Automated calibration of the simulation model of irrigation projects by harmony search optimization

Milan ČISTÝ

Slovak University of Technology, Faculty of Civil Engineering, Department of Land and Water Resources Management, Radlinského 11, 813 68 Bratislava, Slovak Republic; e-mail: milan.cisty@stuba.sk

Abstract: The paper deals with calibration of the simulation models of hydraulic part of an irrigation project. Calibrated simulation model can be used in design, reconstruction, enlargement or maintenance of the pressurized irrigation systems. Computer model of the water distribution system is a valuable tool which can assist engineers and planners in analyzing the hydraulic performance of water delivery systems. Calibration of the water distribution model consists in comparison of pressures and flows predicted with observed pressures and flows for known operating conditions (i.e., pump operation, tank levels, pressure-reducing valve settings), and adjustment of the input data for the model to improve agreement between observed and predicted values. In practice, given a set or sets of measured state variables, engineers apply trial and error techniques with their judgment to vary the parameters and accomplish this task. Trial and error techniques are tedious do not guarantee reasonable results. The paper introduces the methodology of determination of calibrated parameters automatically. Described methodology of calibration is based on optimizing procedures using the harmony search approach.

Key words: *calibration, hydraulic simulation model, sprinkler irrigation system*

INTRODUCTION

Simulation models are used in designing new irrigation systems, reconstruction or modernization of the existing system or maintenance of different tasks while managing them. Several simulation models have been developed for analyzing hydraulic networks of irrigation and drinking water systems. Among all those models, the three most commonly used for irrigation networks are: EPANET (ROSSMAN, 1994), COPAM (LAMADDALENA and SAGARDOY, 2000), and GESTAR (ALIOD *et al*., 1997). In this paper, EPANET was used because it is a reliable model that has been applied worldwide for various types of water distribution networks.

When simulation model is to be applied, one should be certain that results from the model bear close resemblance to the actual performance of the hydraulic system. However, various factors always make difference between reality and results, including errors and presuppositions of simulation model design period, human and tool errors, false simplifying of a design, error in determining border conditions and so on. So, to be sure of correct model function for different operating conditions, model calibration is necessary.

ORMSBEE and LINGIREDDY (1997) state that, in general, a network model calibration effort should encompass seven basic steps:
1. Identifying the intended use of the model.
2. Determining initial estimates of the model parameters.
3. Collecting calibration data.
4. Evaluating the model results.
5. Performing the macro-level calibration.
6. Performing the sensitivity analysis.
7. Performing the micro-level calibration.

Deviations of the results of model application from field observations may be caused by several factors, including:
− Erroneous model parameters (pipe roughness values and nodal demand distribution).
− Erroneous network data (pipe diameters, lengths, etc.).
− Incorrect network geometry (pipes connected to the wrong nodes).
− Incorrect pressure zones boundary definitions.
− Errors in boundary conditions (incorrect pressure regulating valve settings, tank water levels, pump curves, etc.).
− Errors in historical operating records (i.e., pumps starting and stopping at the wrong times).
− Measurement equipment errors (i.e., pressure gauges not properly calibrated).
− Measurement error (i.e., reading the wrong values from measurement instruments).

If measured state variable values are significantly different from the modelled values, the reason for the difference is probably in the input data. The only way to adequately address such macro level errors is to systematically review the data associated with the model and compare them with the real – field data. This is macro-level calibration.

The calibration process in its micro-level means mainly the determination of pipeline roughness coefficients, after several years of the system operation. It should cover also the specification of any additional data and maximum possible elimination of errors, obstructing the attainment of conformity between the model and reality. There are many parameters that are uncertain and affect values of pressures in junctions or pipes flow rate. Traditional model calibration of a water dis-

tribution model is based on a trial-and-error procedure, by which modeler first estimates the values of model parameters, then runs the model to obtain predicted pressure and flow, and finally compares the simulated values with observed data. If the predicted data do not compare closely with the observed data, the engineer returns to the model, makes some adjustments to the model parameters, and runs it again to produce a new set of simulation results. This may have to be repeated many times to make sure that the model produces a close-enough prediction of the water distribution network in the real world. The traditional calibration technique is, among other things, quite time consuming. In addition, a typical network representation of a water network may include hundreds or thousands of links and nodes which modeler should deal with. The paper introduces the methodology of determination of calibration parameters automatically. Described methodology is based on optimizing procedures using the harmony search methodology.

