SOME ALGORITHMS SUPPORTING THE WATER NETWORK MANAGEMENT BY USE OF SIMULATION OF NETWORK HYDRAULIC MODEL

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KEYWORDS
IT systems for waterworks, water net revitalization, water leaks detection, water age and chlorine concentration computing.

ABSTRACT
The short description of an ICT system for computer aided management of communal water networks that has been developed at the Systems Research Institute of Polish Academy of Sciences (IBS PAN) is presented (Studzinski 2013A) in this paper. Several waterworks management tasks requiring mathematical modelling, optimization and approximation algorithms can be solved using this system. Static optimization and multi-criteria algorithms are used for solving more complicated tasks like calibration of the water net hydraulic model, water net optimization and planning, control of pumps in the water net pump stations etc.(Stachura et al. 2012). But some of the management tasks are simpler and can be performed by means of repetitive simulation runs of the water net hydraulic model. The water net simulation, planning of the SCADA system, calculation of water age and chlorine concentration in the water net, localization of hidden water leaks occurring in the network and planning of water net revitalization works are the examples of such tasks executed by the ICT system. They are described in this paper.

INTRODUCTION
Three essential goals that can be reached by computer aided management of municipal water networks are reduction of costs and simplification of waterworks operation as well as improving the quality of drink water supplied to the city. Main problems connected with the water network management are water losses caused by the network damages, unsuitable water pressures on the end user nodes caused by inappropriate work of pump stations installed on the network or by wrong planning of the water net, and a bad quality of produced water caused by incorrect control of the network or by inaccurate planning of water net revitalization. All these problems can be solved in relatively simple way by using new informatics technologies and this idea led to the concept of an integrated ICT system for complex management of communal water networks. The system developed at IBS PAN is now tested in some Polish waterworks.

ICT SYSTEM DESCRIPTION
The ICT system for water networks consist of four main modules, i.e. of GIS (Geographical Information System), SCADA (Supervisory Control And Data Acquisition) and CIS (Customer Information System) systems and of Computational Module (CM) with several algorithms of applied mathematics (Fig. 1). GIS, SCADA and CIS systems are adapted from outside and treated as sources of all data describing the water net investigated and its functioning. All calculations solving the tasks of water net management are executed by the Computational Module applications. The communication between the modules and the applications inside the CM module is done via data files.

Figure 1. Structure and functions of the ICT system.

Figure 2. Optimization and kriging applications of the Computational Module of the ICT system.

The CM module includes presently 20 applications with the algorithms of mathematical modelling (Studzinski et al. 2013), kriging approximation (Studzinski and Bogdan 2007) and multi-criteria optimization (Straubel and Holznagel 1999). Concerning the structure of the ICT system the programs are divided into three groups for solving the tasks of optimization, kriging approximation and mathematical modelling (Fig. 2).
But basing on functionality the programs can be separated in three other groups responsible for hydraulic calculation of the water net, for solving the management tasks for which the optimization is needed and for solving the tasks when only repetitive simulation runs of the hydraulic model must be done (Fig. 1). In the paper only the programs of the last group will be discussed.

**MANAGEMENT TASKS SOLVED BY MEANS OF SIMULATION**

One can see that the ICT system presented consists of the programs operating on three levels of the system functionality. The first level contains programs collecting the data concerning the investigated water net and these are GIS, CIS and SCADA systems. On the second level there are programs solving the management tasks with repetitive simulation runs of the water net where the main operating routine is the water net hydraulic model. The third level consists of programs using optimization algorithms for solving more complicated tasks of the water net management. In the paper six programs of the second level of the system functionality are described.

1. **Hydraulic calculation of the water net**

Hydraulic model of the water net plays the main role in the ICT system. It uses in its calculations the data collected in GIS, CIS and SCADA systems and is used as data source by all simulation and optimization programs of the ICT system. The model itself may contain as many as several thousand linear and nonlinear algebraic equations depending on the size of the water network modelled. These equations are solved using the Newton-Raphson algorithm. The network graph is exported to the model from the Branch Data Base of the GIS system and the data concerning the water consumption at the end user nodes of the water net are supplied from CIS. With the model the main parameters characterizing the water net, i.e. the flows and pressures of the water are calculated and with them the state of the network functioning can be quantitatively assessed. Additionally the state of the water network can be assessed qualitatively by using the kriging approximation for designing the colour maps of flow and pressure distributions in the network (Fig. 3).

