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Real time water supply system hydraulic and quality modeling – a case study

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Abstract

This paper presents a real time water supply system hydraulic and quality modeling framework that is applied in a case study. The simulated quality parameters include age, traced water source, temperature, pH, hardness and free chlorine.

A full-scale and well-calibrated hydraulic model of the whole water supply system is built using an extended version of EPANET, allowing storing and restoring the state of plug flow in links. Once an hour, the simulator is updated with the previous hour's hydraulic and quality state from the utility's supervisory control and data acquisition (SCADA) system and a simulation is performed. The results are stored both in GeoJSON format for geographic information systems (GIS) and in a relational database for later use. Some results are presented to the general public in a geographically aggregated form over a web user interface and as open data using Representational State Transfer (REST) web service interface.

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Keywords: quality modelling, real-time, EPANET, SCADA

1. Introduction

Water distribution network (WDN) modelling has got a lot of interest in terms of optimization/calibration ([1], [2]), but much less attention is paid to general model usage as online decision support system, soft sensor and online quality simulations.

Online modelling is not something new ([3], [4], [5]). It has been used in various decision makings. Most commonly in risk studies [6] and/or for fault detection [7]. Risk studies has been played an important role in water quality analysis, where any kind of intrusion or human error causes changes in water quality parameters that may cause a serious risk for human life [8]. Offline calculations has been preferable due to large amount of data analysis/calculations that are needed for any updates in the model. Online models needs different problem descriptions to optimize the calculation time or allocation of more calculations cores either offline [9] or online like cloud services ([10], [11]).

Online modelling is not important only because of water quality aspects, but using optimal control settings in the system at all times, can save a lot of operational costs. ([12], [13]) Obviously not all calculations can be done in real

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time. Therefore in reality offline calculations are combined with online calculations. Optimal pump scheduling in real time with or without tank near-optimal tank water levels has been research by [14] and [15]. Offline calculations are common for some particular network components that do not change in time, for example optimal pump working combinations that can be selected during online calculation step [16] so that the energy use will be optimal. Any kind of real-time optimization needs also real-time measurements. Those measurements are usually received through supervisory control and data acquisition (SCADA) and used in terms of real-time control model ([17], [18]).

There are some problems that should be acknowledged when real-time data is used, both in quality and quantity. [19] [20] defines real-time modelling as integration of network hydraulic and quality model with operations data collected and stored via SCADA. They use an open source hydraulic modelling packages EPANET ([21]) in conjunction with Real-Time Extension (RTX) module ([22]).

Online model provides a way to have better overall view of the current water supply system state, and to analyse the historical performance, when the simulation results are stored in an appropriate format to facilitate later analysis. Comparing the simulated and measured parameters, automatic anomaly detection can be performed. Especially the online quality modelling can be useful, because, for example, source tracing and water age, that are hard to measure, can be simulated online and shown in SCADA to facilitate decision making process and system analysis.

This paper describes a framework for online WDN modelling, and presents a case study of an online quality modelling and energy balance analysis [23] developed for a large Finnish water utility. In the case study, the model is used as a soft sensor [17] and the online quality results are published online for general public and water users in an aggregated form in an open manner. The modelling results are used for supporting decision making and system analysis.

The framework includes a new software, called Sahti, for SCADA and laboratory information management system (LIMS) connection and data preprocessing, and some quality modeling related extensions to EPANET simulator. An extended methodology for real-time energy assessment is also provided.

The framework can be used as a basis for other applications, such as online whole cost optimization of a water supply system.

2. Materials and methods

2.1. SCADA connection

FCG Design and Engineering Ltd. (FCG) has developed a software called Sahti, which was used for accessing and analysing the SCADA and laboratory data. Sahti is developed in Java programming language version 7[24], and it provides both an graphical user interface (GUI) for end users and an application programming interface (API) for developers.

Sahti software can connect to variety of different data sources, that can present any numerical data in a time series, via different APIs, including but not limited to SCADA system connections via direct SCADA API usage or Open Process Control (OPC), to relational databases and SCADA systems using Java Database Connectivity (JDBC) or Open Database Connectivity (ODBC), to tab and comma separated files and Excel-worksheets, and to various laboratory and customer information systems. The data sources can have different time zones, and different and time-varying time resolution.

