conductivity meter in predictable time interval. The second approach of tracer measurements are based on EC measurement in the network with two online meters in near distance to track minor changes of EC due to production/consumption ratio. All field measurements were recorded for several hours and were made from hydrants or at the taps in the buildings belonging to drinking water supplier. For field measurements, there were used online instruments 3400sc™ with controller sc 100™ (Dr. Bruno Lange GmbH&Co, Düsselfdorf, Germany) and condu::lyser™ with controller con::stat™ (s::can Meßtechnik GmbH, Vienna, Austria) supplemented with portable manual EC meter Cond 315i, (WTW, Germany). To validate hydraulic model within two year period (autumn 2008 – spring 2010) there were made more than 50 sets of measurements using tracer and two point pattern tracking approach in 24 locations of the distribution network. All instruments were calibrated in lab-scale and measurement error was calculated according to standard method for electrical conductivity. It was estimated that the uncertainty of the method is 17.923, consisting of apparatus, temperature, buffer and sample conductivity measurement uncertainty. For example, if the electrical conductivity is 500 µS/cm, combined uncertainty will be 3.6% (17.923x100/500) and extended uncertainty – 7.2% (3.6%x2).

2.3 Hydraulic Model

The hydraulic model is build up in the EPANET 2.0 (Rossman, 2000) and hydraulic conductivity is calculated with Darcy-Weisbach equation. Total length of distribution network in model is 538 km

(39.16% from total length in nature). The hydraulic model consists of 919 pipes and 571 nodes (Figure 1). There are not included 80% of pipes with diameter 100, 150 mm. In general hydraulic model do not have high pressure areas located all around of city (Figure 1). The topography served by Riga Water system varies from an elevation of 0.7 to 17 m above sea level.

Before model verification and validation, the model was updated with the newest data which serves as input parameters for model – adjusting of the daily patterns of consumption and pump flows for node demands. There was performed correction of nodal demands in model according to the newest consumptions. The water level changes in reservoirs and pressure calibration in model were corrected using 15 online pressure measurement points in network from SCADA system and adjusting pipe roughness in transient lines.

In EPANET 2.0 software the model calculates average water residence time at the nodes by counting water age and flow products, and dividing this total amount with the flow at the input of nodes.