2. **SCADA system planning**

The exactness of hydraulic calculation of the water network depends strictly on the quality of the calibration of the water net model. On the other hand the proper calibration depends on the rightness of the SCADA system located on the network. The best solution would be the installation of devices for flow and pressure measurements on each pipe and each node of the water net, but this is impossible from the economical point of view. The SCADA system for proper monitoring the water network and the exact calibration of the water net model must be specially planned. It means that with minimal number of measure devices a possibly maximal amount of information concerning the flow and pressure changes in the water net can be obtained. To reach this goal the measure devices of SCADA shall be installed in characteristic points of the network in which the parameter changes occurring even far away from these points can be recorded. To find these characteristic points of the water net successive simulation runs of water leaks in the nodes of the network are performed and the sensitivity against pressure and flow changes is calculated with the following formulas (Straubel and Holznagel 1999):

\[
SP_k = \frac{\sum_{m \in k} \left( \frac{|P_{m} - P_{m,0}|}{\max(P_{m,0}, P_{m})} \right) L_{km}}{\sum_{m \in k} L_{km}}
\]

\[
SQ_k = \frac{\sum_{m \in k} \left( \frac{|Q_{m} - Q_{m,0}|}{\max(Q_{m,0}, Q_{m})} \right) L_{km}}{\sum_{m \in k} L_{km}}
\]

where: \(k\) – node with the water leak simulated, \(m\) – potential measurement point, \(P_{m}\) or \(Q_{m}\) – pressure or flow value in the node \(m\) without leak simulation, \(p_{m}\) or \(q_{m}\) – pressure or flow value in the node \(m\) with the leak simulation, \(L_{km}\) – distance between the nodes \(k\) and \(m\), \(SP_{m}\) and \(SQ_{m}\) – sensitivity values against pressure and flow changes in the water net nodes.

After the water net sensitivity is calculated the measurement points with highest sensitivity values are chosen for the SCADA system in number depending on the amount of the finances in disposition (Fig. 4).

![Figure 4. Calculation of the water net sensitivity and the sensitivity map designed with the kriging approximation.](image)

3. **Water age calculation**

Water age in the net decides of the water quality which is worsening with the extending time of water staying in the network, especially in older water nets. While calculating the water age the hourly curves of water consumption in the network nodes and the formulas for mixing the water in nodes and pipes of the net must be given. The water age values are usually established after a couple of days of the simulated work of the water net. For the water mixing the weighted average formula with (1) equal or (2) linear or (3) exponential growing weight coefficient \(w_i\) is used:

\[
(1) \quad w_i = 1.0 \\
(2) \quad w_i = 1.0 + 0.050t \\
(3) \quad w_i = \exp(0.030t)
\]

with \(t\) – time in days.
At the start of the program the water age in all nodes and pipes of the network are equal to zero. For the successive time steps the hydraulic calculations are made and the water age for successive water packets moving in the pipes is calculated depending on the water consumption amounts in the end nodes. The mixing of the water occurs in the nodes and there the water changes its age while in the pipes the water packets are only pushed. As the flow velocities in each pipe and the pipe lengths are known one can calculate exactly the movements of the water packets in all pipes for each time step. As the result many water packets with water of different age can be located in the pipes. The results of water age calculation for exemplary water net are shown in Fig. 5.

Figure 5. Calculation results of water age and its distribution in the water net designed by kriging approximation.

4. Calculation of chlorine concentration

With the water age calculated the natural decrease of chlorine concentration occurring with the time in the network can be computed. The functions for this decrease depends on the chemical composition of the produced water and on the material structure of the water net pipes and the suitable coefficients have to be adapted individually to the specific conditions of the waterworks investigated.

Figure 6. Exemplary functions of dropping of chlorine concentration $Y$ in [mg/l] with time $X$ in [h] in network pipes.

In the ICT system presented the exemplary exponential functions used for calculating the dropping of chlorine concentration in the network are shown in Fig. 6. The function coefficients can be easily changed while using the system in other waterworks. Some exemplary results of calculating the distribution of chlorine concentration for a Polish waterworks are shown in Fig. 7. Different concentration values are marked at the water net graph with different colours. For the fast assessment of chlorine contents in the scale of the whole network the map of chlorine distribution is designed by means of kriging approximation.

