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Procedia Engineering 70 (2014) 959 – 968

Procedia Engineering

www.elsevier.com/locate/procedia

12th International Conference on Computing and Control for the Water Industry, CCWI2013

# Database driven updatable hydraulic model for decision making

M. Koor[a], R. Puust[b,]*, A. Vassiljev[b]

[a]*AS Tallinn Vesi, Ädala 10, Tallinn 10614, Estonia*
[a]*Tallinn University of Technology, Ehitajate tee 5, Tallinn 19086, Estonia*

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## Abstract

During Feb 2011 – Dec 2012 *Tallinn Water Company* (*AS Tallinna Vesi*) took a target to improve the previous hydraulic model creation procedures that can be updated through the available *geographic information system* (GIS), *client information system* (Navision), *supervisory control and data acquisition system* (SCADA). The *Phase 1* was finished in May 2012. The current phase, *Phase 2*, started in summer 2012 and included pressure measurement point selections, data validation and model calibration.

*Keywords:* Geographic Information System (GIS); SCADA; Hydraulic network model; Calibration; Genetic Algorithm

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## 1. Introduction

City scale water network modelling has been recently described in several research papers (Crozier et al., 2012; Loubser et al., 2012). Depending on the available tools, techniques and also considering the fact if the water company is willing to pay for additional software developments and/or licenses, various routes can be taken. The current study started in 2011 when *Tallinn Water Company* (*AS Tallinna Vesi*) was interested to update their water network model with the scope that it can be managed (updated) by their own personnel in the future. *Phase 1* that lasted to May 2012 was mostly dealing with database connections, model skeletonization and demand aggregation that are fully described in Koor et al., (2012). *Phase 2* started in summer 2012 and included pressure measurement point selections, data validation and model calibration. *Tallinn University of Technology* has been involved in

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* Corresponding author. Tel.: +372-620-2552; fax: +372-620-2020.
*E-mail address:* raido.puust@ttu.ee

doi:10.1016/j.proeng.2014.02.107

*Tallinn Water Company* full scale city model creation and calibration also during 2001 – 2004. For model building, *Bentley WaterCAD* (then *Haestad Solutions*) was used; calibration was purely done in *EPANET* with custom calibration tools (Ainola et al., 2000; Vassiljev et al., 2005). For the current project *Bentley WaterGEMS* V8i *(SELECTseries 3)* was used from start to finish, including calibration with *WaterGEMS* built-in tools (*Darwin Calibrator*). *Genetic algorithm* has had many successful stories since its first appearance in water network related problems (Simpson et al., 1994; Savic and Walters., 1995; 1997) including real, city-scale calibration studies (Randall-Smith et al., 2006).

This paper details city-scale water network model creation procedures starting from the *Phase 1* conclusions, emphasizing to model calibration topics and its representation with close-to-real-life model components so that it can be used for daily decision making tasks.

## 2. Additional data/model management

After model import (pipes, nodes, hydrants, pumping stations and valves), additional information was included with pipe/node elements based on pressure zones. The same zones were also measured by additional pressure loggers to carry out separate calibration studies (see from later chapters). In addition to zone information, also necessary boundary data (flow inputs) was included with the model. All sub-models where test-run to ensure the integrity of the model. During the build-up of the model, various pump-stations representations where considered as can be seen on Fig. 1, including also ground-water pumping stage if present at source or pressure booster stations.

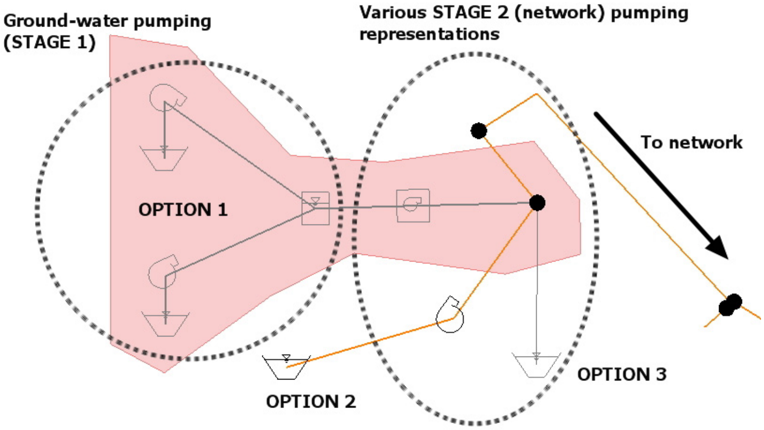


Fig. 1. Various representations of pumping stations.

