ICS System Supporting the Water Networks Management by Means of Mathematical Modelling and Optimization Algorithms

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Abstract:

In the/this paper a concept of an integrated information system for complex management of water networks is presented. The ICT system is under development at the Systems Research Institute (IBS PAN) in Warsaw for a couple of years and it is gradually tested in some Polish communal waterworks of differentiated size. 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. [4] 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.

Keywords: *drink water distribution system, water net hydraulic model, hydraulic optimization, water net management*

1. Introduction

The world trend in computerization of waterworks is currently the implementation of integrated information systems for complex management of whole enterprises or their whole key objects and under them of water networks what is the simplest venture from the technical, organizational and financial point of view. An integrated management system for a communal water network consists usually from GIS (*Geographical Information System*), SCADA (*System of Control and Diagnostics Analysis*) and CIS (*Customer Information System*) systems which are integrated strictly with some modeling, optimization and approximation algorithms [7]. Due to this strict cooperation under several programs all tasks of the water net management concerning technical, organizational, administrative and economic problems can be automatically executed or computer supported [8]. 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.

2. ICT System Description

According to the mentioned trend in waterworks computerization an integrated ICT system for complex water networks management has been developed at the Systems Research Institute and its structure is shown in Fig. 1. The system is built in modular form and it consists of the following components:

- GIS – for generating the numerical maps of the water net investigated;
- SCADA – for monitoring the water net parameters, i.e. pressures and flows of the water;
- CIS – for recording the water consumption of the end users of the water net;
- 20 computing programs with algorithms of mathematical modeling, optimization and approximation for solving the water net management tasks.

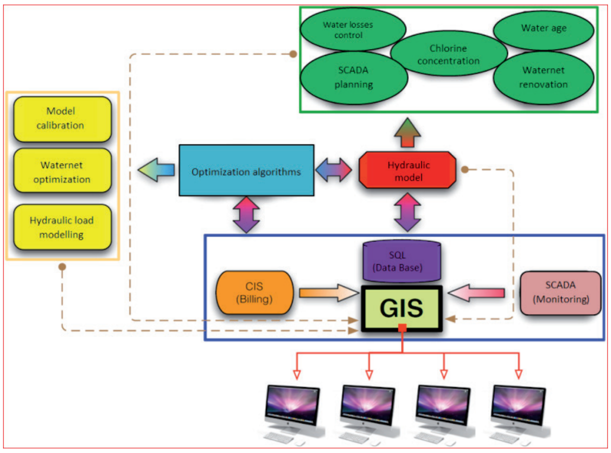

Fig. 1. Block diagram of the ICT system for water networks management

The components GIS, SCADA and CIS are adopted from other firms and integrated with the computing programs via data files or data tables. The computing programs are responsible for realization of all management tasks by means of water net hydraulic model and optimization algorithms. Some functions realized by the programs are as follows:

1. Hydraulic modeling of water nets;
2. Optimal planning of SCADA systems for water nets;
3. Automatic calibration of hydraulic models;
4. Optimization and planning of water nets;
5. Control of pump stations in water nets;
6. Control of pumps installed in pump stations;
7. Detecting and localization of leakage points in water nets;
8. Calculation of water age in water nets;
9. Calculation of chlorine concentration in water nets;
10. Planning of water net revitalization;
11. control of network valves changing the water flows distribution in water nets.

The programs realizing the functions specificated above work with the water net hydraulic model and while realizing the tasks concerning the model calibration, water net optimization and planning, pumps control and planning of SCADA they use an heuristic algorithm of multi criteria optimization [6]. For the solution of other tasks of the water net management only multiple simulations of the hydraulic model under different work conditions of the water net are executed [8]. The functions realized in such the way by the ICT system are:

12. calculation of height coordinates for the water net nodes;
13. drawing the maps of water flow and pressure distributions in water nets;
14. drawing the maps of water net sensibility toward the leakage events occurring in water nets;
15. drawing the maps of water age distribution in water nets;
16. drawing the maps of the distribution of chlorine concentration in water nets;
17. drawing the maps of value distributions for some environmental parameters like temperature in the area of the water network.