Figure 7. Calculation of chlorine distribution in the water net and its distribution in the network designed by kriging approximation.

5. Water leaks detection and localization

Detection and localization of water leaks in the water net and especially of these hidden ones is one of the most important problems for the waterworks management because of financial costs caused by the water losses. The algorithms that could solve this problem are very desirable by the waterworks management although their implementation into operational practice is connected with costs which are fairly high. There are in general three approaches dealing with this problem.

The first and simplest approach consists in installation of a dense SCADA system on the water net and this SCADA density enables to detect all changes in flow or pressure values in the network which differs essentially from the standard ones. With this approach the water leaks detection is possible but their more exact localization is unfortunately, very difficult.

The second and most complicated approach consists in adding the water net hydraulic model to the SCADA system and in development of a neuronal classifier with which the potential places of water leaks can be fast localized (Rojek and Studzinski 2014). In this approach the hydraulic model describes the real water net and the neuronal classifier models the hydraulic model. It means that identification of two algebraic models of different arts must be performed.

The third approach is an indirect solution between two earlier approaches and it consists of the following steps:

- Development of SCADA system for the water net investigated using the program for SCADA system planning with which the characteristic, most sensitive points can be defined for the network.
- Development of the water net hydraulic model and its calibration with the data gathered by SCADA.
- Development of standard curves of water flows and pressures for all monitoring points of the SCADA system; to do it the moving averages from the last several days can be used.
- Waiting for alarm signal coming from SCADA and informing about deviation between the standard and current value of water flow or pressure observed and recorded at any monitoring point.
- Recording the current distributions of flows and pressures measured on the monitoring points.
- Performing simulation runs of the hydraulic model with water leaks simulated successively in all nodes and pipes of the water net.
• Recording the flow and pressure distributions calculated for the monitoring points for all water leak simulations.

• In the set of the calculated flow and pressure distributions finding out these ones which are most similar to the just measured values; as the criterion for comparing the different value distributions (1) the sum of errors for all monitoring points or (2) minimal value of the maximal error noted on the monitoring points can be used:

\[
(1) \quad Cr = \min_i \sum_{k=1}^{K} (Q_k - Q_{ki})^2 + \min_i \sum_{k=1}^{K} (P_k - P_{ki})^2 \\
(2) \quad Cr = \min_i (\max_k |Q_k - Q_{ki}| + \max_k |P_k - P_{ki}|)
\]

This third approach of water leaks detection and localization proved to be very effective by testing it on the real data from some Polish waterworks and the illustration of some of its steps is shown in Fig. 8.

**Figure 8.** Water leaks localization; clock wise from the left up: water network with monitoring points; ICT system in stand up state; alarm signal arriving; water leak localized.

6. Water net revitalization

Planning the revitalization of the water net can use different approaches for changing the network pipes. In the first case the network revitalization means the exchange of some pipes against the ones with bigger diameters what shall improve, i.e. heighten the water pressures at the end user nodes of the network. To do it the pipes for the exchange have to be chosen and their diameters must be changed by means of an optimization algorithm. The solution of such task with the use of a genetic optimization algorithm is presented for example in (Fajdek et al. 2014).

In another approach to the revitalization task the exchange of some pipes in the water net is needed because of their wrong technical state and usually against the pipes with the same diameters. The goal of this approach is to reduce the liability of the network to break down and, in result, to reduce the potential water losses in the water net. The susceptibility of water nets to accidents can cause in older municipal waterworks the water losses reaching even up to 30% of the water production and that means essential financial losses for the enterprise (Saegrov 2000). Such revitalization tasks are important for both the water and wastewater nets and in the latter case the reconstruction of the damaged sewage canals protects the environment that would be polluted by the sewage escaping from them. To solve revitalization tasks for wastewater networks the fuzzy sets invented by Zadeh (Zadeh 1965) can be used. Such the solution has been applied in (Sluzalec and Ziolkowski 2013) where for modelling the wastewater network the SWMM model (Rossman 2012) developed by EPA (US Environmental Protection Agency) is adopted.