As noted in later chapters, the detail level of pumping stations may have serious drawbacks on calculation (calibration) speeds and/or for the convergence of the simulation results. *OPTION 1* (Fig. 1) might be the true representation of the pumping station but it will tremendously increase the calculation times and for non-calibrated models causes various issues. In normal situations, simpler pump-stations representations are used. For example, for calibration, *OPTION 3* (Fig. 1) is used where pumping station is represented by a simple reservoir element with a measured head pattern (derived from pumping station measurements). *OPTION 2* would be much more preferable for calibration but again, during the calibration, the preliminary hydraulic calculation might not converge and might cause a backflow through the pump station. It was especially problematic in *Zone 11* where a large number of pumping stations are present (see Fig. 2). Therefore, *OPTION 1* was considered for calibration studies and later on, *OPTION 2* was used with a calibrated model (including pump relative speed patterns or fixed head behavior).

For pipe initial roughness values no ageing was considered. Although there are various ways how to assume pipe roughness values initially, those were rounded to almost new pipe values. The reason was again in model convergence as some pipe roughness arbitrary estimations may affect the hydraulic calculations quite a bit and for convergence very high calculation accuracy was needed. It was decided that it is better to leave the estimation of pipe roughness into calibration stage, including the fact that with so called "new pipe roughness values" the model run was perfect with much lower calculation accuracy values. Of course such consideration affects the way, how the model is initially calibrated and it is discussed in coming chapters.

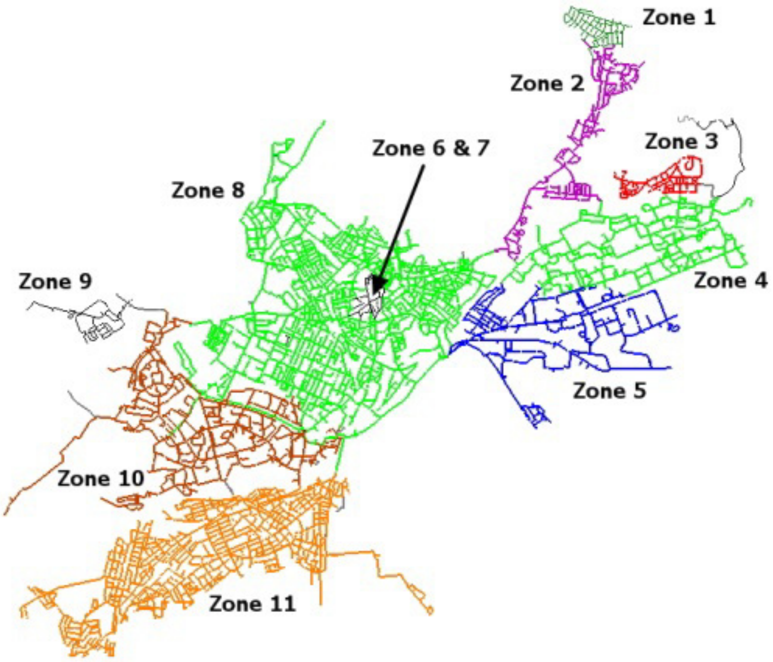
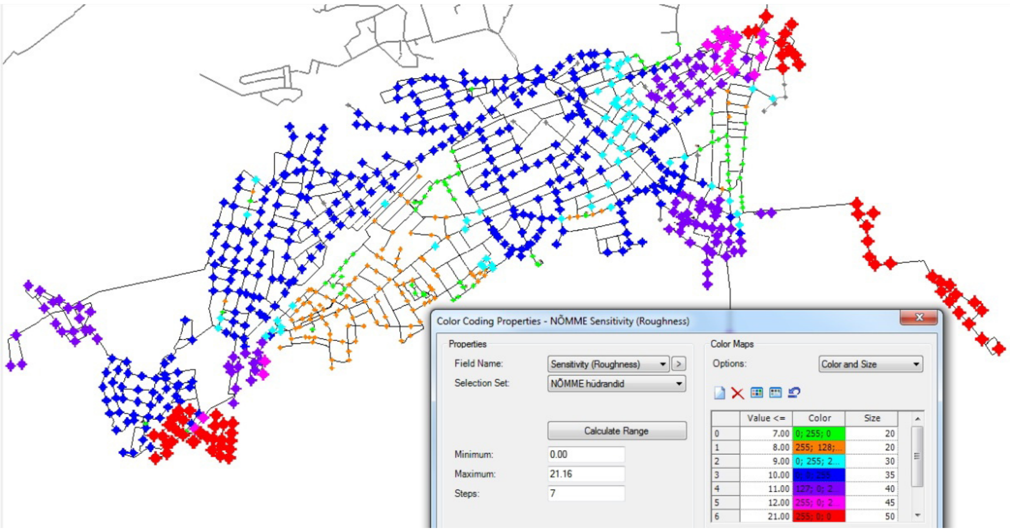