The programs that realize these functions use the algorithms of kriging approximation that enable to picture in graphical form the value distributions of parameters connected with water nets and their operation [1]. The last part of the management functions realized by the ICT system concerns the calculation of mathematical models for forecasting the hydraulic load of water nets and of their end user nodes. This is done by means of the following time series methods [2]:

18. Least squares method of Kalman;
19. Generalized least squares method of Clarke;
20. Maximum likelihood method.

Due to the cooperation of several programs while solving different management tasks a synergy effect arises what boosts essentially efficiency of the running programs.

In the following some algorithms supporting the water nets management and implemented in the ICT system are described.

3. Algorithms of Modelling and Optimization

3.1. Hydraulic Model Calibration

Calibration procedure in case of water nets consists usually in changing the roughness values of the network pipes in such the way that flows and pressures measured and calculated are possibly the same in the net points where the sensors of SCADA system have been installed. This changing occurs normally by hand for in the waterworks; there are not the appropriate programs that could support this action by automatic computing [9]. The algorithm presented executes the calibration procedure in three following steps:

1. Preparation of the initial data consisting in division all network pipes in groups depending on pipe diameters, age and material;
2. Changing the roughness of pipes regarding the pipe groups and not individual pipes;
3. If the roughness change in a group exceeds the values field given then changing there the nominal pipe diameters; this change occurs either in frame of a given values field.

In this way the algorithm has got two phases of calculation regarding the roughness and diameter changes that follow one after another.

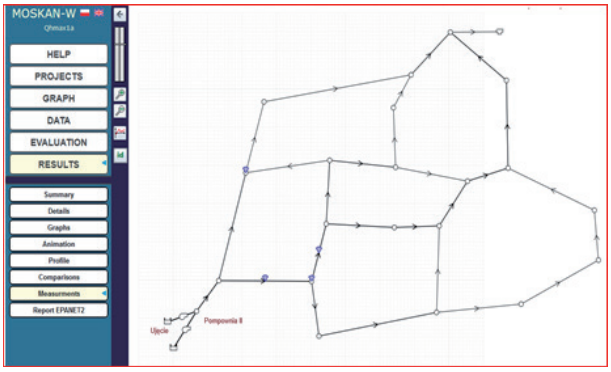

Fig. 2. Exemplary water net model calibrated

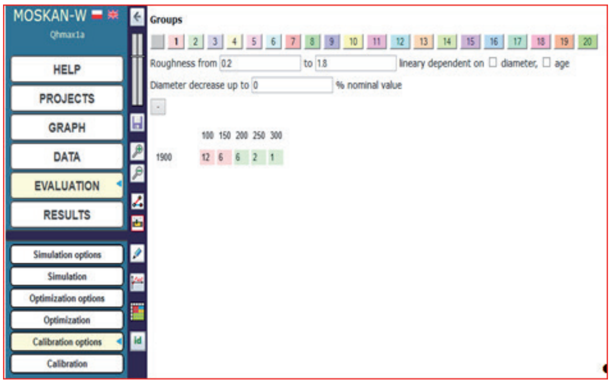

Fig. 3. Preparation of data for the exemplary water net model calibration

In Figures 2 and 3 the exemplary water net model and the data preparation for its calibration are shown. The net consists of 25 pipes of the same age and made of the same material. On two pipes and on two nodes of the net the measuring devices for flow and pressure are installed. In Fig. 3 one can see the diagrams of calculated and measured flow and pressure values designed for 24 hours and shown for one pipe and one node before the calibration run. The pipes are divided into 2 groups regarding their diameters. By the calibration only the roughness values in two pipe groups will be changed.

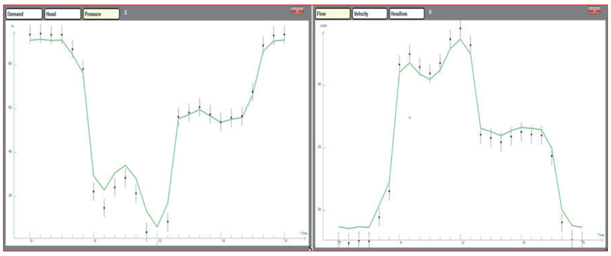

Fig. 4. Differences between measurement data (in grey) and calculation values (in green) in node 2 (pressure values – left) and in pipe 5 (flow values) before calibration

