FAILURES LOCATION WITHIN WATER SUPPLY SYSTEMS BY MEANS OF NEURAL NETWORKS

Submitted: 20th March 2013; accepted 30th August 2013

Izabela Rojek, Jan Studziński

DOI 10.14313/JAMRIS_2-2014/15

Abstract:
In the article the neural networks used for failures location for water supply networks are presented. To do this a hydraulic model of the water net, as well as an appropriate developed monitoring system have to be used. The current applications of monitoring systems installed in the waterworks do not realize their possibilities. The monitoring systems provided as autonomic programs to collect and record the information about flows and pressures of water in source pumping stations, in the pump stations bringing up the water pressure inside the water net and in the pipes of water supply network give a general knowledge about state of its work, but if they would be used as elements of IT systems supporting the water network management, they could help to solve the tasks concerning detection and localization of water leaks. The models of failures location in water nets described in the paper are created by means of neural networks in the form of MLP nets.

Keywords: *water-supply networks, network hydraulic model, detection and location of water leakages, neural networks*

1. Introduction

The main goals of a municipal water network are the supply of water to the water net users and correct operation of the water net assuring an appropriate water pressure in the water net end nodes, efficient removing of the failures, as well as planning and executing of activities concerning conservation, modernization and extension of the network whereas the water supplied and distributed under the water net users has to be of a suitable quality and sufficient quantity [1]. The operation and control of a water network is a difficult and complex process. The problem of detection and localization of hidden leakages in the water network is one of the most important water net management tasks. This is because of the water losses caused by the water net damages; and the resulted water losses can reach sometimes even 30% of the total water production what has essentially and negatively financial results of waterworks. Therefore, the fast location and elimination of water leaks and (especially of these hidden ones) can bring the measurable economic advantages both for the waterworks and for the water net end users.

The different stages of the whole process of elimination of water leaks can be defined in the following way:

- failures detection – a failure case can be determined by observation of a bigger water tribute, but the failure location cannot be defined;
- failures location – the failure place in the water net can be determined by means of some suitable algorithms and with the use of a monitoring system, the water net hydraulic model and particularly also of neuronal networks;
- failures counteraction – using the failures historical data, development of models to forecast the water net emergency and the subsequent planning of network revitalization, the rate of the water net unreliability can be essentially reduced.

2. The Algorithm for Water Net Failures Localization

Different approaches and computational algorithms to aid detection and location of water leaks in water networks have been already presented in the past and current literature [1, 2, 3, 4]. In every case a water network hydraulic model and a monitoring system installed on the water net are the basic tools for making the calculations. An appropriate computer infrastructure exploited on the water network is needed for practical realization of these algorithms. A monitoring system, a calibrated hydraulic model of the water net, as well as a GIS system for generating the water net numerical map should be included as key components into this infrastructure. Such the extended computer infrastructure permits not only to detect and locate the water net failures but also to manage the network executing the tasks like water net control, water quality analysis and improvement, water net optimization and design, etc. [5, 6]. This means that the high developed ICT tools are useful and indispensable for water network management making it easy, right and optimal.

In the following an algorithm to detect and locate the water leaks in municipal water networks is described. It uses the neuronal nets to create a classifier identifying and situating the water leaks arising in the water net. The algorithm consists of the following steps:

1. Determination of a ranking list of sensitive points in the water net, using an algorithm for planning the monitoring systems.
2. Choice of a suitable number of the most sensitive measuring points for the monitoring system to be installed on the water network.
3. Development of a hydraulic model of the investigated water net and its calibration using the data from the monitoring system installed.

4. Determination of standard distributions of pressure and flow values using the data from the measuring points of the monitoring system; these distributions are calculated for standard loads of the whole water network and of its end nodes.
5. Simulation of leakage events in subsequent nodes of the water net by means of the hydraulic model and recording of pressure and flow values measured in the measuring points of the monitoring system.
6. On the base of the failures data recorded, creation of the water leaks classifiers in form of neural networks and choice of the best classifier regarding the criterion of largest sensibility.
7. On line measuring the water flow and pressure values in the water net using the monitoring system and comparison of the current data with these standard ones.
8. In case of an essential difference between the standard and current data recorded by the monitoring system, use of the classifier to find out the water net node in which the water leak possibly happened.