Fig. 2. Eleven pressure zones at Tallinn City water network.

## 3. Selection of pressure measurement points

Any calibration study needs good, quality measurement data. The *Tallinn City* network has 11 main pressure zones that were measured independently by additional pressure loggers, including inflows/outflows (Fig. 2). Each pressure zone was measured for about one week that included all the weekdays at least once. The size of the pressure zones varied quite a lot, ranging from 110 pipes (smallest) to 11'200 pipes (largest) but the number of additional pressure loggers was fixed. In addition to zone inflows/outflows and fixed pressure measurement stations (*SCADA*-based), temporary pressure loggers were used in every zone for about one full week to record pressures with 1-minute time-step. Before the pressure measurements, simple, model sensitivity analyses were carried out at zone level to find out the best measurement point locations. As measurements were carried out at hydrants, also the sensitivity analysis was carried out at hydrant level and so called *sensitivity coefficient* was calculated for every hydrant. Sensitivity coefficient was assumed to be a combined value of two different approaches. Firstly, roughness sensitivity was searched at maximum demand hour at hydrants (08:30 AM). Secondly, fire flow test (model based) was carried out with all hydrants to find sensitive areas for possible measurement points. Sensitivity maps were created in conjunction with *WaterGEMS User Defined* parameter values for nodes. Sample results can be seen in Fig. 3 and Fig. 4.



Color Coding Properties - NÕMME Sensitivity (Roughness)

Properties

Field Name: Sensitivity (Roughness)