METHODS

EPANET (ROSSMAN, 1994) simulation model that analyzes hydraulics in water distribution systems was used in this work. Like other mentioned network models, EPANET abstracts an actual distribution system into a network of links connected together at their endpoints called nodes. Links can represent pipes, pumps, or control valves. Nodes can be junctions, reservoirs, or tanks. Junctions are the points where pipes join together and where water either enters or leaves the network. Reservoirs represent fixed head boundary locations, such as treatment works or groundwater aquifers. Tanks are storage facilities where the volume and water level can change over time. Junctions can also contain emitters (or sprinklers) which make the outflow rate dependent on the pressure.

EPANET receives input data of the network being modeled through an input file. The input file describes the properties and connectivity of the components in a pipe network. Based on the information contained in the input file, EPANET will compute flows, pressures and other parameters throughout the network. EPANET can be used for many different kinds of applications in distribution systems analysis.

EPANET exists in two basic forms – as standalone application with graphical user interface and as EPANET Toolkit. The EPANET Programmer's Toolkit is a dynamic link library (DLL) of functions that allows software developers to customize or call EPANET's computational engine according to their own needs. The toolkit is useful for developing specialized applications that require running many network analyses, which is the case of simulation model calibration. EPANET Toolkit and hereinafter described harmony search algorithm principles were used for developing software for calibration purposes of hydraulic model of the irrigation network by means of the Visual Basic programming language.

Harmony search (GEEM *et al*., 2001) algorithm proposed to use in this paper was adopted from musical process of finding "pleasant harmonies" by improvisation. For instance, when several notes from different musical instruments are played simultaneously on a random basis and this process is repeated, there is a possibility to find better harmonies. In harmony search methodology (HS), these better harmonies are saved in a certain size of memory by replacing the worst harmony in the memory until the predefined maximum number of improvisations, generating a new harmony, is reached.

Fundamental five steps of a HS could be summarized as follows:

Step 1: Design variable and algorithm parameters initialization;

Step 2: Harmony memory initialization;

Step 3: Generation of a new harmony;

Step 4: Harmony memory update if needed; and

Step 5: Improvisation stopping criterion check.

Step 1: Design variable and algorithm parameters initialization

The optimization is expressed as follows:

$$\text{Minimize } f(x) \tag{1}$$

$$\text{Subject to } x_i \in X_{i,j} \, ; i = 1, 2, ..., N \, ; j = 1, 2, ..., K \tag{2}$$

where

$f(x)$ – an objective function;

x – the vector of calibrated variables (mainly roughness coefficients of pipes),

X_i – the set of the possible values of each variable which is bounded by the pre-defined range;

N – the total number of searching variables;

K – the number of possible values for the variables (for instance we design 10 possible roughness coefficients for particular pipe or emitter coefficients for particular irrigator working on field during measurements).

Model of the irrigation network with lengths and connections of the pipes and other necessary data is read by harmony search optimization calibration model in the form of the EPANET INP file (ROSSMAN, 1994).

Four harmony search algorithm parameters that need to be initialized are harmony memory size (HMS), harmony memory considering rate (HMCR), pitch adjusting rate (PAR), and maximum number of improvisations (NI).

Step 2: Harmony memory initialization

The harmony memory is a memory location (matrix) where solution vectors (sets of roughness coefficients or other calibrated parameters) and corresponding

objective function values are stored. The initial HM memory consists of HMS different randomly generated solution vectors. Each such solution vector contains randomly generated pipe roughness values or other calibrated parameters of EPA-NET model (taken from pre-defined range of the possible values). All the harmonies found are stored in the harmony memory which has a form of (HMS) × (N+1) matrix. Columns one through N store design variable values, and the last column contains the objective function values.