2.1. Determination of Sensitive Points in the Water Net Investigated

In order to find out the best location of sensors for the measuring points of the monitoring system to be installed on the water net the so-called *sensitive points* of the water net have to be determined. There are in state to collect the information concerning the changes in the water network not only in the points where they are installed but also from the remote surroundings. These sensitive points one can name as *characteristic points* of the water net in contrary to the so-called *dead points* in which only the local changes of the water network can be noticed. The usual practice while developing monitoring systems consists in extension of number of the monitoring points what stays in opposition to the procedure shown above. A suitable choice of a comparatively small number of characteristic points in the water net can be equivalent regarding the quality and quantity of the information collected with larger number of points situated in less sensitive places of the network. To determine the sensitive points of the water net the following formulas [7] can be used:

$$S_{pm} = \frac{\sum_{k \neq m} (\Delta p_m / p_m) L_{km}}{\sum_{k \neq m} L_{km}} \qquad S_{qm} = \frac{\sum_{k \neq m} (\Delta q_m / q_m) L_{km}}{\sum_{k \neq m} L_{km}}$$

where: k –node with the water leak simulated, m – measurement point considered, p – water pressure, q – water flow, Δp_m and Δq_m – differences in measurements for standard and emergency states of operation of the water net, L – distance between the points k and m.

The correct measurement points are these ones with the highest sensitivity values. In Fig. 1 the circulation of information while planning the monitoring system is shown. The data collected from the water

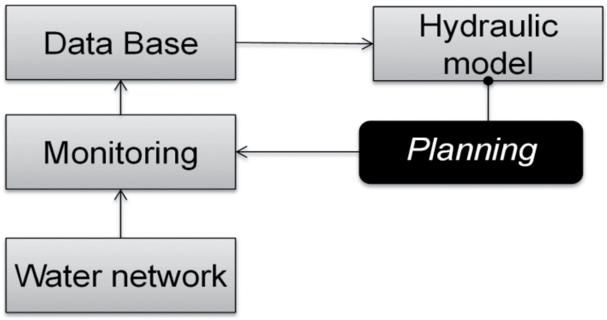


Fig. 1. Structure of the procedure for planning the monitoring system

net by the monitoring system are recorded in the data base, which is mostly the branch data base of a GIS system and then there are used by a hydraulic model to calculate the sensitivity values of the water net nodes. One can see that to calculate these values a monitoring system installed on the water net, as well as a calibrated water net hydraulic model are needed what is not the case at the beginning of the procedure. Because of that the procedure is realized iteratively in the following steps: the first step means a calibration of the hydraulic model using data got from a measurement experiment performed at the water net; the second step means the sensitive points calculation using the hydraulic model calibrated and then the installation of the monitoring system in the selected measuring points; the third step if realized means mostly the recalibration of the hydraulic model with use of the monitoring system already installed.

2.2. Development of a Hydraulic Model of the Water Net

To find out the sensitive points of the water net for planning the monitoring system the hydraulic model of the real Polish water net has been used. The hydraulic calculations can be made only with the hydraulic graph of the water net, which is topologically correct, that is compact and without any un-continuities. Hydraulic graphs can be generated and exported to the hydraulic models by GIS systems and such the mechanism is shown in Fig. 2. Such the operation makes

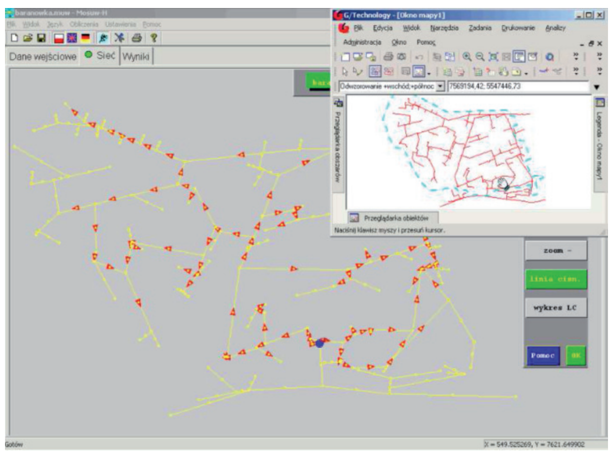


Fig. 2. Export of a water net hydraulic graph from a GIS system to the water net hydraulic model