An Extensible Markup Language (XML) configuration file describes the data sources and describes what values Sahti provides and how those values are calculated based on the data read from the sources. Typically the calculations include, for example, calculating a water balance for a pressure zone based on the flows in and out of the zone and changes in the possible water tower volume.

Each value provided by Sahti can freely perform calculations on data from all declared data sources. The raw data can be either or lagged interpolated at this stage to cope with different time intervals in sources.

The expression language in Sahti supports all typical arithmetic operations and mathematical functions, such as `floor`, `ceil` and `sqrt`. In addition the expression system supports boolean algebra and time algebra. For example, definition for a measurement are can be different before and after certain date and time, such as 2014-01-01.

An example of the configuration file part, where the Sahti positions are defined is shown in Listing 1. In the example the demand for Pressure Zone 1 is calculated as difference between incoming and outgoing flows to the area, defined by the in and out attributes at station definitions. For water tower flow is calculated as volume difference divided by the time between two measurements in hours. Station 100 pumps water out of Pressure Zone 1 into another zone identified by code “AREA02”. The station’s flow is defined differently before and after 2014-01-01.

Listing 1: An example of defining a few stations and an area with water balance calculation in Sahti

```
<data-sources>
    <data-source name="hdata" native-interval="3600000" ... />
    [...]
</data-source>

[...]

<area name="Pressure Zone 1" number="AREA01">
    <parameter name="Demand" expression="IN - OUT">
        <value name="IN" position="Flow" all="in"/>
        <value name="OUT" position="Flow" all="out"/>
    </parameter>
</area>

<watertower name="Water Tower 1" number="TOWER01" out="AREA01">
    <parameter name="Level" expression="hdata:wt01_li"/>
    <parameter name="Volume" expression="hdata:wt01_V"/>
    <parameter name="Flow" expression="(hdata:wt01_V-hdata:PREV_wt01_V)/(step/3600)"/>
</watertower>

<source name="Source 102" number="STATION102" in="AREA01">
    <parameter name="Flow" expression="hdata:source102_fi"/>
</source>

<pumpingstation name="Station 100" number="STATION100" in="AREA02" out="AREA01">
    <parameter name="Flow" expression="if(now < date(2014,1,1),
        hdata:stat100_fi-hdata:stat100_fi2,
        hdata:stat100_fi2-hdata:stat100_fi)" />
</pumpingstation>
```

Sahti enables to return data for multiple parameters at once for a user-requested timespan using user defined time step. All the required raw data is fetched at once from the different data sources, and all Sahti parameters values, like water use for a certain area, are calculated in the user defined time steps. Raw data is averaged, interpolated and extrapolated as needed in a predictable and user defined manner. Typically, for example, an hourly averages for data stored in minute long intervals is retrieved.

2.2. EPANET extension for storing and restoring pipe plug flow state

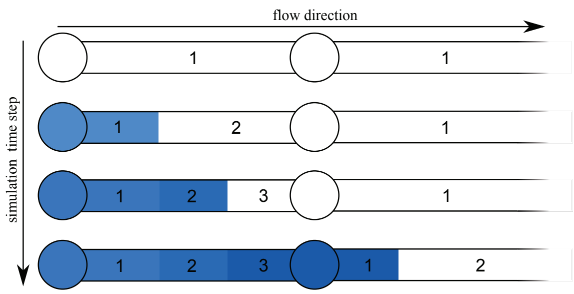


Figure 1: Plug flow in pipe in EPANET

EPANET models the quality in and through a pipe as plug flow, as shown in Figure 1. Water with a certain quality is fed into a pipe and the water existing in the pipe is released from the other end. At same time the constituent in the pipe can react and thus the concentration can change in the different plug flow segments.

By default EPANET initializes the plug flow segments so that in each pipe there's only one segment, that has the initial concentration of the down-stream node. This means, that even if the node concentrations at the end of the previous simulation are saved and restored, when a new simulation is initialized, the concentrations inside the pipes will be wrong. This is especially apparent for long pipes with large diameter, and when the simulated time period is short.