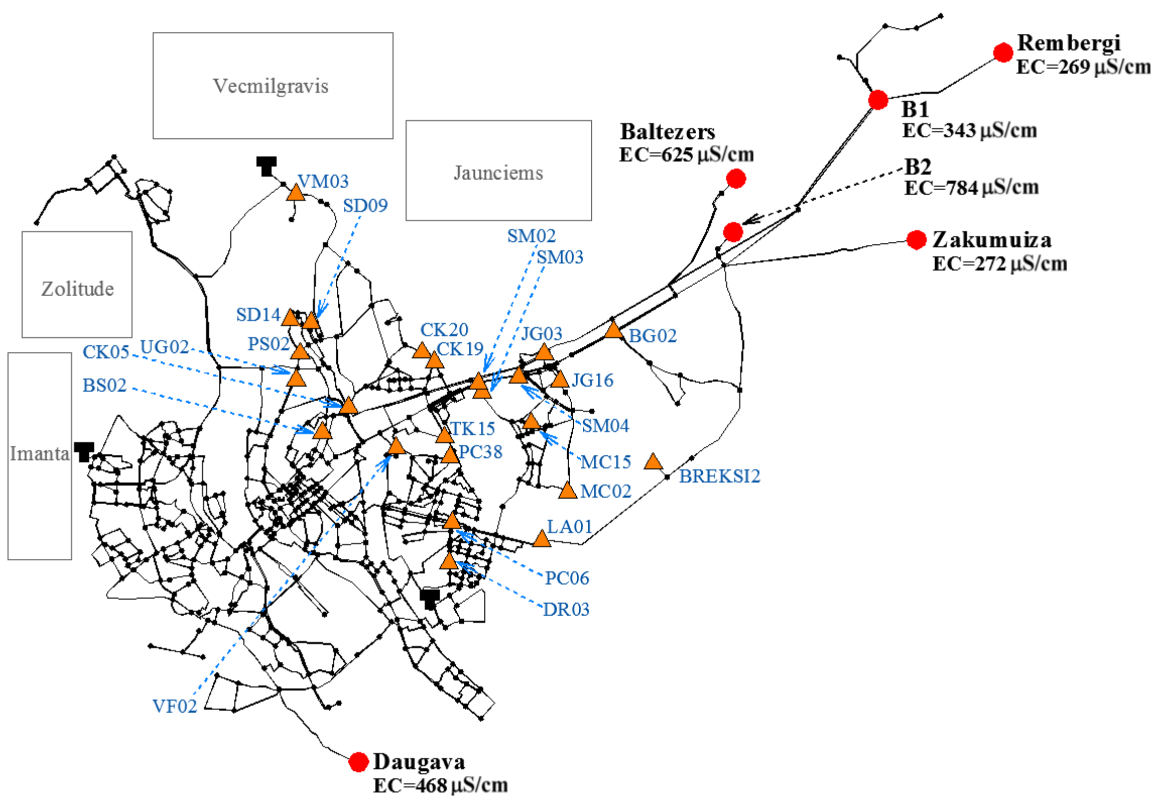

Figure 1. Service area of Riga Water treatment plants in EPANET 2.0. with three reservoirs; as a circles indicated WTP *viz.* Baltezers, Zakumuiza, Baltezers-1 (B1), Baltezers-2 (B2), Rembergi, Daugava and EC at sources; with triangles and abbreviations for example BG02 – monitoring locations of EC in network; and with grey squares *viz.* communities of Imanta, Zolitude, Vecmilgravis and Jaunciems – high pressure zones which are not included in this hydraulic model

3. RESULTS AND DISCUSSION

To achieve a successful water age model validation, it is necessary to obtain accurate water residence time data from measurements on the field. In this case online meters were used to measure water age applying EC tracer from different WTP-s with various concentrations of salt ions, where capturing of significant decrease or increase of EC in distribution system were one of the most important component in the measurement process. Figure 2 shows an increase of the EC in one of the locations (SM04) in distribution network on 9th of October, 2009. A week before the measurement was done the WTP Baltezers was shut down for maintenance, at the same time WTP Zakumuiza and WTP Baltezers-2 were running. Modelling the situation in hydraulic model using option "Quality" and parameter "Trace", it was obtained that during malfunction of the WTP Balterzers, at the node SM04 was 75% of water from Zakumuiza (Figure 3.a) and 25% of water from Baltezers-2 (not showed). It means that for one week the EC should be relatively low (~400 µS/cm) since major part of water at source had EC 272µS/cm. On the day of measurements the pumps at the WTP Baltezers was turned on, WTP Baltezers-2 turned off and rapid increase of EC was predicted in model, because when the WTP Baltezers is operating in normal regime, at node SM04 is only water from the WTP Baltezers (Figure 3.b) with relatively high EC (~625µS/cm). Measurements showed that both the obtained value of water age (approximately 9 h) at this node is reasonable and the trace of concentration of water from different WTP is rather good.