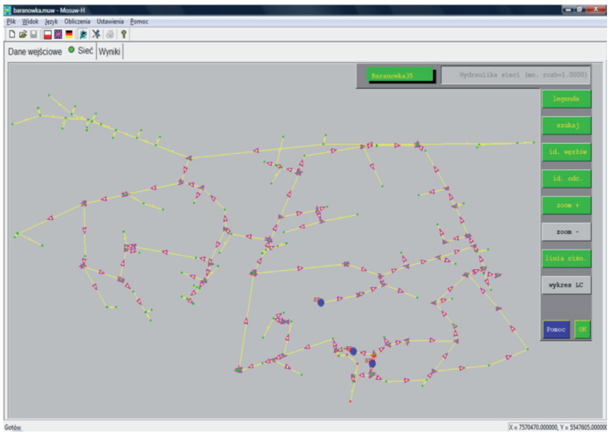


Fig. 3. Hydraulic model of the water net investigated ready for simulation of water leaks

the calculation with the hydraulic model much easier and faster as if the hydraulic graph would be designed using the software interface of the hydraulic model. After the data export from GIS system is already completed then the calculation with the hydraulic model can be executed quite apart from GIS (Fig. 3).

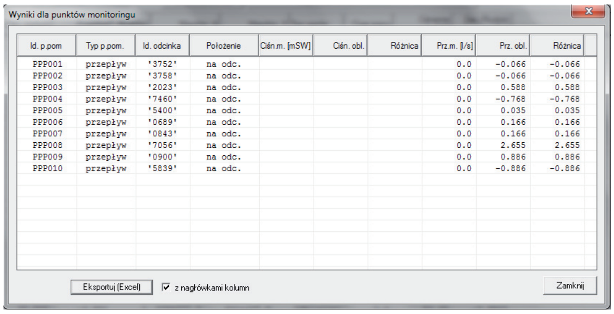
2.3. Simulation of Leakage Events in The Subsequent Water Net Nodes

In the research presented two cases of investigation have been realized: for the monitoring systems consisted of 10 and of 20 monitoring points located on the water network in its most sensitive nodes. The execution of hydraulic calculations of the water net for its standard load without any water leaks, simulation of leakages in the subsequent water net nodes using the hydraulic model and recording of flow values from the monitoring points for both cases of the monitoring systems and for both cases of the water net operation, in standard and in failures modes, leads to the preparation of learning files for the neural networks.

In Fig. 4 one can see the data file got from the hydraulic model with the flow values calculated for 10 measuring points of monitoring system for the standard mode of the water net operation. Similar files can be got from the hydraulic model for the water leaks subsequently simulated in all net nodes. While simulating the water net failures the following activities have to be made:

- simulation of water leaks in all water net nodes with several changes of the flow values (by means of the hydraulic model),
- computation of flow differences in the monitoring points, occurring between the standard and failure modes of the water net operation,
- determination of the measuring points with strongest reaction on the water leak in the dedicated water net nodes,
- making data files with recorded flow values from the monitoring points for standard and failure modes of water net operation and with most sensitive monitoring points determined.

With the data files made, the neuronal classifiersof water leaks to signalize the cases of water net failures and to notify their possible localization can be created.



Wyniki dla punktów monitoringu

Id. p.pom	Typ p.pom.	Id. odcinka	Położenie	Ciśn.m. [mSW]	Ciśn. obl.	Różnica	Prz.m. [l/s]	Prz. obl.	Różnica
PPP001	przepływ	'3752'	na odc.				0.0	-0.066	-0.066
PPP002	przepływ	'3758'	na odc.				0.0	-0.066	-0.066
PPP003	przepływ	'2023'	na odc.				0.0	0.588	0.588
PPP004	przepływ	'7460'	na odc.				0.0	-0.768	-0.768
PPP005	przepływ	'5400'	na odc.				0.0	0.035	0.035
PPP006	przepływ	'0689'	na odc.				0.0	0.166	0.166
PPP007	przepływ	'0843'	na odc.				0.0	0.166	0.166
PPP008	przepływ	'7056'	na odc.				0.0	2.655	2.655
PPP009	przepływ	'0900'	na odc.				0.0	0.886	0.886
PPP010	przepływ	'5839'	na odc.				0.0	-0.886	-0.886