In order to enable an hour-by-hour quality simulation, EPANET was extended to allow saving and loading the pipe plug-flow segments. Two new functions were added into `quality.c` source module: `ENgetinitisegments(int linkIndex, char* ret, int len)` and `ENsetinitsegments(int linkIndex, char* segments)`. `initsegs()` function in the same module was modified to do the actual initialization based on the given initial segments.

The first function returns string presentation of the plug flow segments in a pipe. The string presentation was chosen, because it's easy to store, and validate visually. The format of the string is "`flow direction; [volume; concentation]...`", where flow direction is either '+' or '-' relative to the link's native direction, and there are as many `[volume; concentration]` pairs as there are segments in the pipe. Volumes are relative to pipe's full volume and concentrations are expressed in the model units. An example of the initial segments string for pH could be `-;0.5;8.5;0.3;8.0;0.2;8.2`.

The second function sets the initial segments for a pipe, parsing the string in same format as `ENgetinitisegments` returns. If the flow in pipe is in opposite direction relative to initial segments' direction, the order of segments are reversed. The initial segments have to be set after calling `ENinitQ` but before `ENrunQ`, because that function call will do the actual setup of the segments in `quality.c:initsegs()` function called when $Qtime = 0$.

2.3. Energy balance calculation

An hydraulic energy balance for the whole network, raw water extraction and conveyance, water treatment, and each pressure zone is calculated for analysing the system efficiency and how the performance changes over time. The energy balance methodology was first presented in Cabrera et al.[23] and subsequently applied and extended in Hernández et al.[25], Souza and Soares[26] and Cabrera et al.[27]. Compared to the earlier work, some new components are added to the balance.

The original balance formulation and the later work fail to include energy deficit in the balance. Energy deficit exists when for some node the available pressure is lower than the required pressure: $p_{avail} < p_{required}$. For control volume approach, the energy deficit is an energy input into the system.

Other component that is important when analysing single pressure zones is the potential energy delivered to other pressure zones. One final component that is missing from the earlier formulations, is the actual electrical energy used. Using the methodology developed in [28] and [16], accurate estimates for pump shaft energy, motor energy and variable-speed drive energy are calculated and included in the balance.

Figure 2 shows schematically the different components of the balance. The components can be divided into three categories: $E_{consumed}$ presenting the energy consumption in the supply system, E_{input} presenting the energy fed into the system, and finally $E_{electrical}$ presenting the electrical energy needed to operate system.

From the balance useful efficiency metrics can be developed, for example hydraulic efficiency of the system

$$\eta_{hydraulic} = \frac{E_{required}}{E_{input}} \quad , \tag{1}$$

and total electrical efficiency

$$\eta_{electrical} = \frac{E_{required}}{E_{electrical}} \quad . \tag{2}$$

Besides these two, specific hydraulic and electrical energy consumption for revenue water have been useful metrics.

The FCGnet simulation software, based on EPANET and developed by FCG, was extended to automatically calculate the balance and provide an API through which the balance calculation and result extraction can be performed from an external program or a Python[29] script driving the program.

The online simulator calculates the energy balance for both the current parallel pumping control algorithm, corresponding to naïve 1 algorithm, and the optimized control algorithm. [16] The energy balance results are saved on

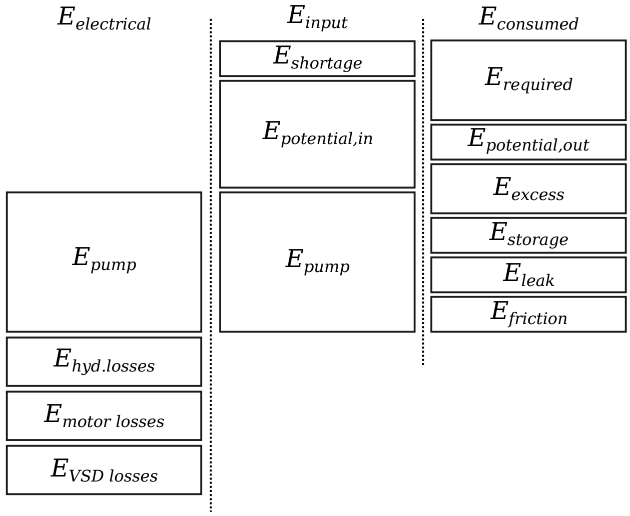


Figure 2: Components of energy balance

pressure zone level in a relational database on hourly time scale. This way it is possible to analyse, how changes the system operation affect the system performance.