Selection Set: NÕMME hüdrandid

Minimum: 0.00

Maximum: 21.16

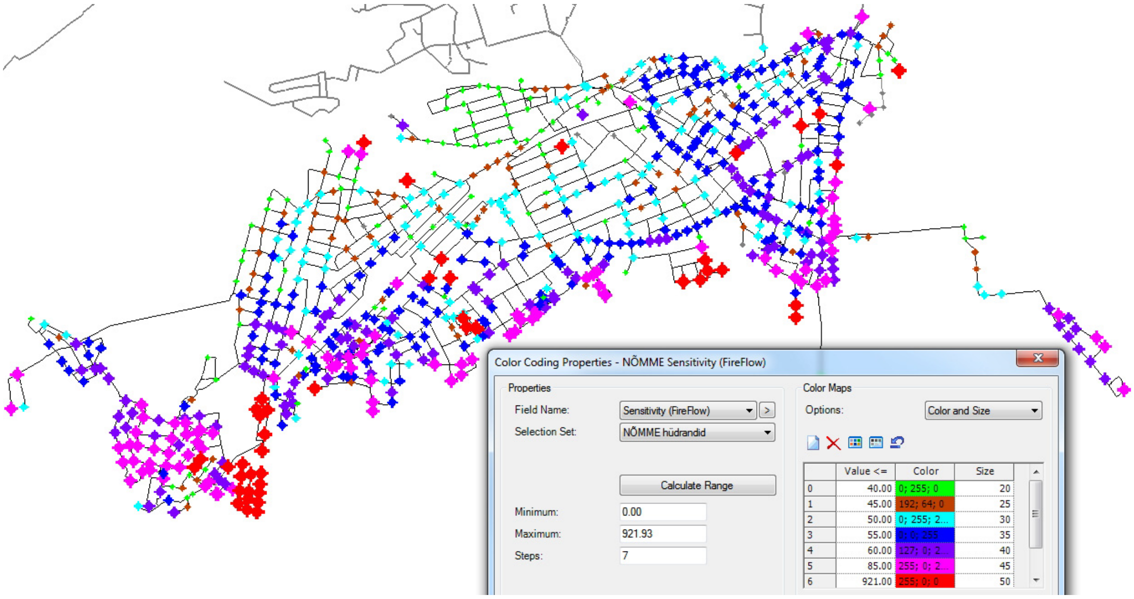
Steps: 7

Color Maps

Options: Color and Size

| | Value <= | Color | Size |
|---|---|---|---|
| 0 | 7.00 | 0; 255; 0 | 20 |
| 1 | 8.00 | 255; 128;... | 20 |
| 2 | 9.00 | 0; 255; 2... | 30 |
| 3 | 10.00 | 0; 0; 255 | 35 |
| 4 | 11.00 | 127; 0; 2... | 40 |
| 5 | 12.00 | 255; 0; 2... | 45 |
| 6 | 21.00 | 255; 0; 0 | 50 |

Fig. 3. Roughness sensitivity map for Zone 11.



Color Coding Properties - NÕMME Sensitivity (FireFlow)

Properties

Field Name: Sensitivity (FireFlow)

Selection Set: NÕMME hüdrandid

Minimum: 0.00

Maximum: 921.93

Steps: 7

Color Maps

Options: Color and Size

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|---|---|---|---|
| 0 | 40.00 | 0; 255; 0 | 20 |
| 1 | 45.00 | 192; 64; 0 | 25 |
| 2 | 50.00 | 0; 255; 2... | 30 |
| 3 | 55.00 | 0; 0; 255 | 35 |
| 4 | 60.00 | 127; 0; 2... | 40 |
| 5 | 85.00 | 255; 0; 2... | 45 |
| 6 | 921.00 | 255; 0; 0 | 50 |

Fig. 4. Fire flow sensitivity map for Zone 11.

It can be easily seen that when comparing two different sensitivity analyses (Fig. 3 and Fig. 4), two different colour maps are derived. For example the most sensitive points with fire flow test are mostly shown at dead-ends. For final pressure logger locations there are various, endless number of combinations to choose from, especially when the amount of loggers is limited (15 at our case) and large zones should be measured. It can be seen in later chapters that calibration results are greatly affected by the number of pressure measurements per pipe kilometre or simply per number of pipes/nodes/hydrants. Previously done simple as well as quite effective sensitivity analysis help us to draw attention to some particular sub areas in the network and pressure logger locations can be chosen more calibration-safely. The same procedure as described here was carried out with each zone (11 altogether) and a color-map as well as final hydrant selection (ex. Zone 11, Fig 5) was shared with *AS Tallinna Vesi* team members.