Eksportuj (Excel) z nagłówkami kolumn Zamknij

Fig. 4. Data file with the measured values of flows in the monitoring points of the water net; case with 10 monitoring points

2.4. Creation of the water leaks classifier in form of neural network

The models of failure location in the water net have been created by use of neural networks of MLP type. These neural networks are invariably the most widespread and universal networks used currently for solving much differentiated scientific and practical problems like technical, economical, medical ones, etc. In a multi-layer network with the error back-propagation algorithm (called multi-layerperceptron, MLP) the choice of a number of neurons put onto the input layer is conditioned by the dimension of data vector x. The neuronal model consists of the sum of elements $x_1, x_2, ..., x_N$ (in form of the input vector $x = [x_1, x_2, ..., x_N]^{T)}$) multiplied by weight coefficients $w_{i1}, w_{i2}, ..., w_{iN}$ (in form of the weights vector $w_i = [w_{i1}, w_{i2}, ..., w_{iN}]^T$ regarding neuron i) and of an additional value w_{i0}:

$$u_i = \sum w_{ij} x_j + w_{i0}$$

The resulted signal u_i is given to a non-linear activation function $f(u_i)$ which is mostly an one-polar sigmoid function:

$$f\,(u_i) = \frac{1}{1 + \exp(-\beta u_i)}$$

The algorithm of the error back-propagation is the basic algorithm supervising the learn process of the multi-layer and one-way neuronal networks. While executing the algorithm a gradient method is used to minimize the error function.

On the first step of investigation the monitoring system with 10 measuring points has been used and in 36 selected nodes of the water net the water leaks have been simulated. The whole water net investigated contains 390 nodes. On the second step of investigation the number of monitoring points raised to 20 and the number of water net nodes with the water leaks simulated raised to 44.

The water leaks classifier has been created according to the methodology developed in [8]. When the calculation runs have been realized while creating the classifier in form of a MLP two parameters of the neuronal network have been changed: number of neurons on the hidden layer of the network computed and number of its learning epochs. The first parameter changed its value from 5 to 25 and the second parameter has taken optionally the values 200, 500 and 1000.

24	25	26	27	28	29	30	31	32	33	34	35	36	37
2158	2186	2447	2740	2779	3028	6144	3587	3596	4138	4181	4250	4411	Monitoring point
-25.74	-4.2	-4.83	-5.04	-94.46	-2.71	-2.79	-3.1	-8.43	-6.31	-2.2	-1.69	-4.76	4
-5.74	**-20.2**	-4.83	-5.04	-94.46	-2.71	-2.79	-3.1	-8.43	-6.31	-2.2	-1.69	-4.76	6
-5.74	-4.2	**-20.83**	-5.04	-94.46	-2.71	-2.79	-3.1	-8.43	-6.31	-2.2	-1.69	-4.76	6
-5.74	-4.2	-4.83	**-25.04**	-94.46	-2.71	-2.79	-3.1	-8.43	-6.31	-2.2	-1.69	-4.76	7
-5.74	-4.2	-4.83	-5.04	**-470.46**	-2.71	-2.79	-3.1	-8.43	-6.31	-2.2	-1.69	-4.76	10
-5.74	-4.2	-4.83	-5.04	-94.46	**-10.71**	-2.79	-3.1	-8.43	-6.31	-2.2	-1.69	-4.76	4
-5.74	-4.2	-4.83	-5.04	-94.46	-2.71	-2.79	-3.1	-8.43	-6.31	-2.2	-1.69	**-20.76**	2
-5.74	-4.2	-4.83	-5.04	-94.46	-2.71	-2.79	-3.1	-8.43	-6.31	-2.2	-1.69	-4.76	0

Fig. 5. A fragment of data file for teaching the neural networks

In Fig. 5 a fragment of the data file used for teaching the neuronal nets is shown in the case of 10 monitoring points considered. The columns from 24 till 36 in the file show the flow values in the water net nodes in which the water leaks have been simulated. These flow values are calculated using the hydraulic model for both modes of the water net operation, i.e. for the standard load of the water net and for its different failures loads. The last column of the data file shows the numbers of the monitoring points that reacted strongest on the flow changes caused by the water leaks simulated in the subsequent water net nodes; number 0 in the column means the standard mode of the water net operation, i.e. the work of the water net without any water leak.