In the case of the simulation model calibration, various objective functions can be used. In this work the following equation was chosen:

In the case of the simulation model calibration various objective functions can be used. In this work was following function chosen for searching of minimum difference between observed and calculated values:

$$ min \left(\frac{\sum_{n=1}^{NP}(1-\frac{Pcalc_n}{Pobs_n})^2}{NP} + k \frac{\sum_{n=1}^{NQ}(1-\frac{Qcalc_n}{Qobs_n})^2}{NQ} \right) \tag{3} $$

$Pobs_n$ – pressure measured within the system, MPa;
$Pcalc_n$ – pressure calculated with EPANET, MPa;
$Qobs_n$ – flow measured behind the pump station, $l \cdot s^{-1}$;
$Qcalc_n$ – flow calculated by EPANET behind the pump station, $l \cdot s^{-1}$;
k – weight coefficient stresses the importance of the requirement to comply with measured flows behind the pump station;
N_p, N_q – number of junction nodes with observed pressures and flows.

Step 3: Generation of a new harmony

In this step evolution of new solutions is accomplished. Improvisation or generation of a new harmony (generation of new – better combination of roughness coefficients or other calibrated parameters) is performed based on three rules: 1. memory consideration, 2. pitch adjustment, and 3. random selection. This is the main part of algorithm – similar as crossing, mutation or selection in the case of genetic algorithms. These general harmony search algorithm principles can be found in GEEM (2006).

Step 4: Harmony memory update

In this step EPANET model is running with data taken from the new harmony where they are coded. By comparing results of computation with observed values (Eq. 3) one gets value of the objective function. If the new objective function value is lesser than the worst objective function value in the harmony memory, the worst harmony vector is replaced by the new harmony vector. Lesser objective function

value means, that in the case of new harmony the differences between modeled and observed pressures or flows are smaller when using parameters coded in new harmony.

Step 5: Stopping Criterion

A conditional statement is applied to judge whether this harmony search loop needs to be repeated or stopped. In the case of calibration problem the harmony search stops if no improvement in comparing observed and modeled values by objective function (Eq. 3) is found in the last five hundred iterations.

RESULTS AND DISCUSSION

Described procedure of irrigation system calibration was applied to the irrigation system Kuty (South-west Slovakia). Its layout is shown in Figure 1. This is one of the relatively old irrigation facilities with large area in Slovakia, with applied sprinkler irrigation and an underground pressurized water network. Layout of the irrigation network is branched and it consists of approximately 25 km of pipes (steel, cast iron and some new PVC pipes). Its construction was completed in the middle of the 1960s, and thus the whole facility is coming close to the end of its service life. For this reason it can serve as a suitable model for testing the proposed methods of calibration. Parameters such as roughness coefficients, pump operation characteristics etc. were changed and their values should therefore be searched for. The irrigated area is 942 ha. The irrigation system consists of irrigation water take off complex located at the irrigation inlet to the irrigation pump station; pump station itself, pressurized network for delivering the irrigation water and of sprinklers. Presented work is primarily aimed at verification of the methodology for evolving reliability of simulation model for this irrigation system. Simulation model could be than used for the rehabilitation design or for finding best operation rules under various conditions (new crops, new irrigators in the system etc.). The process of micro-calibration included in this case changing emitter coefficients of irrigators (see EPANET manual), fine-tuning the roughness of pipes and altering pump operating characteristics. Considering the scale of the input and output data the results of the calculation are described only generally; detailed information could be provided by author of this article.