2.4. Online simulator

The actual online-simulator was programmed in Jython programming language, which is a version of Python that runs on Java platform. The FCG's network simulation package, FCGnet, is also developed in Java and has a built-in Jython interpreter, which allows to easily extend and script the software. Some of the tools available for scripting, include previously mentioned Sahti, GeoTools Geographical Information System (GIS) toolkit, and the hydraulic simulator based on an extended version of EPANET.

The sequence of online-simulation is as follows:

1. The simulation period is determined: either the previous full hour is simulated or the time period given as a command line argument to the program
2. The base model is loaded
3. If a model file is found, that contains the quality simulation results for the hour preceding the simulation start, then node initial concentrations and pipe plug flow segments are set to the last time step results in the model. Otherwise the base model contains some reasonable initial values, based on previously run long-term simulation.
4. Data for the simulation period is fetched from SCADA and laboratory information system using Sahti API
5. Each pressure zone's demand is updated, based on the calculate water balance. Demand patterns are calculated for each zone, and each node's share of the total demand is assumed to stay constant.
6. Initial level in water towers is set to match the measurements
7. Flow at each station is set to follow the measured data
8. The source quality parameter values at each water source are set to match the measured values from either online measurements or laboratory analyses
9. The hydraulic network simulation is performed
10. All quality parameter simulations are performed subsequently
11. The hydraulic and quality results for each station and water tower in the model are stored into a relational database for later use, together with energy balance analysis results for both current and optimized parallel pumping control algorithms, overwriting any previous results for the same time period if they exist
12. The simulation results are stored in GeoJSON[30] format for all nodes and pipes

13. The quality simulation results are stored as regional averages in GeoJSON format and uploaded to the intermediate server, from where the consumer facing interface can fetch them

Ordinarily the online simulation is run once an hour by a scheduled task.

3. Case study

The online simulation was developed for Tampere water utility, which serves city of Tampere and municipality of Pirkkala in southern Finland. The population in the municipalities is 241 996 (30th April 2015), from which about 90 % is served by the utility via 21 500 metered connections. The water supply system consists of six groundwater sources and two surface water sources, 16 pressure booster stations and six water towers. In total there is about 780 km of network, and the typical water demand is about 49 000 $m^3\ d^{-1}$.

The hydraulic model was prepared by FCG in 2011 using FCGnet modeling package. The model has been subsequently updated every year. The model is a full-scale model, including every single pipe, except the consumer connections, and each water user in the system.

The latest update in January 2015 added raw water extraction, conveyance and water treatment processes into the model. In addition all pumping stations with variable-speed controlled parallel pumping were replaced with pump batteries[31], and motor and variable speed drive efficiencies were properly modeled as per Sunela and Puust[16].

The model has about 5400 nodes and 6500 links. The total modeled network length is 800 km, which is larger than the reported length, because the model includes the pipes used for raw water conveyance, too.