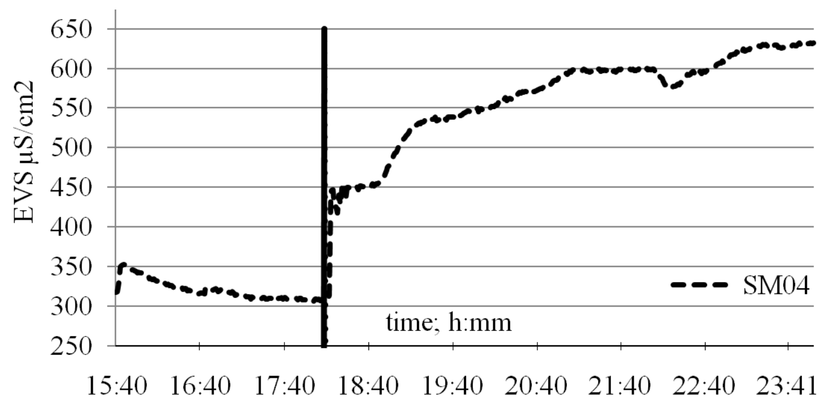

Figure 2. Measured development of conductivity during tracer studies in model node SM04. Vertical line in bold indicated predicted time in model when increase of EC concentration begins

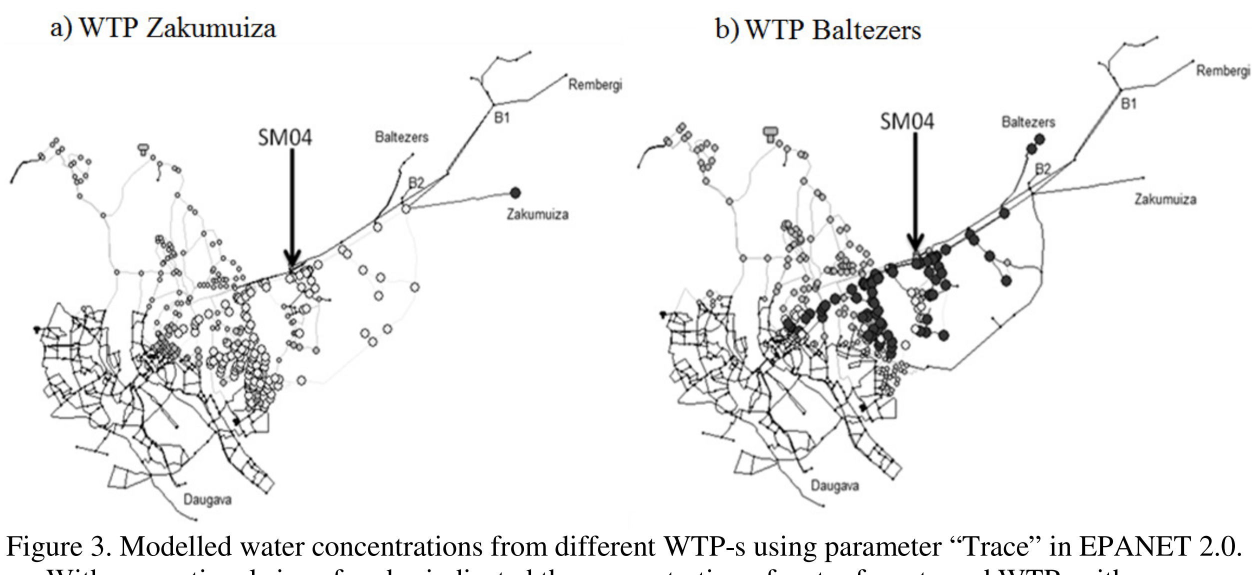

Figure 3. Modelled water concentrations from different WTP-s using parameter "Trace" in EPANET 2.0. With proportional size of nodes indicated the concentration of water from traced WTP; with arrow indicated one of locations *viz.* SM04 of field measurements