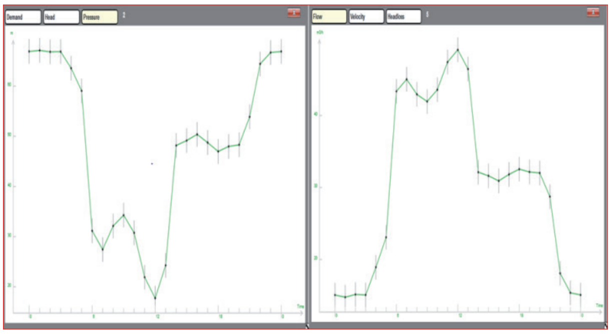

Fig. 5. Results of calibration shown for node 2 (pressure values – left) and pipe 5 (flow values)

The results of the calibration done by means of a genetic algorithm are shown in Fig. 5. One can show there that the pressure values in the node and the flow values in the pipe (which are the same as before) are the practically identical for the calculation results and for the measurement data what allows to consider the calibration algorithm to be very effective.

3.2. Water Net Hydraulic Optimization

Another algorithm supporting the water net management concerns the hydraulic optimization of the water network by means of exchange of particular network pipes and/or of control of pumps in the water take out stations or in the works raising the water pressure within the water net. In the algorithms solving the task in small and medium waterworks the calculation can be done for all pump stations in the same run for there are not more than only several pumps in such the enterprises. In the case of big waterworks the situation is more complicated because there are many pump stations and also a lot of pumps in them and finding the control schemes for all devices simultaneously is practically not possible. Because of that the algorithm proposed consists of two stages when on the 1st stage the controls are calculated for the pumps stations seen as single generalized pumps and the 2nd stage the calculation is done for each pumps station and for the pumps there individually. Such the division of the hydraulic optimization task in two separated stages makes the problem solvable from the computational point of view.

In the following the realization of the 2nd stage of the algorithm done for a real pumps station of a Polish waterworks is described. In the object only 1 pump works and from it 2 pipes ended with 2 nodes go out. The pressure values in these nodes are too small against the values that have been calculated on the 1st stage of the algorithm. The problem is to find out the pipes with new diameters and to calculate the pump velocity in such the way that the obtained node pressures will fit to the indicated earlier value areas.

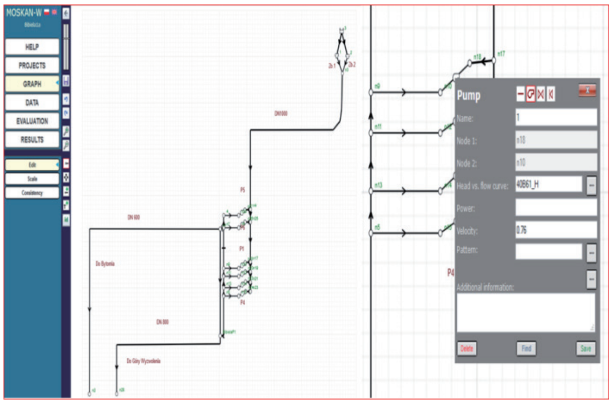

Fig. 6. View on the pumps station calculated and the parameters of the pump to be controlled

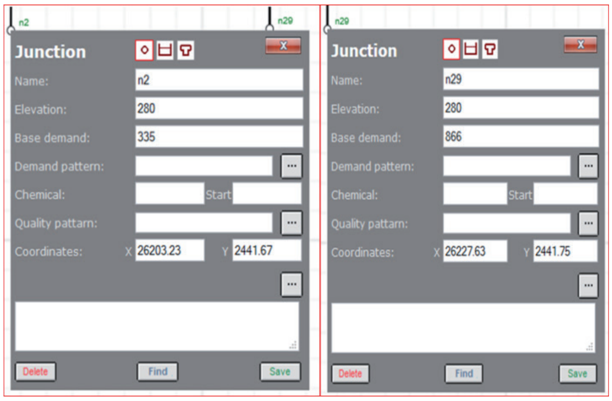

Fig. 7. Parameters of two nodes being the outputs of the pump station calculated

In Figures 6 and 7 the scheme of the pipe connections in the pumps station investigated and the characteristics of the pump and of the nodes concerned are shown. In Figures 8 and 9 the screens of the program developed at the IBS PAN and prepared for introducing the input data for changing the pump velocity and the pipe diameters are to see [5]. In this example the pump velocity can be change/changed? in the area between 60% and 100% of its nominal speed, the new pipes can have their diameters between 100 mm and 1.200 mm and the acceptable or preferable node pressures are lying between 20 m and 70 m or 28 m and 36 m for one node and between 10 m and 70 m or 37 m and 45 m for another one, respectively. To solve the problem a genetic algorithm of optimization with the use of fuzzy sets while calculating the node pressures is applied; the fuzzy sets are used to make a distinction between the acceptable and preferable value areas while calculating the node pressures.