During some hydraulic situations insufficient pressures were detected within the system, hampering for instance the irrigation of asparagus and potatoes in the area of branches A3, A4 and in the area of an enlargement of the original system (end parts of branches A3, A4 – Fig. 1). Since the described site is very much suitable for growing the said crops, farmers plan to enlarge the acreage of these crops. Gradually one can expect further increase in growing these and other crops, with subsequent enlargement of simultaneously irrigated area. This is caused by the fact
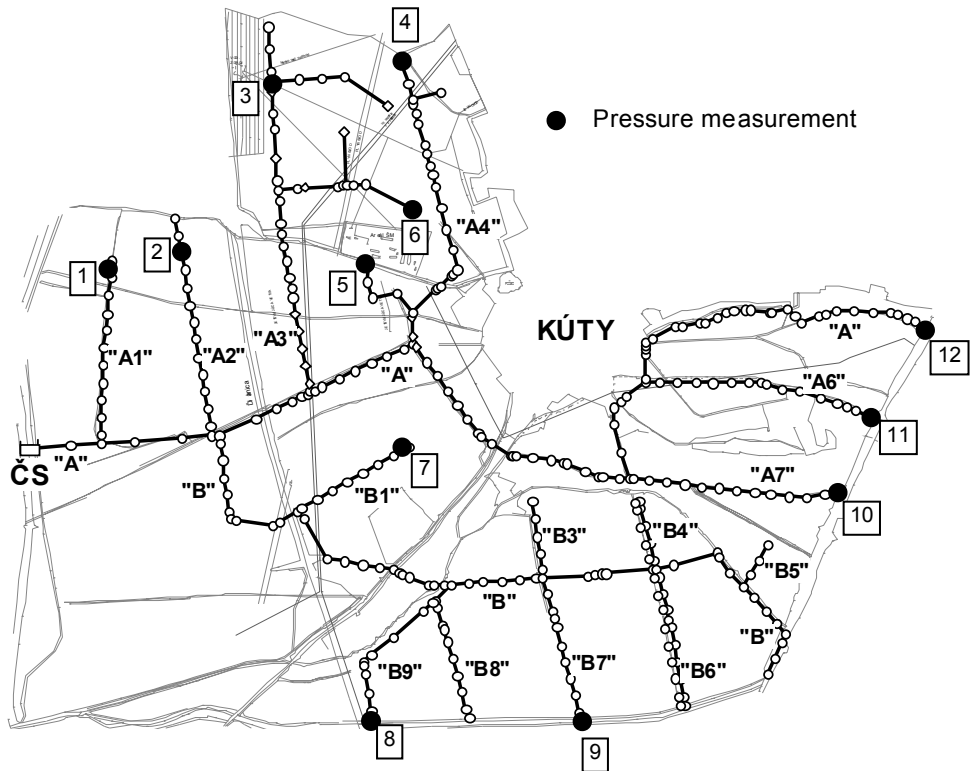
Fig. 1. Layout of an irrigation system in which calibration of simulation model was verified

that modification of the growing crops leads towards a "monoculture" growing pattern. It could be expected that such events will occur more often, because of globalization of the economy, trade and farming, which results in the environment where specialization in a narrower assortment of crops (which are cheaper and better traded) is more beneficial. From irrigators' point of view such a situation is more demanding in terms of the pipeline network capacity, which seems to be insufficient already now. Experience of irrigation users as well as measurements made by author of the article in irrigation system Kuty have shown that during the operation of the irrigation system an insufficient pressure in hydrants occurs quite often.

A good solution to low pressures is for instance the creation of a loop in some parts of the pipeline network, e.g. making the loop of branches A3 and A4 or of other parts of the system. Such a solution is optimal from economic viewpoint as well as in terms of achieving required technical parameters (pressures). It also simplifies work during the operation and seems to be favorable also in the events of failure (in cases of malfunction in the pipe system it provides an alternative way to transport water to hydrants). Such reconstruction cannot be accomplished without composing, calibration and application of a simulation model. An example of

model application in the optimization of a reconstruction design is not the aim of present work (author is focused only on calibration of this tool which is necessary for accomplishing this task) and it is described for instance in (ČISTÝ, 2002).

Hydraulic condition was analyzed using measurements performed both in pump station and in irrigation pipeline network. In order to analyze hydraulic behavior of the system for this purpose, more detailed measurements as well as calibrated simulation model were needed. In the first step, preliminary hydraulic model was developed. There are 316 junctions and 315 pipes in this model. In preliminary model some simplifications were made – for instance irrigators were modeled with a constant demand, not in the pressure dependent regime. Measurements and this tool enable the identification of various failures, operation malfunctions etc., repair of which is inexpensive (e.g. partially closed network valve was detected on branch A3. This was signalized by significantly big difference between measured and computed pressures on it). Elimination of such problems was the first step and at the same time the first profit generated by the calibration effort. If some reparations are not possible, they should be also modeled as any other hydraulics phenomenon in the system. This was completed in so-called macro calibration part of the process which was described before.

In addition to that, another problem often occurs during the operation of irrigation system. It was the incorrect working scheme of irrigators (e.g. the high concentration of sprinklers in some parts of irrigation system), which also results in insufficient pressures. Since such events took place within the described system, an operator should be instructed and given recommendations to reorganize the irrigation system usage. For evolving such rules more detailed calibration (micro calibration) procedure was applied described in chapter about methodology.