A different approach to measure water age was used instead of significant changes of concentration of EC. It is based on the EC measurement in the network for several days with two online meters located close to each other with the purpose to track minor changes of EC due to hourly production/consumption ratio. In the location~~s~~ of node SM04 water age was determined before these measurements and corresponds to 9 h. Modelling the situation in hydraulic model showed that during measurements in both locations: node SM04 and PC38 water was mixed and supplied from WTP Baltezers and WTP Zakumuiza in following proportions: 75-85% and 15-25%, respectively. The distance between both locations (SM04 and PC38) is 4.5 km and the measurements of EC had a different pattern in a range from 378-428µS/cm. Even there is a statistically significant difference between mean values of EC measurements in locations SM04 and PC38 ($z=4.69$; $P<0.05$, two-tailed z-test) we accepted these results as successful since in both places were detected typical pike of EC line at 14:14 and 15:02 o'clock (Figure 4). Statistical difference in both measurements can be explained with complicated layout of network since water is supplied in two 600 mm parallel lines with at least 4 cross-connections between them and numerous smaller diameter loops of 100-400 mm close to the main pipes (Figure 5) which brings possible mixings etc. Applied principle of two parallel online meter measurements to validate hydraulic model can be much successful in smaller networks where pipe layout is much simpler compared to the network of 700 000 inhabitants like Riga city.

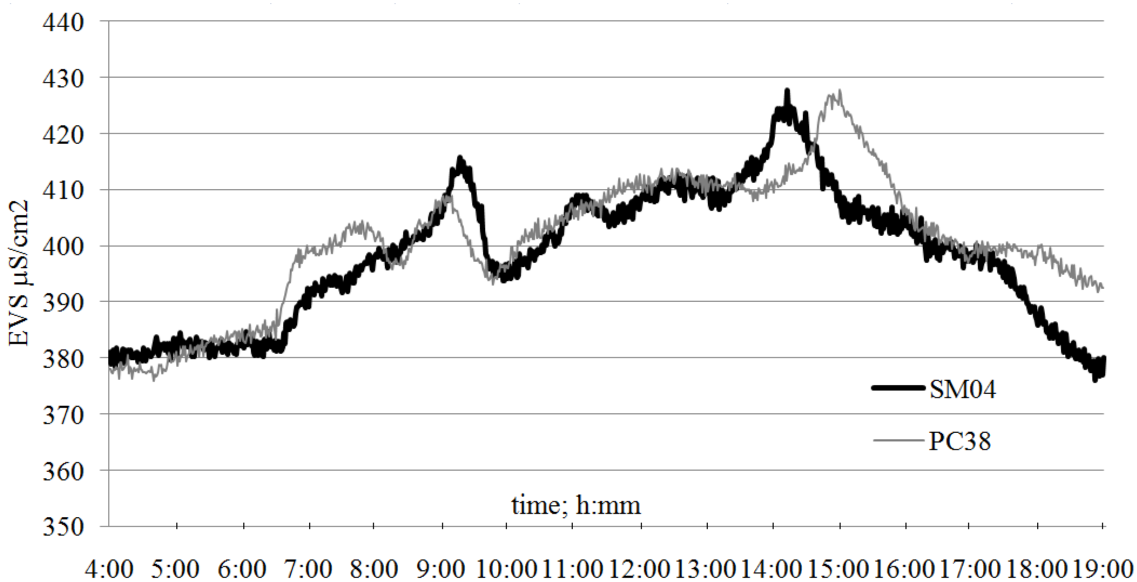

Figure 4. The pattern of normalized EC measurements during tracking process with two online meters in model nodes SM04 and PC38. The pikes at 14:14 and 15:02 o'clock for both lines were accepted as sufficient to determine water age

In total, the model results were compared to the measured water age by EC tracer in 24 locations. In ten locations significant decreases/increases of EC concentration cannot be contributed to usage for model verification. In these nodes retention time ranged from 10-60 h according to simulations with hydraulic model. Some of these nodes (MC02, MC15 and VF02) were deeply located in internal networks far from transit lines and had significant fluctuations of retention time according to model, such as 35-60, 24-28 and 18-24 h, respectively.