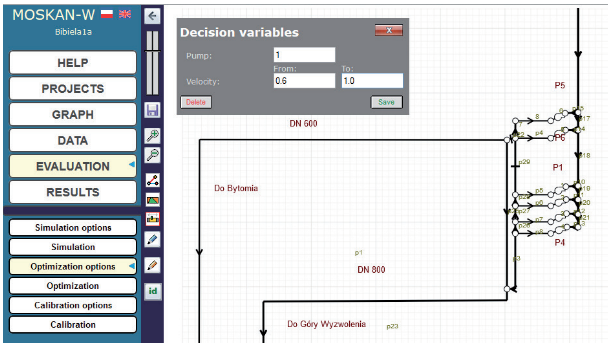

Fig. 8. Preparation of input data for the pump control

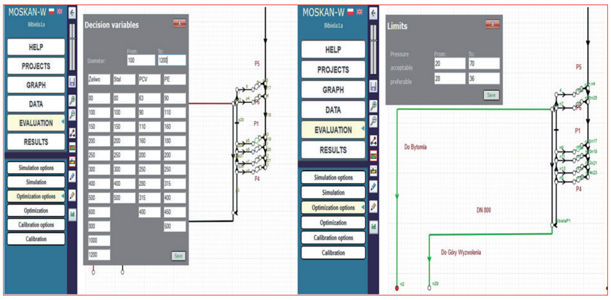

Fig. 9. Preparation of input data for the exchange of pipes

In Fig. 10 the results of the hydraulic optimization made for the single pumps station are given. The pressure values at the end nodes of the pumps work raised from 11.82 m to 35.86 m and to 37.24 m, respectively, what is the consequence of the pipe diameters change from 600 mm to 488 mm for one pipe and from 800 mm to 1.048 mm for another one, and of the pump velocity change from 0.76% to 0.89% of its nominal speed.

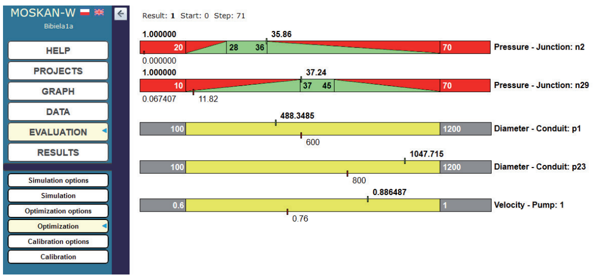

Figure 10. Results of the hydraulic optimization of the pumps station calculated

3.3. Water Net Revitalization

Water net revitalization belongs to the planning tasks that can be divided into 3 kinds: hydraulic optimization, drawing up new networks or extension of the old ones and revitalization or renovation. In the first two kinds of the tasks computer simulation of the water net hydraulic model as well as optimization algorithms must be used to secure right hydraulic conditions of the water net operation. They mean relevant water pressures in the end user nodes of the network and possibly fast velocities of water in the network pipes. In case of revitalization the network works right from the hydraulic point of view and the reason to undertake the action is an old age of water net objects, mostly of pipes, or their wrong technical state causing the risk of failures. 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 what means essential financial losses for the enterprise [3].

In the presented algorithm the revitalization task means the exchange of several pipes in the water net because of their wrong technical state and against the pipes with the same diameters. While planning the revitalization with such approach only multiple simulation runs of the network hydraulic model are done for the exchange of old pipes against new ones with reduced roughness values does not worsen but improves the hydraulic conditions of the water net. The goal of the algorithm is to reduce the liability of the network to break down and, in result, to reduce the potential water losses in the water net.

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. After the indicators are calculated for all pipes a ranking list for them is prepared according to the diminishing indicator values.
- 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.