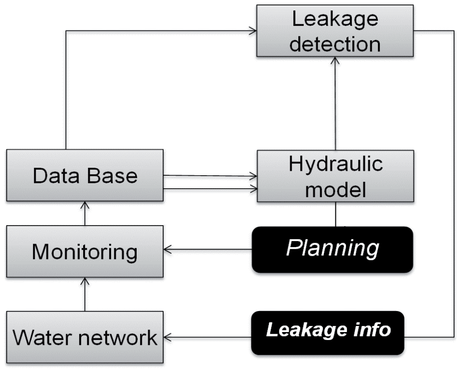


Fig. 6. Structure of the procedure for simulating the water leaks

Table 1. Calculation results for 10 monitoring points and water leak simulations in 36 water net nodes

No.	Neural Network Name	Learning quality	Testing quality	Validation quality
1	MLP 36-08-11	88.32	95.56	88.89
2	MLP 36-15-11	97.66	97.78	95.56
3	MLP 36-22-11	94.39	97.78	93.33
4	MLP 36-19-11	97.66	97.78	95.56
5	MLP 36-21-11	94.39	97.78	93.33
6	**MLP 36-24-11**	**97.20**	**97.78**	**97.78**
7	MLP 36-23-11	97.66	97.78	95.56

Table 2. Calculation results for 20 monitoring points and water leak simulations in 44 water net nodes

No.	Neural Network Name	Learning quality	Testingquality	Validation quality
1	MLP 44-25-21	97.22	100.00	98.15
2	**MLP 44-18-21**	**100.00**	**100.00**	**100.00**
3	MLP 44-21-21	98.02	96.30	98.15
4	MLP 44-18-21	87.70	85.19	83.33
5	MLP 44-19-21	90.08	88.89	83.33
6	MLP 44-24-21	80.56	75.93	81.49
7	MLP 44-08-21	93.66	90.74	94.44

In Fig. 6 the circulation of information while simulating the water leaks in the water net is shown.

In the first case of investigation, with 10 monitoring points and with 36 water net nodes with water leak simulations, the number of examples (records) included into the data file used for teaching the neuronal nets amounted to 304 and in the second case, with 20 monitoring points and 44 water net nodes with water leak simulations, the number of examples amounted to 360. In each case the teaching data file was divided into 3 under-files, i.e. the learning file containing 70% of examples, the testing file with 15% of examples and the validation file with 15% of examples.

The results of calculations done with different structures of the MLP neuronal nets and for 2 cases of investigation are shown in Tables 1 and 2. The quality values of learning, testing and validation of the neuronal nets are given in % in the tables. An exemplary notation MLP 36-8-11 in Table 1 means a MLP neuronal net with 1 hidden layer and with 36 neurons on the input layer (due to 36 water net loads with water leak simulations), with 8 neurons on the hidden layer and with 11 neurons on the output layer (due to 10 monitoring points and to 1 standard mode of the water net operation).

One can see from the results shown that a MLP neuronal net can be a good IT tool for finding out the water leaks in municipal water networks. The quality of calculation depends principally on 2 variables: on the number of monitoring points which are installed on the water net and on the number of neurons on the hidden layer in case of 3-layer MLP neuronal nets. If the number of monitoring points is relatively small then better results will be get with a larger number of neurons on the hidden layer. But if the number of monitoring points is relatively great than for getting a good quality of results an optimal number of neurons must be find out for the hidden layer and it shall be not especially big. The best neuronal model that has been calculated for 10 monitoring points is MLP 36-24-11 with 24 neurons on the hidden layer and in the second case with 20 monitoring points the model MLP 44-18-21 issued as the best one with only 18 neurons on the hidden layer. There is interesting to see that in both cases of neuronal nets modeling the validation results are not worse than these ones of learning and testing runs. This means that the neuronal models of MLP type are good fitted for solving the problems of detection and localization of water leaks in municipal water networks.