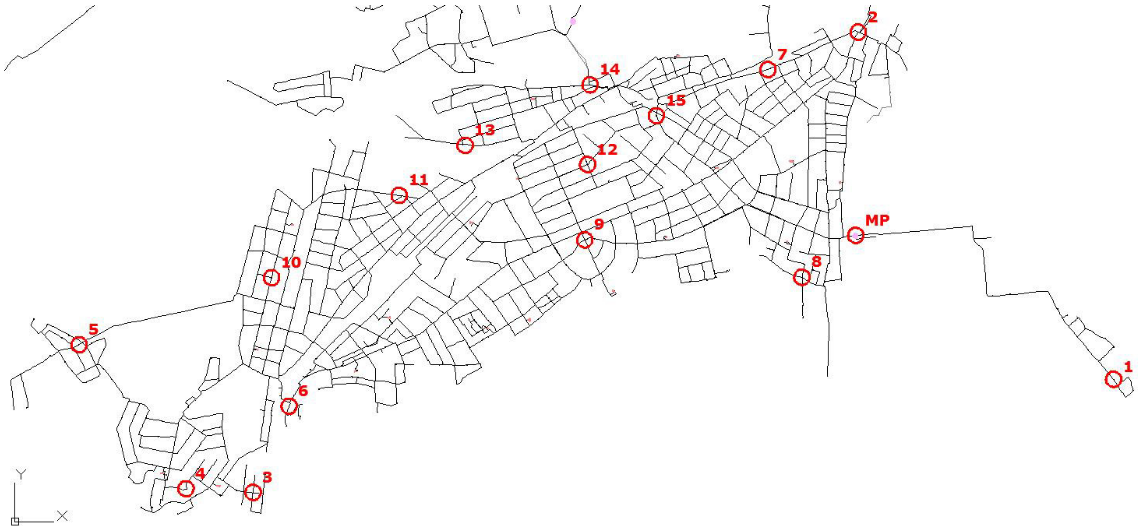

Fig. 5. Pressure measurement points for Zone 11.

Measurements were carried out during 2012 (spring to autumn) and measurement period varied from 7 – 20 days (Table 1). Although 7 days was planned for each zone, longer period were gathered at some zones due to vacation seasons. Therefore optimum measurement period, assuming 2 day relocation period was 99 days but it took altogether 105 days. *Zone 9* was not measured because of the different type of hydrants in that region and additional pressure loggers were not used there. That zone was also excluded from later calibration studies.

Table 1. Measurement periods.

| Zone | Zone name | Measurement period | Full days |
|---|---|---|---|
| 1 | Merivälja | 19.06.2012 - 08.07.2012 | 20 |
| 2 | Pirita | 07.06.2012 - 16.06.2012 | 10 |
| 3 | Kose | 12.07.2012 - 18.07.2012 | 7 |
| 4 | Lasnamäe-III | 26.05.2012 - 03.06.2012 | 9 |
| 5 | Lasnamäe-II | 04.05.2012 - 17.05.2012 | 14 |
| 6 | Linna-III | 25.08.2012 - 02.09.2012 | 9 |
| 7 | Toompea | 06.09.2012 - 12.09.2012 | 7 |
| 8 | Linna-II | 21.04.2012 - 01.05.2012 | 11 |
| 9 | Taela | <not measured> | n/a |
| 10 | Mustamäe-Õismäe | 11.04.2012 - 18.04.2012 | 8 |
| 11 | Nõmme | 18.09.2012 - 27.09.2012 | 10 |

All measurements were gathered with 1-minute time-step. Before importing that data into calibration module, the basic filtering and averaging was carried out. Final measurement data was with 1-hour time-step, if some anomalies were discovered within measurements, those were not accounted for final data selection. For example there was one pressure logger that was showing most of the time higher pressures in the network than at zone inflow point (pumping station). As final measurement data should be imported directly into *WaterGEMS* calibration module, *ModelBuilder* was used to connect with the filtered measurement data source. For online loggers (pump flows/pressures, fixed pressure measurement stations) two different import alternatives where evaluated. At first, *WaterGEMS* module *SCADAConnect* was considered as a most obvious choice to carry over the historical data based on zone measurement period.

It turned out that the capabilities of that module were not suitable with our workflow. Namely, we faced with the two major problems: (a) There was no possibility to save the settings of signals for future updates, for example when model is rebuild by *ModelBuilder* links into new file, no possible way to import pre-defined signals definitions and (b) There was no possibility to combine various timesteps into one calibration study. The latter one was most problematic for our planned workflow as it can be seen in later chapters where the overview of calibration module is given. As an alternative, all live (historical *SCADA* data) was imported into calibration module in a same way as with off-line measurements. For that puropose, an additional data table was needed to be prepared that included flows, pressures from the pumping stations and from the fixed measurement stations. *ModelBuilder* was used to connect with that data tabel and as such all the needed measurement data was gathered into *WaterGEMS* calibration module called *Darwin Calibrator*.

## 4. Model calibration

At the very first stage of the project it was decided that the main goal for the current project is to use out-of-the-box tools that are readily available for *Tallinn Water Company*. Previously it has been shown that *Levenberg-Marquardt* optimization algorithm works much faster than *genetic algorithm* (Koppel and Vassiljev, 2009; Vassiljev and Koppel, 2012) but as the *Darwin Calibrator* calibration module resides inside the *WaterGEMS* environment, it was the most obvious choice.