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.

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:

$$IR = w_c * Cn + w_t * (1.0 - Tn) + w_a * An + w_s * Sn \quad (1)$$

where w_c, w_t, w_a and w_s 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 standarized range of values from 0.0 to 1.0.

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 as well as flow velocities in some pipes will be enlarged.

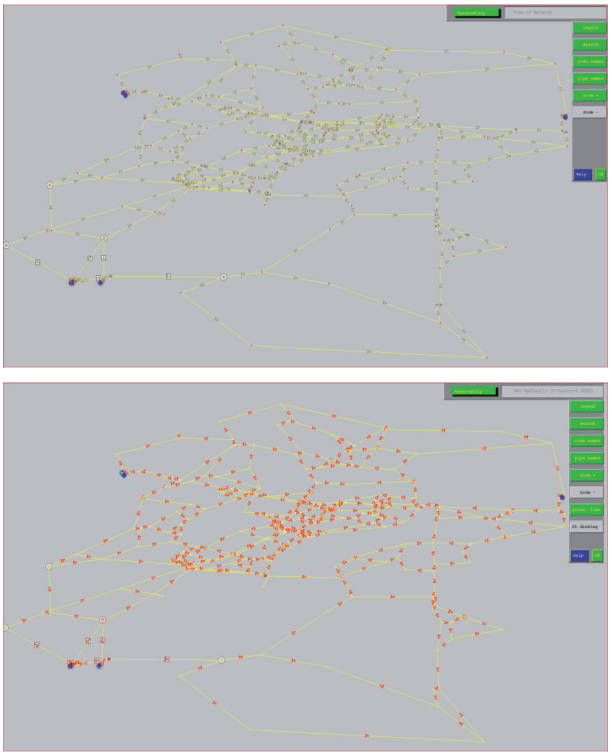

Fig. 11. Water net investigated before (up) and after (down) hydraulic calculation

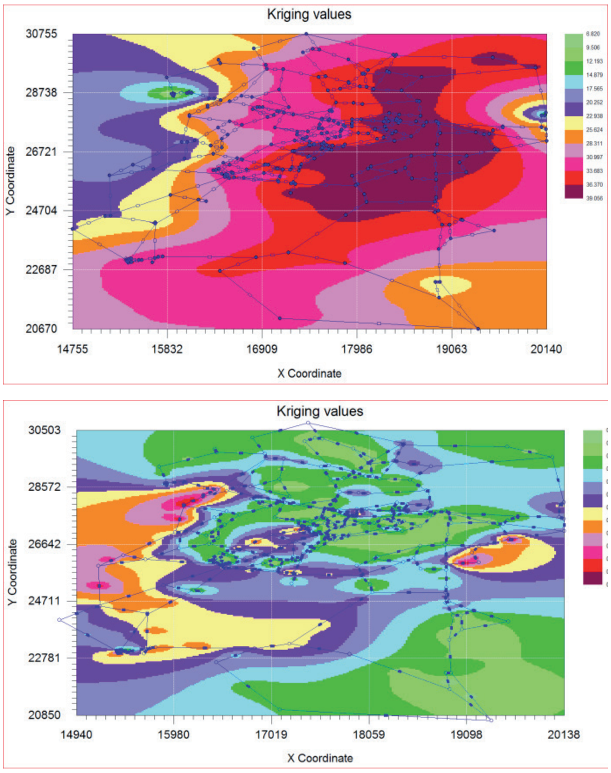

Fig. 12. Pressure (up) and flow (down) distributions in the water net after its hydraulic calculation

The hydraulic graph of the water net investigated before and after the hydraulic calculation is shown in Fig. 11. The network is supplied with water by 2 pump stations located on its left-bottom side. On the right side of the network and overhead 2 retention tanks are installed. The graph of the water net consists in total of 280 nodes and of 398 pipes. The distributions of flows and pressures in the water net before the revitalization action are shown in Fig. 12. The flow and pressure values are highest in the areas where the pump stations and tanks are situated.