In six locations (DR03, LA01, CK05, UG02, BS02, and BREKSI2) reasonable decreases/increases of EC concentration were measured, but calculated water age significantly differs from the model results. In all of these six locations difference between the model and measured age was in the range between 3-8h. For example, location DR03 in model indicated 27h of retention time while in the field it was measured as 24h, but for location LA01 modeled retention time reached 18h while measured – 26h. In overall, the model statistically has been validated in 8 nodes with maximum age of 25:40 hours (Figure 6). The more distal location in which measured water retention time was accepted as validated was SD14. To validate the nodes, firstly a first-degree polynomial from measured results on field was obtained, which shows the average value of data. To determine whether the model age are close enough to measured age on field, the average standard deviation was calculated (s=1.68 h), defining the limits of validation.

The EC decreases/increases were difficult to determine too far from transient pipes and at the beginning of the network, because of water mixing at nodes from different stations and proximity to reservoirs (example near node VM03) where fluctuations of inflow/outflow from them greatly influenced detection of correct water age. At these locations the model also do not produced reliable results.

Figure 5. Location of nodes SM04 and PC38 in the water supply network where measurements with two online meters within close distance was done. The pipe diameter is indicated by different thickness of lines *viz.* the boldest lines indicate the largest diameters

Water age determination in model depends on water mixing at nodes. The current approach included in EPANET 2.0 (Rossman, 2000) provides a good first approximation but, in reality, it is not possible to mix different ages in this way to produce a mean age (Machell, 2006), as a result it is impossible to identify the older age component information by examining a mean age time series. Machell et al (2006) shows, that approximately 5% of the age contributions are 5 times the mean age at the node.

There are different lengths of pipelines from the water source to the nodes for calculation of water age. At the nodes there are inflows with different water age, but the outflow from the node is only the one water age which takes into account a complete mixing at the node and, basically, is some imagine of water age. On the field it is different, because each water molecule has its own age and it does not change at nodes because of mixing. The water from each source has a different water age of retention time. Increasing

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distance from the WTP, hydraulic model inaccuracy is growing, because the model's uncertainty due to water mixing at nodes is increasing.

Considering, the methods of complete mixing at nodes are not accurate to validate a hydraulic model. It is possible to do it only in certain distribution region or at some nodes, where there are not many pipe connections and loops, otherwise problems in water age calculation start. One of the main reasons is incorrect water age calculation in model, whereas the model assumes the average water age after mixing at node. While nodes are close to WTP, the distribution region has not many loops or water age is not large (average 1-24 h), the water mixing has negligible influence on model age calculation and nodes can be validated. Otherwise model's uncertainty in water age calculation gets increased. It is necessary to take into account the fact, that the larger the system is (loops, pipe connection, and water consumption), uncertainty in accurate data input in model is growing. It also affects an acquirement of correct results.

