DIAGNOSTIC MEASUREMENTS IN POORLY DOCUMENTED WATER SUPPLY SYSTEMS

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ABSTRACT

The authors' long experience in diagnostic measurements conducted on the number of Water Supply Systems is summarized in this paper. The need for this kind of measurement is emphasized, as is the need for thorough and compulsory data accuracy assessment for each work step. Using a number of examples from practice, different kinds of diagnostic measurements are presented: for calibration of numerical simulation model, property determination for certain system details like pumps, valves etc, assessment of pipe-reservoir system dynamic behaviour, system analysis during pipe line failures and measurements for leakage detection. Besides the measurement management and suggested set of equipment that a Water Supply Company should maintain, the paper will analyze the economic issues regarding the expensive and demanding diagnostic measurements.

Key words: Diagnostic measurements, Water Supply Systems, WSS, Data accuracy

1. INTRODUCTION

Water Supply Systems (WSS), as well as many other technical systems, are going through an accelerated technical and technological development phase in developing countries. From the obsolete organizations, whose only task was to deliver a certain quantity of water, regardless to the economical or quality issues, they are transforming to high-tech Companies, where one of the most important criteria is a realized profit (Obradovic, 1999). In such an environment, real information about produced and delivered water, as well as accurate data regarding water quality issues are becoming significant, mostly because the system control is based on that information, as well as the evaluation of economic sustainability (Alegre, 2000). The main problem of almost all WSSs on Ex Yugoslavia area is a total lack of measurement culture. Currently, there is no WSS with reliable data neither about water balance, nor with data about the actual water supply network state (position, diameter, pipe type, etc.) and hydraulic quantities (pressure, flow, estimated losses). The introduction of high-tech monitoring systems in such cases can be a very expensive adventure, which usually neither has support from municipal authorities, nor from the WS Company.

In the situation where reliable information about a WSS is unavailable, the diagnostic measurements are the only solution to assess the hydraulic parameters of the system. In last 10 years, the authors have conducted a number of such measurements on WSSs as well as on other complex systems (TPP Obrenovac A and B, HE Djerdap – a ship lock, etc.) Based on the accumulated experience, the authors emphasize problems in diagnostic measurements, types of measurements as well as their organizational issues in this paper. Nevertheless, the main objective of this paper is to stress the need of reestablishment of a measurement culture and the need to work with accurate data, as the basic element of complex WSS sustainability improvement.

2. DIAGNOSTIC = MEASUREMENTS+ANALYSIS

Through the "life" of a WSS, a number of measurements are conducted (Maksimovic, 1993). The system diagnosis should be performed in regular working conditions, to obtain the valuable additional data about the behaviour of individual system elements, and it has to be combined with continuous measurements used for the system process management. The hydraulic system analyses are based on the diagnostic measurements, and they are used either for solving the certain actual problem (water hammer at a pump switch-off, for example), or for simulations of the WSS behaviour in planned future system extension phases.

Unfortunately, in most WSSs the existing situation is such that diagnostic measurements are the only measurements. They are performed only when it is really necessary: in the case of significant water shortage (Prodanovic and Maksimovic, 1995), when a pipe breaks (Prodanovic, Ivetic and Pavlovic, 1994), big international consultancies are engaged in design projects, or when a masterplan is being developed. As a rule, when the problem is solved, there is no further interest or commitment to the system monitoring.

The diagnostic of a WSS must be accomplished with precisely defined requirements and with precisely planned objectives, which are to be achieved. Depending on the final objective, a suitable choice of measuring methods and equipment is done, as well as the data processing tools. It is expected often (but completely unrealistic) that based on the examination of one system detail (for example, the pump characteristic in the wellhead), that one may obtain the answer to the key question: where are the main water losses and how big they are?

2.1. *Measurements*

There are a number of parameters at a WSS that can be measured: pressures, flows, velocities, water levels in reservoirs and wells/piezometers, a pump power, water quality parameters etc (Maksimovic, 1993). It has to be taken into account that all those quantities are variable in time (Simic, 1994).