3. Conclusions

The use of the methods of artificial intelligence and especially of neuronal networks can be very helpful while solving the problems of computer aided management of municipal waterworks. The application of neuronal networks to detect and locate the water leaks in water networks is only one of several tasks which are to solve in the waterworks and where the neural nets can be used. The solution of the whole set of management tasks concerning the so-called *soft management* and *hard management* can be effectively computer supported and automatically executed by integrated ICT systems consisting of many close cooperating programs under which the neuronal net algorithms are only ones of key elements [9].

The calculation results presented here have got as yet only an academic worth for they have not been tested under practical conditions. A practical application of the algorithms described requires an advanced computer infrastructure installed on the water network and this concerns especially the installation of an adequate monitoring system. Unfortunately such the situation exists until now in not any waterworks in Poland because of very high costs of measurement devices needed. It seems nevertheless that an application of neural networks for solving some management tasks in waterworks can be very useful and can introduce a new quality while operating the municipal water networks.

AUTHORS

Izabela Rojek*–Kazimierz Wielki University in Bydgoszcz, Institute of Mechanics and Applied Computer Science, Chodkiewicza 30, 85-064 Bydgoszcz, Poland, e-mail: IzaRojek@ukw.edu.pl

Jan Studziński – Systems Research Institute Polish Academy of Sciences, Newelska 6, 01-447 Warszawa, Poland, email: Jan.Studzinski@ibspan.waw.pl
*Corresponding author

Acknowledgements
The paper is a result of the project No NR14-0011-10/2010 financed by the Polish Ministry of Sciences and Higher Education.

REFERENCES

[1] Studziński J., "Decisions making systems for communal water networks and wastewater treatment plants". In: Studzinski J., Hryniewicz O. (eds.), *Modeling Concepts and Decision Support in Environmental Systems, System Research Institute*, Polish Academy of Sciences, Series: System Research 49, Warsaw, 2006.
[2] Rojek I., Studziński J., "Failures location algorithms for water-supply network by use of the neural networks", *Studies and Proceedings of Polish Association for Knowledge Management*, Bydgoszcz, vol. 8, 2011, pp. 146–156 (in Polish).
[3] Wyczółkowski R., Moczulski W., "Concept of intelligent monitoring of local water supply systems". In: *Materials of AI-METH 2005 – Artificial Intelligence Methods.* 16th-18th November, 2005, Gliwice, Poland.
[4] Wyczółkowski R., Wysogląd B., "An optimization of heuristic model of a water supply network". In: *Computer Assisted Mechanics and Engineering Science*, *CAMES,* no. 14, 2007, pp. 767–776.
[5] Studziński J., "*The innovations of XXI age – the modern information techniques as management aids in network enterprises"*. In: Straszak A. (eds.), Innovative Mazovia, Publishing House of SWPW, Płock, 2010 (in Polish).
[6] Farmani R., Ingeduld P.,Savic D., Walters G., Svitak Z., Berka J., "*Real-time modeling of a major water supply system"*. In: International Conference on Computing and Control for the Water Industry, no. 8, Exeter, ROYAUME-UNI, vol. 160, no. 2, 2007, pp. 103–108.
[7] Straubel R., Holznagel B., "*Mehrkriteriale Optimierung für Planung und Steuerung von Trink- und Abwasser-Verbundsystemen"*. Wasser Abwasser, 140, no. 3, 1999, pp. 191-196.
[8] Rojek I., "*Support of decision making processes and control in systems with different scale of complexity using artificial intelligence methods*". Publishing House of Kazimierz Wielki University, Bydgoszcz, 2010 (*in Polish*).
[9] Studziński J., "*IT System for Computer Aided Management of Communal Water Networks by Means of GIS, SCADA, Mathematical Models and Optimization Algorithms"*. In: *Proceedings of the First International Conference on Information and Communication Technologies for Sustainability ICT4S*, L.M. Hilty, B. Aebischer, G. Andersson, W. Lohmann (eds.) ETH Zurich, 14th–16th February, 2013, pp. 123–127.