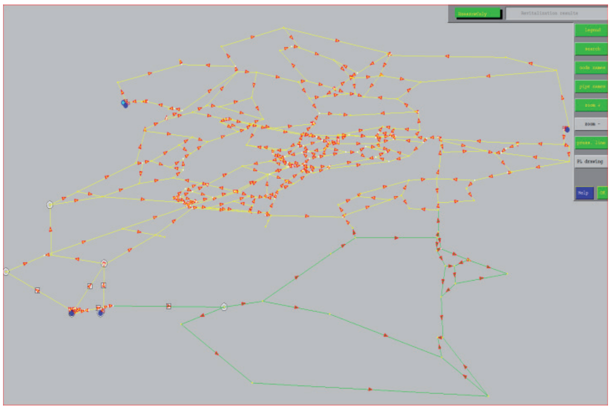

Fig. 13. The graph of the water net with the pipes selected for revitalization

In Fig. 13 the pipes selected for the exchange are marked with the green colour. According to formula (1) and to data assumed, concerning all relevant factors 31 pipes from 398, i.e. 8% of the whole, have been taken for the replacement.

The effects of the revitalization after performing the hydraulic calculation for the whole water net with roughness values equal to null for the selected pipes are shown in Figures 14 and 15. In Fig. 14 the curves received before the revitalization are marked with the blue colour.

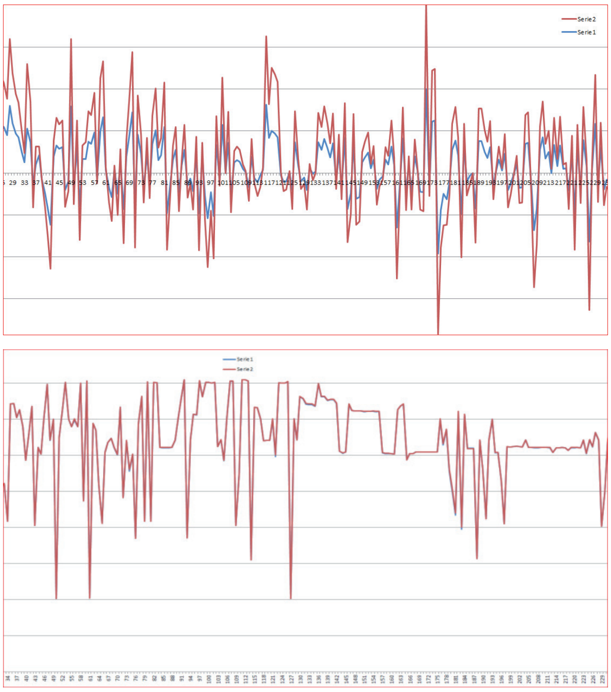

Fig. 14. Comparison of water flows (up) and pressures (down) before and after the water net revitalization performed for 31 pipes

One can see from Figures 14 and 15 that in accordance with expectation the values of pressures and flows in the water net have increased after the revitalization. Nevertheless the changes of pressure values are very small and insignificant towards the changes of the flows. In that case not only the values but also the flow directions changed as the result of revitalization.

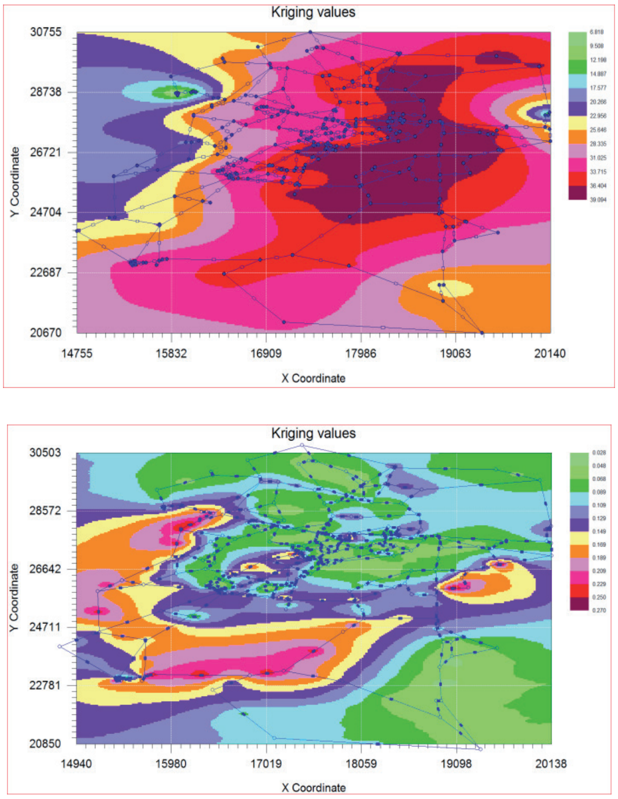

Fig. 15. Pressure (up) and flow (down) distributions in the water net after its revitalization performed for 31 pipes