In addition to measurement data, various other settings should be defined before calibration can be started. Calibration was carried out for pipe roughness values (*Darcy-Weisbach*) as well as for emitter coefficient values (leakage representation). Therefore pipe and node groupings were created. For pipes, plastic and metal pipe groupings were created separately considering only the diameter aspect with 50mm increment. It was found that smaller increment didn’t add a value for calibration procedure both as calibration speed and there is truly no big difference if the pipe belongs into group of 100 mm or 110 mm. Maximum roughness value for metal pipes was up to 75% of its diameter with the increment of 10% of its maximum value. Plastic pipe groups were separated from the metal pipes because much lower maximum possible roughness (up to 52 mm with increment of 12 mm) and it is was assumed that the maximum value does not depend on pipe diameter. The same principles were used in all zones to create pipe groupings.

Leakage node groupings were purely based on measurement locations. Due to the fact that pipes are mostly oversized in the whole city area and because of that very low flows exist in the system there is no point to search a leakage far away from the measurement point. Therefore the groupings were created around measurement point. The closest node to the measured hydrant location was considered as a leakage candidate. Although each node group has one single leak candidate the results of leakage calibration should be expanded over all other nodes that are in that region. Various methods how to calibrate leakages has been reviewed by Puust et al., (2010). Leakage calibration in the current study was defined as a search problem of optimal emitter exponent for each node grouping. The ranges for emitter exponent were assumed so that any one maximum exponent value can cause about 10% of additional outflow from the zone.

In addition to pipe/node groupings that help to keep the calibration times in reasonable timeframe, the increment values that drives all possible roughness/emitter exponent values, plays an important part. Roughness increment has been chosen so that at maximum 15 different values (metal pipes) are considered in one particular pipe group. Emitter coefficient increment has been selected so that 30 different values fall into the demand group. The number of all possible groupings and possible values greatly affects the speed of calibration. In current study we calibrate pipe roughness and emitter exponents in a separate calculation but multiple times with different initial values. The last thing to consider before calibration run is to check the parameters of calibration algorithm. Most of values that are used were suggested by the software and only slight changes were made like increasing the maximum trials (5’000’000) and population size (200).

After setting up all the needed parameters the sensitivity analysis of measurements was carried out. There are various research studies how to pick the most sensitive data for final calibration (Bowden et al., 2002). In the current research a different approach was used. Considering the fact that no real fire hydrant tests were carried out to get additional pressure data, the whole measurement cycle was fed into the calibration module and so called *all-data-calibration* was carried out at zone level. For example, if a particular zone was measured for 10 days, 10 days x 24 hours = 240 time steps were fed into calibration procedure. Of course such calibration has a dramatic effect on calculation speed and our main purpose was to test the robustness of the calibration procedure itself and not to optimize the calculation time. *Virtual Machine* (64-bit, 4GB memory) was used to carry out calculations. The so called sensitivity calculation took about one hour (small zones) to two days (large zones). After calculation the general model agreement with the measurements was drawn by *WaterGEMS* tools.

Based on the measurement sensitivity results the error of observed and simulated HGL values are ordered and divided into smaller groups. Additional pre-calibration studies are carried out to find out how the number of good measurement snapshots affects the final result (in sense of error and calculation time). It was concluded that 6 – 12 different measurement snapshots are enough to carry out the final calibration study. In addition to pipe roughness evaluation over all the measurement data, the analogous analysis where carried out with leakage studies to get the overall feeling which data is good enough to use in final calibration. The final calibration was divided into three main stages: (1) roughness calibration was carried out with up to 12 different measurement snapshots; (2) using the solution from previous calibration, leakage calibration was carried out as a separate calibration procedure; (3) finally, the roughness calibration was performed once again taking account the emitter coefficient values from previous stage. Table 2 concludes the procedure of the calibration that was applied for each, separate zone.