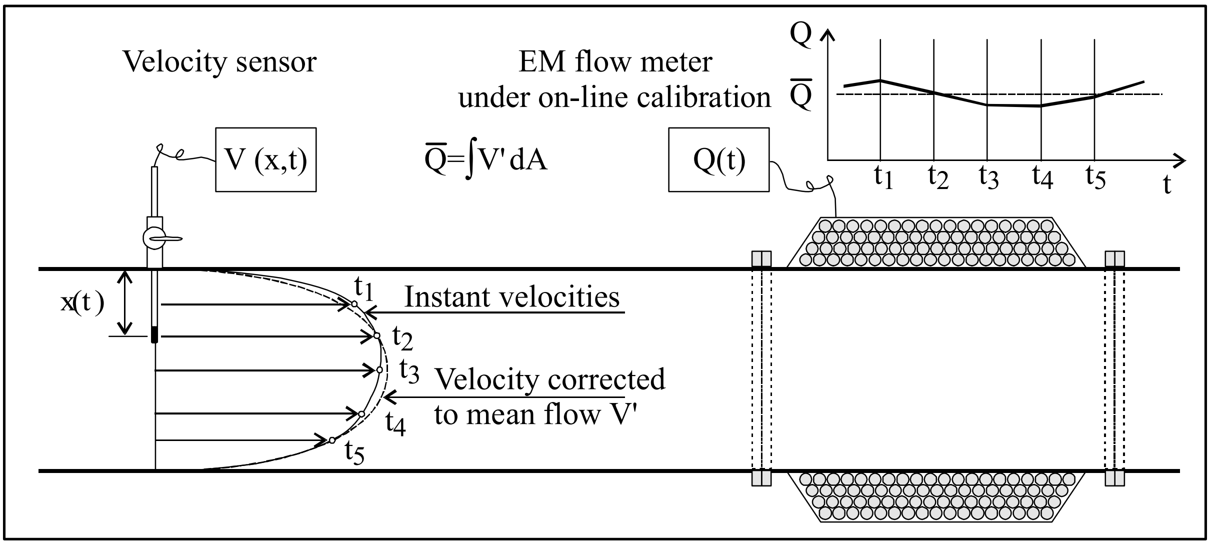

Figure 1. Recalibration of the fixed flow meter by velocity profiling in unsteady conditions

For example, Figure 1 presents the procedure for checking the in-line flow meter by measurement of the velocity profile in the pipe. As the procedure lasts often more than an hour, it is not reasonable to assume that the flow in the pipe is constant during that time. Because of that, another flow/velocity sensor (or the flow gauge under the test, as shown in Figure 1) has to be used in order to record the flow changes, those data are then used in off-line velocity profile processing to correct the flow field to mean flow. The rate of a particular quantity change can also differ by an order of magnitude (water level in a pumping reservoir during a pump start period, and in a stationary work regime) throughout the measurement, so the data acquisition algorithm has to match it.

The choice of measurement equipment mostly depends on the explored problem. If there is a need for long time recording of certain quantities (for several days or weeks), it is necessary to use modern, standalone computer based devices (loggers) that are able to collect data, pre-process measured values and store them unattendedly in real time. For measurements that last for up to one day, “manual” data storing can be done, but it is usually less reliable (for example, if there is a need to observed pressure gauge on every hour, most of us will write the time as the whole hour, eg. 14:00, 15:00, … although the readings were done at 14:15, 15:03; that causes significant problems during the result analysis phase).

Simple, handy methods can often be used in diagnostic measurements. For example, the authors had the opportunity to monitor a WSS in a small municipality with a constant water shortage. Measurements of a flow rate at the wellhead were not a part of planned activities. But when some unexpected measurement results were obtained, it was sufficient to do a simple measurement of an overflow depth at the water intake structure, as well as a measurement of a water flow that overflows to a small creek (by measuring a superficial velocity with a small piece of a paper and a cross section) to determine that the water loss rates in the main pipe were over 50 %.

A choice of a measurement method, as well as measurement equipment, is an easier part of the job. The authors of the paper, in most of the conducted diagnostic measurements, had the biggest organizational problems with the people from the local WS Companies. Although everybody is generally aware of the need for measurement, when the sensor connection has to be installed, the leaking valve repaired or malfunctioning flow meter replaced, the enthusiasm rapidly vanishes because of the worker's lack of motivation for additional engagement.

2.2. *The Analysis*

Diagnostic measurement data should be first translated to the standard system of measurement units through a pre-processing phase (if a pressure is measured by sensors, a measured quantity is electricity or voltage – it should be translated first to pressure and then to piezometric level). After that, the measured data processing can be done, mostly off-line, depending on the explored problem. It could be a relatively simple analysis, as was assessment of pump characteristics in the WSS in Laktasi (Prodanovic, Pavlovic and Jacimovic, 2001), based on water levels measured in the upstream reservoir (indirectly determinate flow rate), water levels in the well and pressures downstream the pump, but also a complex network analysis based on the appropriate mathematical model.