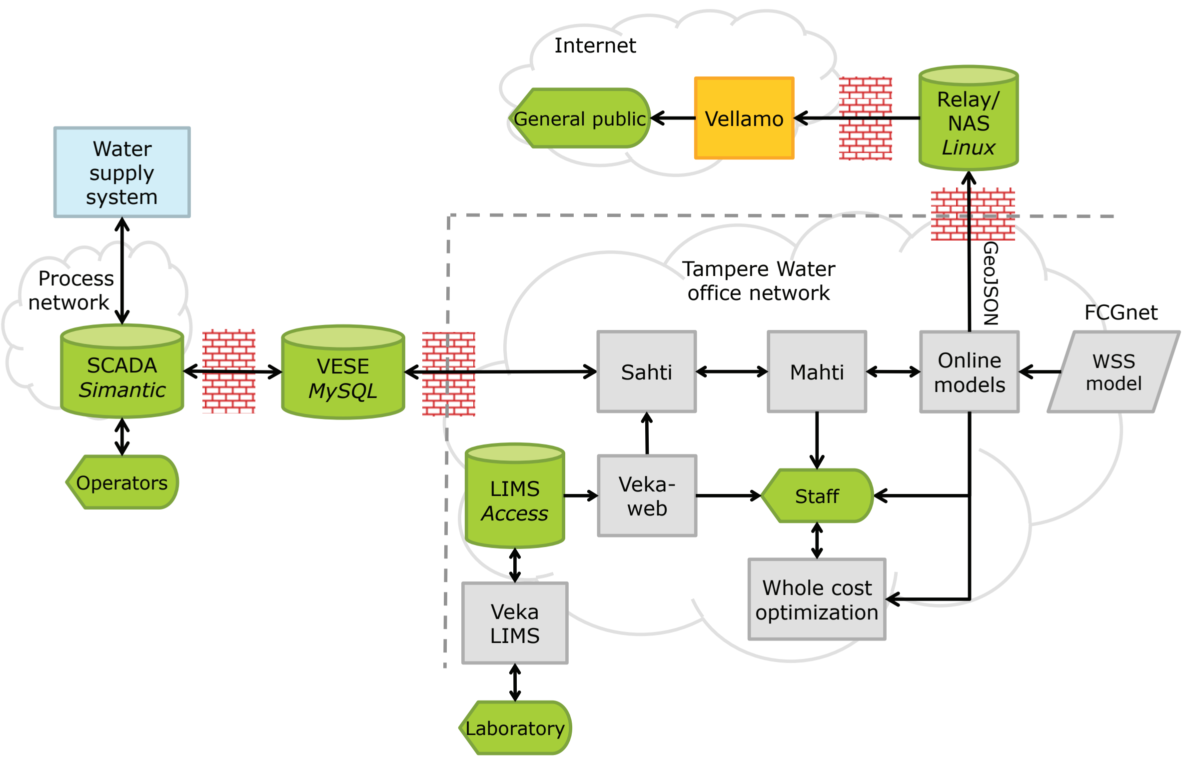


Figure 3: Tampere Water utility online modeling system

The SCADA system stores pressure, flow and level measurements for all stations and water towers once every five minutes into a MySQL[32] relational database. Control strategy (constant head, flow or level) and setting are stored too for pressure booster stations and water sources. Each water source has online measurements for pH, water temperature and free chlorine, that are also stored into the database every five minutes.

The online quality simulator calculates water age, source tracing, percentage of surface and ground water, pH, temperature, free chlorine and hardness. The parameters were chosen on the importance to the customers, what online measurements are available through SCADA and what is easily calculable in the simulator.

Everything else, except water age and free chlorine, is calculated by simply mixing the incoming water qualities at the nodes, that is, the parameters are modeled as first order chemical reactions with all reaction rate coefficients being zero.

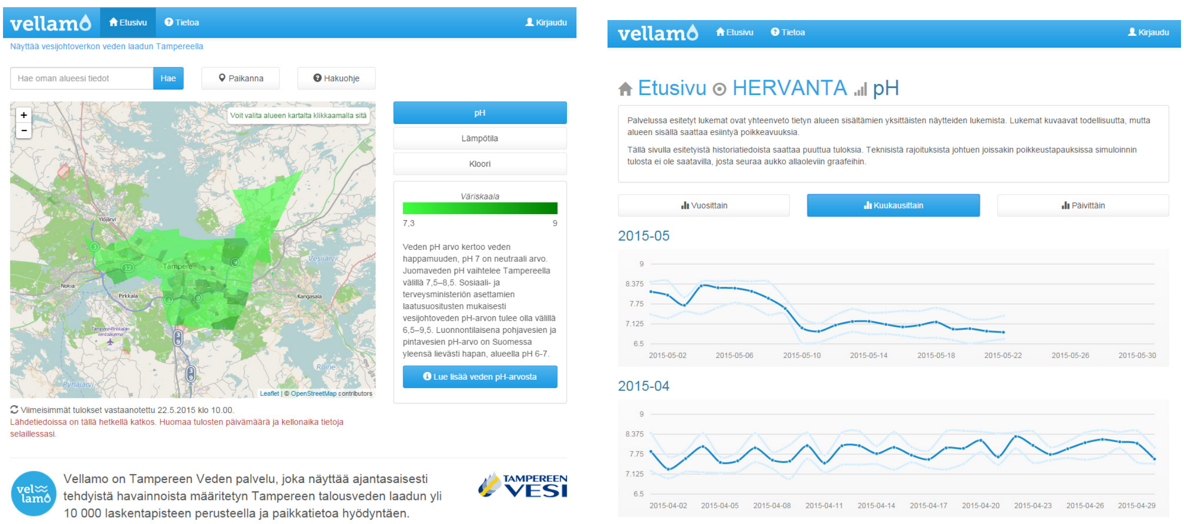
Modeling pH is not a simple task, but it was decided that because the pH changes only a little in network according to the laboratory analysis, modeling pH as non-reactive constituent is accurate enough for the use.