In our case of the ICT system the water net revitalization is realized as the task with the second approach. While planning the revitalization one must decide which pipes are to be exchanged to minimize the water net susceptibility to accidents and at the same time to secure proper functioning of the whole network. The following factors are taken into consideration when choosing the set of pipes to be replaced:

• Technical state of the pipes characterized by their roughness.

• Current durability of the pipes calculated as the difference between the year of pipe construction and the normative pipe durability.

• Pipe liability to break down in percent defined on the base of historical data concerning the pipe damages.

• Risk of the water losses calculated as the pressure in the pipe modified by the pipe diameter: \( p^* (1 + d / 500) \).

• Costs of the pipe revitalization which consists of two components: the costs of the pipe installation and the costs of buying the new pipes.

In order to select the pipes for revitalization from the whole set of the water net pipes the revitalization indicator is calculated from the following formula:

\[
IR = w_c * Cn + w_t * (1 - Tn) + w_a * An + w_l * Sn
\]

where \( w_c, w_t, w_a \) and \( w_l \) are weights coefficients, \( Cn \) means pipe roughness, \( Tn \) means current pipe durability, \( An \) is pipe liability to break down and \( Sn \) is risk of the water losses defined for the pipe concerned. The weights coefficients can be chosen arbitrary by the program user and all factors in the formula are normalized in the standardized range of values from 0,0 to 1,0.

After the indicators are calculated for all pipes a ranking list for them can be prepared according to the diminishing indicator values. For the sorted pipes also the costs of their revitalization can be defined considering two costs components. Depending on the financial funds which are at the management disposal one can make choice of the set of pipes for the exchange taking the pipes from the top part of the ranking list and summarizing the costs of their revitalization up to the funds limit.

When the pipes to be exchanged are already selected then the effects of the planned revitalization can be verified by performing the hydraulic calculation for the whole water net with roughness values equal to null for the selected pipes. When the revitalization action is done then the vulnerability of the water net to the accidents will be reduced and the water pressures in some end user nodes will be enlarged.
Some exemplary results of the revitalization planning are shown in Fig. 9 where the pipes selected for the exchange are marked with the green colour.

**Figure 9.** Water net revitalization; water net graph before (left) and after revitalization planning with the pipes indicated for changing.

**SUMMARY**

In the paper some algorithms supporting the management of municipal water networks have been presented. The algorithms use in their calculations only hydraulic model of the water net and with the simulation runs of this model several useful management tasks can be realized. These tasks are connected indeed only with planning the water net, like SCADA planning and revitalization algorithms, and with informing about the water net functioning, like calculations of network hydraulics, water age and chlorine concentration, but nevertheless they are important for correct water net operation. More complicated tasks like water net optimization or pumps or tank control need for their solution more sophisticated methods like multi criteria optimization algorithms. An important condition of effective operation of the algorithms described is however their using in strict cooperation with GIS and SCADA systems in frame of a united ICT system. Such the solution is more expensive than individual use of only water net hydraulic models but it makes sure that the management tasks will be done fast, easy, suitably and faultless. Such systems for waterworks are under development at the Systems Research Institute of the Polish Academy of Sciences.

**Acknowledgement**

The paper presented has been realized in the frame of the research project co-financed by the European Union from the European Regional Development Fund, Sub-measure 1.3.1. "Development Projects"; project title: "IT system supporting the optimization and planning of production and distribution of water intended for human consumption in the sub-region of the central and western province of Silesia"; project ref no POIG.01.03.01-14-034/12.

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**BIOGRAPHY**

Marek KUROWSKI was born in Warsaw, Poland. He studied Electronic Engineering at Warsaw University of Technology, in 1969 he received his M. Sc. Degree in the field of Automatic Control and Robotics. After studies he started to work at the Systems Research Institute of the Polish Academy of Sciences and simultaneously he established his microenterprise WINDSOFT dealing with programming of complex ICT systems.

Jan STUDZIŃSKI was born in Warsaw, Poland. He studied Electrical Engineering at Warsaw University of Technology and Applied Mathematics at Warsaw University, in 1989 he received his Ph. D. degree in the field of Automatic Control and Robotics, in 2005 a D. Sc. degree. Currently he works at the Systems Research Institute of the Polish Academy of Sciences.