Table 2. Three stage calibration procedure.

| Calibration Stage | Calibration Study | Method | Note |
|---|---|---|---|
| Stage 1 | Roughness calibration | Pick a value between the boundaries | Roughness of the new pipes is assumed as starting point |
| Stage 2 | Leakage calibration | Pick a value between the boundaries | Results from "Stage 1" where used as a starting point |
| Stage 3 | Roughness calibration | Multiply the roughness value in between 0.1 - 2.0 | Results from "Stage 2" where used as a starting point |

In general the error in between of measured and simulated values was reduced at every stage. As up to 12 measurement snapshots where used in every calibration run, the calculation time was reasonable, ranging from few minutes to half an hour depending on the zone size. Table 3 shows an overview of calibration results in sense of maximum errors in between measured and simulated nodal pressures.

Table 3. Main results of the calibration.

| Zone | Zone name | Mean square error (m) | Maximum error (m) (absolute) | Minimum error (m) (absolute) | Number of pipes in zone | Number of pressure measurements | Number of flow measurements | Pipe groups | Leak node groups |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Merivälja | 0.03 | 0.47 | 0 | 819 | 11 | 2 | 2 Plastic, 5 Metal | 11 |
| 2 | Pirita | 0.05 | 0.65 | 0 | 1431 | 13 | 3 | 5 Plastic, 5 Metal | 12 |
| 3 | Kose | 0.06 | 0.74 | 0 | 775 | 11 | 2 | 3 Plastic, 3 Metal | 11 |
| 4 | Lasnamäe-III | 1.42 | 4.25 | 0 | 1332 | 22 | 2 | 6 Plastic, 10 Metal | 22 |
| 5 | Lasnamäe-II | 0.02 | 0.53 | 0 | 1641 | 14 | 3 | 6 Plastic, 13 Metal | 14 |
| 6 | Linna-III | 0.23 | 1.13 | 0.16 | 338 | 8 | 1 | 4 Plastic, 6 Metal | 8 |
| 7 | Toompea | 0.01 | 0.17 | 0 | 112 | 5 | 1 | 1 Plastic, 4 Metal | 5 |
| 8 | Linna-II | 0.58 | 1.62 | 0.03 | 11274 | 34 | 3 | 8 Plastic, 13 Metal | 34 |
| 9 | Taela | n/a | n/a | n/a | 477 | n/a | n/a | n/a | n/a |
| 10 | Mustamäe-Õismäe | 1 | 3.19 | 0.01 | 2436 | 18 | 3 | 8 Plastic, 9 Metal | 18 |
| 11 | Nõmme | 0.13 | 1.39 | 0 | 8316 | 28 | 15 | 5 Plastic, 7 Metal | 28 |

An advantage that supports the three stage calibration procedure is that we can use a separate portion of measurement data. Because the sensitivities in sense of pipe grouping might be different than with emitter exponents, we can use different data portions for those sub-calibrations.

In general, it can be clearly seen that calibration results are better for smaller zones (more measurements per overall unit of pipes). Maximum errors in Table 3 are caused by some particular pressure logger. Attention should be drawn that as this logger was showing large error over all measurement snapshots (times) it may indicate that the either the logger was faulty or some errors were made during data analysis (including the logger elevation data at that particular hydrant). It has been shown that using a method described in (Vassiljev et al., 2007) can eliminate the elevation error but in *WaterGEMS* it was impossible to apply that approach.

The most questionable calibration results are in *Zones 4* and *Zone 10*. Both zones are pressure booster zones where various hydraulic head targets are kept throughout the day in pump stations. As much larger errors were noticed at times when there was a change in pressure regime, it may indicate a false interpretation of pump *SCADA* data. Additional analyses are therefore needed in the future to better understand the problematic side of those calibration results. Pipe roughness and emitter exponent coefficient values were exported into final model to create a calibrated model with proper pump components.

## 5. Calibrated model

After model calibration, the whole network model was built. The key in this step was to analyse what model components (ex. reservoir with a hydraulic grade pattern, pumps in parallel with on-off timing controls, pumps with variable speed patterns or variable speed pump batteries) to use to mimic a real network operational model as closely as possible. It turned out that as a complexity of the model (sub-model) increase the choice of available pumping station representations decrease.