Calibration works in irrigation system Kuty included the measurement of pressures in the outlet from a pump station, flow right behind the pump station and measurement of pressures in typical points of an irrigation system (Fig. 1). Placement of irrigators, its type and other parameters (sprinkler nozzle diameter) were also checked. Based on specifications declared by the producer it was important to define the sprinkler characteristic curve. Because this entry depended on the technical condition of the equipment, parameters of sprinkler pressure-flow characteristic curve were also calculated in the context of the calibration computation (as emitter coefficients in EPANET).

During the very first calculation run, pipeline roughness coefficients were taken separately for each section and this enabled identification of different anomalies within the distribution system, caused by errors in data set. In subsequent program runs, groups of pipeline sections were created with assumed identical roughness coefficients using the criteria of identical pipeline diameter and material.

Calculation results in the system calibrated for the testing operation condition (other set of observed pressures and flows than used in calibration process) re-

vealed disparities in pressures up to 4.8% and in flows up to 4.9% (Fig. 2). Obtained results represent a good conformity. Larger disparity between observed and simulated flows was caused e.g. by oscillation of this entry due to the instability of the flow. As it was mentioned above, the accuracy of calibration depends not only on the roughness coefficients set-up but also on other parameters, which can generate various errors. More accurate results can be achieved using additional specifications, such as section length determined from maps in the scale 1:2000 (no numeric data were available). More accurate section length could be determined either from longitudinal profiles or by doing direct measurements in the field. The outcome confirms the suitability of the method even in cases with insufficient data available, which is often the case in practice.
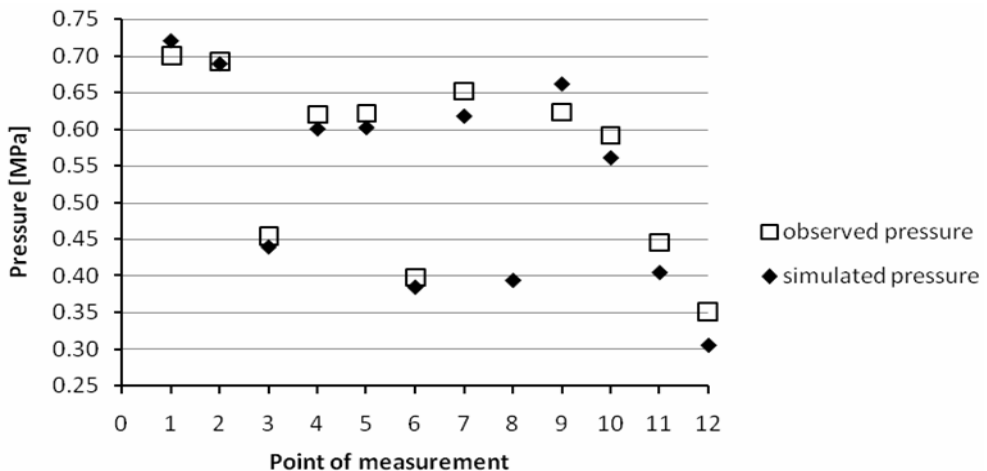

Fig. 2. Calculation results in the system calibrated for the testing operation condition

SUMMARY AND CONCLUSIONS

The paper deals with the use of simulation models in design and maintenance of pressurized irrigation systems. In order to use simulation models e.g. for the design of the reconstruction of these systems one has to perform their calibration. Traditionally, calibration of hydraulic network models has been a manual task, the modeler making changes to the parameter values on a trial-and-error basis to achieve an effect which he considers will result in an overall convergence between field and model data. The paper introduces the methodology of determination of calibration parameters automatically. Described methodology is based on optimizing procedures using the harmony search methodology. Model calibration is really an optimization problem, although most modelers would perhaps not immediately

recognize it as such. The objective is to produce a mathematical model whose predictions agree closely with the field observations. However, there are vast numbers of potential combinations of parameter values, which could be investigated before reaching a good calibration. There is, therefore, scope for achieving a calibration much more efficiently and consistently using an optimization technique (e.g. HS) rather than the traditional trial-and-error adjustment adopted by most network modelers.