Water age was modeled as zero-order reaction, and chlorine as first order decay with different reaction rates used for bulk and wall reactions. While chlorine simulation have quite high level of uncertainty and the use of more complex models are recommend, it is still shown that first order kinetics can provide usable estimates for chlorine content in network but care should be used when applying the methodology. [33,34] The average wall and bulk reaction coefficients for the whole network were roughly calibrated manually comparing the laboratory samples collected in the network to the simulated results. Bulk reaction coefficient $K_{bulk} = -0.018$ and wall coefficient $K_{wall} = -0.005$.

An end user web interface was developed by SuperHelio Ltd. The end user interface allows all interested parties to see different quality parameters on map, and lookup the historical variations of the parameters. Besides the web interface, also an Representational State Transfer (REST) Application Programming Interface (API) is provided in the spirit of open data for third-party application developers. The user interface is shown in Figure 4 and it can be accessed online at `http://vellamo.tampere.fi/`.

For the end user interface, only pH, free chlorine, temperature and hardness were included. The detailed results for all nodes in the model is not provided, instead the city of Tampere was divided into about 200 statistical areas, for which a demand weighted average of the quality simulation results of all nodes within area is calculated.

All hydraulic and quality results on a single node and link level are stored in open geographical file format, GeoJSON, as time series and are available to the utility. The hydraulic, quality and energy results are also stored in a relational database for each water tower, water source and booster pumping or measurement station. From the database, the SCADA system can show the simulated quantities, like water source tracking, age, chlorine and pressures in addition and besides the measured values.



(a) Main page

(b) History of pH in an area

Figure 4: Vellamo web interface

In addition to the traditional modelling results, both the current energy balance and parallel pumping optimized energy balance results for the whole network, raw water extraction and conveyance, water treatment and each pressure zone are stored in the same database as time series, and thus the system performance can be analysed using reporting and data analysis software.

4. Discussion and Conclusions

A real-time hydraulic, quality and energy usage simulator framework was developed and presented. The framework includes a new tool for SCADA connection, EPANET quality model extensions and an extended version of energy balance assessment. The framework was applied in a case study for Tampere water utility in Finland.

So far the public reception of the Vellamo has been good, and providing this kind of simulated quality results to the general public has sparked a lot of interest. The system performance has been good. However, there has been several occasions, that the online quality measurements show incorrect results, which then propagate through the simulation and cause some additional contacts from the water users. Maybe a bit surprisingly, the most common problem is that the pH meters report pHs below 6.5, tough it is not technically possible for the treated water to have this low pH.

The chlorine decay model, while performing reasonably well, still needs further development in order to give more accurate results and to have a better estimate its inaccuracy.

The actual online simulation has been performing well, and even tough there are occasional holes in the data received from SCADA, the simulation does give good results. Tampere water utility is incorporating more and more soft sensor data into their SCADA and data analysis software. Especially simulated energy consumption, energy balance, and water age have been useful. Currently the hydraulic simulation results, like pressures in different parts of the network is are not actively used, but there's an ongoing project, which will develop a system to detect leakage and other anomalies based on the differences between simulated and measured data.

One major future extension to the system, is to perform real-time whole cost operational optimization. Currently the operators operate the water supply system manually, but the almost finished project will develop an online system to optimize the next 24 hours pumping and water production. Right now, the online simulator calculates energy balance based on the currently used parallel pump control algorithm and other based on the optimal parallel pump control algorithm using the actual flows and simulated heads. This optimization has already shown good results, and it is being planned to be incorporated into the pumping station Programmable Logic Controllers (PLC) in near future.

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