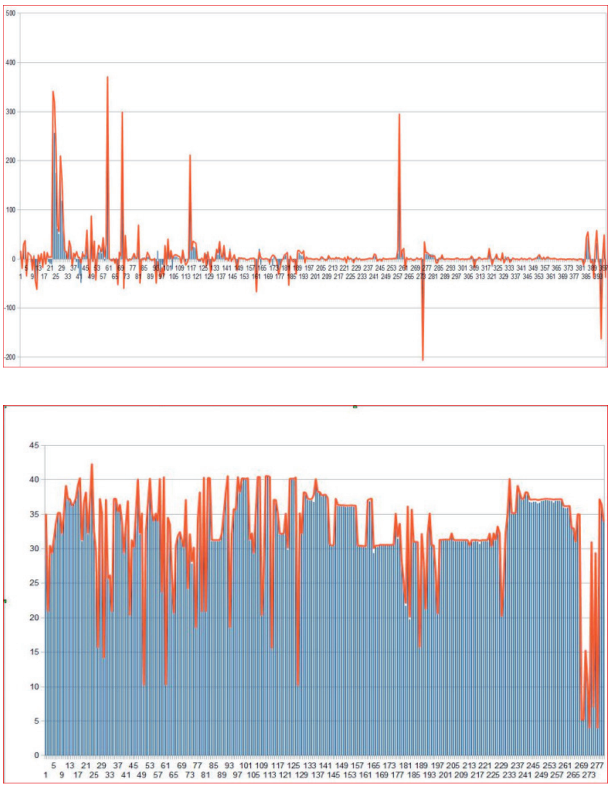

Fig. 16. Comparison of water flows (up) and pressures before (down) and after the water net revitalization performed for all pipes

Table 1. Comparison of flow and pressure values before and after the water net revitalization performed for all pipes

Nr	Flow before revital.	Flow after revital.	Pressure before revital.	Pressure after revital.
1	10.1323	16.2095	20.9	20.91
2	-15.6321	-19.6183	30.4	30.45
3	17.9016	29.9229	29.31	29.36
4	28.0094	37.7194	31.4	31.44
5	-22.4987	-34.7968	33.7	33.73
6	4.5943	13.1449	35.1	35.2
7	0.0599	9.847	35.09	35.2
8	2.3047	5.8978	32,11	32.17
9	-17.493	-22.9548	35.04	35.16
10	7,7127	5.7549	39.02	39.15
11	-38.4735	-44.7111	37.1	37.2
12	-49.7825	-62.1092	37.11	37.2
13	5.1874	8.3333	36.11	36.21
14	-10.1803	-6.506	36.41	36.54
15	1.8669	11.0067	37.21	37.32
16	-9.3078	-17.5968	39.12	39.22
17	13.2529	14.9158	40,09	40.26
18	-9.9838	-10.2465	31.07	31.23
19	10.4993	13.3058	36.59	36.71
20	-6.1282	3.0865	38.1	38.2
21	-9.289	4.3611	32.11	32.24
22	-10.7361	3.4721	36,69	36.81
23	274.2455	341.5322	42.14	42.29
24	256.7525	318.5774	32.48	32.56
25	175.2549	224.9842	20.9	20.91

To see it better in another step of revitalization all pipes of the water net have been replaced. The hydraulic results received are shown in Fig. 16 and in Table 1 for exemplary pipes and nodes. Once again one can see that the pressure values increased but in a very small and practically marginal degree. Against it the flows increased their values essentially and also the flow directions have been changed in many pipes.

4. Conclusions

In the paper some algorithms supporting the management of municipal water networks have been presented. Among many algorithms developed for the waterworks there are several algorithms that 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 calibration of the water net hydraulic model or 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 system for waterworks is for a longer time under development at the Systems Research Institute of the Polish Academy of Sciences and some versions of it have been already made and tested in some communal waterworks in Poland.

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