REFERENCES

1. ALIOD R., EIZAGUERRI A., ESTRADA C., PERNA E., 1997. Dimensionado y análisis hidráulico de redes de distribución a presión en riego a la demanda: Aplicación del programa GESTAR. Riegos y Drenajes 21, 92: 22–38.
2. ČISTÝ M., SAVIČ D.A., WALTERS G.A., 1999. Rehabilitation of pressurised pipe networks using genetic algorithms. In: Water for agriculture in the next millennium. Eds W.A. Price *et al*. 17th Congr. Irrig. Drainage, Granada. ICID: 13–27.
3. ČISTÝ M., 2002. Rehabilitation of irrigation pressurised pipe systems using optimisation techniques. J. Land Water Dev. 6: 117–128.
4. GEEM Z.W., KIM J.H., LOGANATHAN G.V., 2001. A new heuristic optimization algorithm. Harmony Search Simulation 76(2): 60–68.
5. GEEM Z.W., 2006. Optimal cost design of water distribution networks using harmony search. Engrg Optimiz. 38, 3: 259–280.
6. LAMADDALENA N., SAGARDOY J.A., 2000. Performance analysis of on-demand pressurized irrigation systems. Irrig. Drainage, 59.
7. ORMSBEE L.E., LINGIREDDY S., 1997. Calibrating hydraulic network models. J. AWWA 89(2): 42––50.
8. ROSSMAN L.A., 1994. EPANET users manual. Cincinnati OH, US EPA.
9. PIZZO H.S., LUVIZOTTO Jr. E., 2001. Calibração de modelos de distribuição de água através do algoritmo de Nelder-Mead. Proc. 21st Congr. Brasileiro Engenharia Sanitária Ambiental. September 16––21, João Pessoa, Brazil, CD-ROM.
10. WALSKI T.M., 1983. Technique for calibrating network models. J. Water Res. Planning Manag. 109(4): 360–372.

STRESZCZENIE

Automatyczna kalibracja symulacyjnego modelu projektów nawodnieniowych metodą optymalizacji poszukiwań harmonii

Słowa kluczowe: *hydrauliczny model symulacyjny, kalibracja, system deszczowania*

W artykule opisano użycie modeli symulacyjnych w projektowaniu i utrzymaniu ciśnieniowych systemów nawadniających. Aby zastosować modele symulacyjne np. do projektowania przebudowy takich systemów, należy je skalibrować. Tradycyjnie kalibracja modelu sieci hydraulicznej była uciążliwym zadaniem. Autor modelu zmieniał wartości parametrów metodą prób i błędów, aby osiągnąć efekt, który według niego doprowadzi do zbieżności obliczonych i pomierzonych danych. W artykule zaproponowano metodologię automatycznego ustalania parametrów kalibracji. Opisana metodologia opiera się na procedurach optymalizacyjnych, stosujących metodę poszukiwania harmonii. Celem jest zbudowanie matematycznego modelu, którego przewidywania będą ściśle zgodne z obserwacjami terenowymi. W związku z tym otwiera się pole do kalibracji, którą wydajniej i w sposób bardziej spójny można przeprowadzić techniką optymalizacji (np. HS) niż tradycyjnym sposobem prób i błędów.

Wyniki obliczeń w systemie kalibrowanym dla warunków testowych ujawniły rozbieżności ciśnienia, sięgające 4,8% i przepływu – 4,9%. Otrzymane wyniki cechuje więc dobra zgodność. Większa rozbieżność pomiędzy obserwowanymi i obliczonymi przepływami spowodowana była np. przez oscylacje tego parametru w związku z niestabilnością przepływu. Jak już wspomniano, dokładność kalibracji zależy nie tylko od zestawu współczynników szorstkości, ale także od innych parametrów, które mogą generować rozmaite błędy. Dokładniejsze wyniki można uzyskać, stosując dodatkowe specyfikacje, takie jak długość odcinka określona na podstawie mapy w skali 1:2000 (dane numeryczne były niedostępne). Dokładniejszą długość odcinka można uzyskać albo z profilu wzdłużnego, albo mierząc długość bezpośrednio w terenie. Końcowy wynik potwierdza przydatność metody nawet w przypadku niewystarczającej ilości dostępnych danych, co często zdarza się w praktyce.