Although the full city network has 11 major pressure zones not all are independent from each-other on daily basis. Therefore zone flow inputs/outputs that were used at calibration stage are now swapped with proper, real-life network components, like pumps and valves. Depending on the source of water (surface or groundwater) and zone's connectivity with each other, the whole network can be divided into 4 areas as shown on Fig. 6. While *Area 2* and *Area 3* are mostly on surface water source, *Area 1* and *Area 4* are on groundwater source. All areas can be run separately through *WaterGEMS Scenarios Manager*.

Fig. 6. Four main network areas that can be run separately.

Most of the areas can be easily represented with real network components, including variable speed pumps and variable speed pump batteries, fixed head pumps and pressure reducing valves. The most challenging is to represent a variable speed pump with a fixed head setting that change throughout the day and/or weekday. As previous studies indicated, a true model component does not exist for those situations and some alternative way should be used (Koor et al., 2011). For example, multiple pump elements can be used with timely controls. Although it replicates the true situation quite nicely, it affects the network hydraulic calculations (due to heavy amount of time controls for one week) and such representation cannot be used for pump optimization studies.

On the other hand, the available speed pattern based pump representation is good for that time moment when the model was created but it might not be a correct solution in future studies. Demands are changing, leakages appear and are fixed again – those entire situations cause a change in a pump working pattern. At this stage, the future pump optimization routine was more important and therefore pump speed patterns were derived from the *SCADA* data (no direct speed coefficients were available from *SCADA* directly and therefore those were calculated based on pump head measurements).

As mentioned before, some of the zones are mostly pressure booster zones (*Area 2* and *Area 3*) but *Area 4* is purely based on groundwater source having 15 pump stations (Fig. 7). All of those are variable speed drive and are pumping into the same, non-isolated network. At the time of calibration only flow/pressure measurements at pump station were available. It was not clear how those pumps are operating. Do they regulate themself by changes that happen in some particular node or even following companion pump working pattern? From *SCADA* data it was concluded that no pump is fixed to keep a head but works somehow otherwise. From *SCADA* system it was impossible to pick out the pump settings directly (speed coefficient).

Fig. 7. Pumping stations in Zone 11.

It was still noted that some of the pumps do not work at night times (for example from 23:00 – 05:00). Considering pump on/off settings the next stage was to find out pump speed patter coefficients for the whole week so that one pump won't turn off the other pump. Due to the number of pumps, it was the most complicated task in that zone. Although all pumps where able to pump into the same network, basically 3 main sub-areas were recognized that helped to stabilize the system (lower left, centre and right hand side sub-area) towards the whole working area. All four main areas were successfully modeled to the stage where real pump station elements for that moment were used and the model is used at daily basis for decision makings.

## 6. Conclusion

Methods for updatable, large scale, calibrated water network model that can be used for various modeling tasks is researched based on the tools that are readily available for *Water Company* without spending additional resources for software development. Continuing from *Phase 1* that was finished in *May 2012*, the second phase involved: (a) gathering and analyzing measurement data; (b) additional data input into calibration module; (c) carrying out the sensitivity analysis in respect of measurement snapshots; (d) evaluating various possibilities to create calibration groups; (e) calibrating a model at zone level; (f) finding the true representation of model components to mimic the real network behavior as closely as possible (in sense of various pumping situations). Out of the box tools where used mainly for two reasons: (1) readily available tools to connect to *GIS* database and therefore to be able to update the model at regular basis; (2) workflow repeatability by *Tallinn Water AS* personnel in the future that is not possible with custom build research tools due to lack of knowledge or easily manageable user interface/workflows. A direct consequence in a positive manner from the project was also a result from the first phase that current *GIS* system was not able to produce industry standard *shapefile* (network topology file). During 2013 the *GIS* system is rebuild and hopefully it makes the future model updates more easily manageable (some rework is needed at database connection levels using *WaterGEMS ModelBuilder* features). The final, calibrated model is currently used at daily workflows. Some of the other workflows with the current software package were also documented in the final report, including the possibilities of criticality and pipe-break analysis and pump optimization studies.

## Acknowledgements

This research was supported by European Social Fund's Doctoral Studies and Internationalisation Programme DoRa, which is carried out by Foundation Archimedes. Financial support from the Estonian Ministry of Education and Research (SF0140072s08) is greatly appreciated.

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