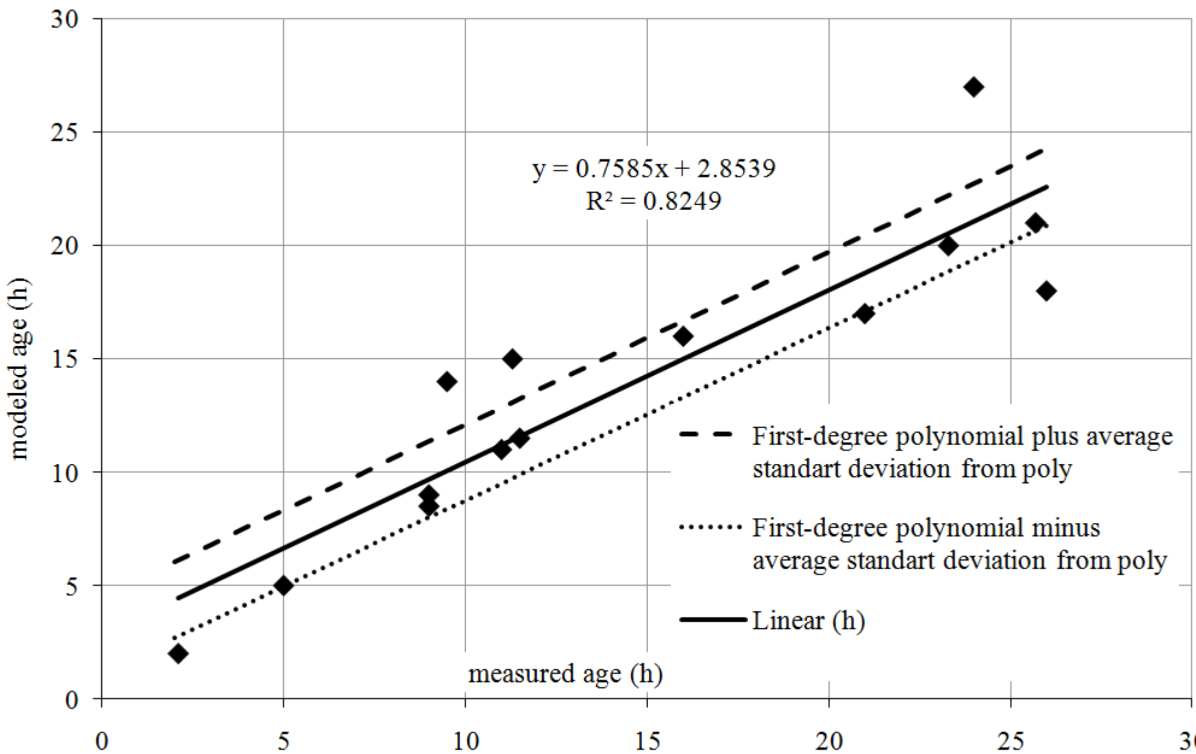

Figure 6. Comparison of water age in model and water residence time measurements on the field from EC tracer

According to measurements of hydraulic model validation were obtained modeled average velocities in pipes for peak hours which ranged from 0.13-0.30 m/s depending on pipe diameter. These values confirmed opinion of oversized pipe diameters due to significant reduction in water production which begins in 1990-ties with saving by inhabitants and stalled industry (Rubulis et al., 2001).

4. CONCLUSION

The online instruments were used in 24 locations in order to measure EC in the field for validation of hydraulic model. For model validation two different measurement approaches were used. Mostly field

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measurements were done due to significant increases/decreases of EC concentration which happens during shut down or starting-up of WTP-s with different salt concentration (from 269-784μS/cm) at source. Secondly, two online instruments located by a close distance were used to track minor changes of concentration of EC due to daily consumption/production ratio.

Based on the validated hydraulic model at 8 nodes using EC as a tracer, consecutive conclusions are made:

- The hydraulic model can be assumed as validated for locations with water retention time 25:40h while more distal nodes in the network are simulated for 60h of retention time.
- It is not possible to measure correct decrease or increase of trace element too far from transient pipes and far in the network because the network has too much loops. The changes in trace element values can be measured only very closely to transient pipes with high flow.
- It is easy to measure the tracer vibrations when the high electric conductivity concentration in water is changed by other.
- The measurements of tracer near reservoirs (example near node VM03) are unpredictable due to proper mixing of water.
- Statistical analysis (z-test) of online data with two parallel recording instruments indicated significant difference between mean values of measurements which can be explained as a result of too many uncertainties (cross-connections of parallel lines, connections, loops). While this method was considered as acceptable for validation of hydraulic model. This method can be more perspective for smaller networks with simpler pipe layout (< 100 000 inhabitants).
- Whereas EPANET 2.0 (Rossman, 2000) calculates the water age inaccurately, it is possible to validate a hydraulic model with this software only in certain distribution region or at some nodes close to WTP, because of less influence of water mixing at these locations.
- Average modeled velocities in peak hours ranged from 0.13-0.30 m/s.

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There hereby follows a disclaimer stating that the authors are solely responsible for the work. It does not represent the opinion of the Community and the Community is not responsible for any use that might be made of data appearing herein.

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