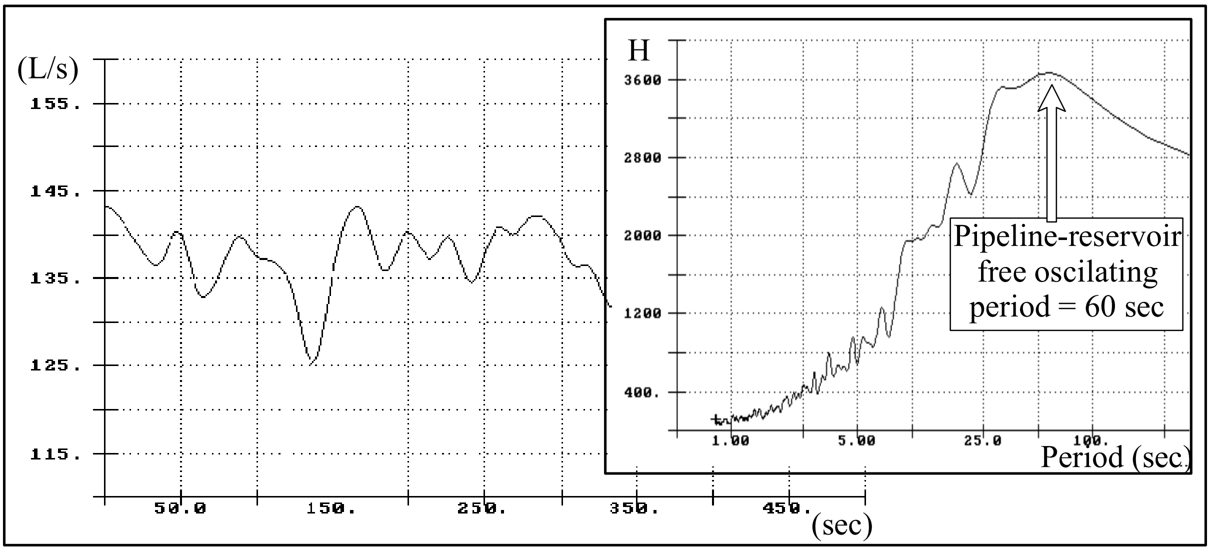

Figure 2. Flow fluctuations on water distribution system Tabanovic – Sabac

Special attention in measured data analysis should be paid to dynamic system behaviour. As an example, the flow instability in the WSS of Sabac is presented in Figure 2. The flow fluctuations are induced by the hydraulic incompatibility of the system elements: pumps, the surge trunk and flow regulating device at the reservoir inlet. Based on the time and frequency domain analysis, the frequency of an oscillation were determined, while possibilities of better adjustment of the surge trunk were checked on the simulation model.

The results of analysis are often used as an input parameter for more complex models of a whole WSS. In order to use correctly those values, it is necessary to save all pre-processed quantities, as well as method of their analysis. However, the authors of this paper were often in a position to see the results of some diagnostic measurement projects, where only final results were presented, without any insight in raw data as well as in numerical method used.

2.3. *Accuracy assessment*

The commonly accepted worldwide trend is the introduction of quality control system, on every level and in every field. In the field of diagnostics the rule is applied on each step: in the phase of measurement the equipment has to be regularly calibrated, and in the phase of analysis, only reliable data can be used. In order to minimize the uncertainty, the measurements should be planned in that way to have some redundant data. For example, it is enough to measure the inflow of the water into a reservoir and a water level to know an outflow from the reservoir. But, if the outflow is also measured at the same time, there is a way of checking the preliminary record of a reservoir surface area – and that value is very important for the mathematical model of a WSS.

Error analysis gives the scope of the measured quantity. If one wants to calculate the pipe roughness based on the pressure measurements at two distant locations, assuming that all measured quantities have certain errors (the pressure measurement using manometers, determination of manometer geodetic heights, flow measurements, estimation of interior pipe diameter - that is often significant), the roughness values range can be $\lambda = 0.005 \sim 0.1$. And if there is also a problem with unsteadiness of water flow, as well as a possibility of existence of some unidentified local disturbance, the conclusion is that such calculation of friction coefficient is useless.

2.4. *Application of obtained results*

An important part of the diagnostic package (measurements – analysis – error analysis) is also the application of obtained results. It often happens that suggestions regarding some problems in system are made, but there is no action from the WS Company to apply it. For example, during the pump characteristics measurement, it was notified that the installed pump is more than twice stronger than it should be. Instalment of the frequency power regulator was proposed, with estimation that the investment will repay within 6 months only through a lowered electricity bill. Nevertheless, that calculation didn't take into consideration one important fact: the WS Company doesn’t pay the electricity bills at all!

3. TYPES OF A SYSTEM DIAGNOSIS

3.1. *Standard flow and pressure measurements*

Mathematical models are used for better in depth understanding of WSS functioning (Gotoh, Jacobs, Hosoda and Gerstberg, 1993). Creation of the model implies digitalization of all WSS elements data (pipes, reservoirs, valves, pumps, consumers etc.), their characteristics and links between them. Each model needs a calibration, fine adjustment of certain system element parameters (consumption disposition, water losses, etc.) based on diagnostic measurements. The number of measurement locations and duration of measurement are in direct relation with available resources (time and money). The rule is: on WSS where there are no previous measurements and enough reliable information about expected values of measured quantities, two series of continuous measurements are needed. The first one will give the general information about the system. Rough calibration of the numerical model should be performed based on that information. Using the model and site visits, the possible critical parts of WSS are detected. In the second measurement campaign, some new measurement locations should be selected, focusing on already noticed problems. The Figure 3 presents an example of flow measurement, where there was no previous information about the measured quantities. Velocities were measured with the electromagnetic probe, generally able to measure velocities up to 10 m/s. In signal conditioning procedure, the upper limit was set to 3 m/s to maintain the best possible resolution. However, it came out later that two pressure zones were directly connected (!) through that pipe, so velocities were significantly above expected.

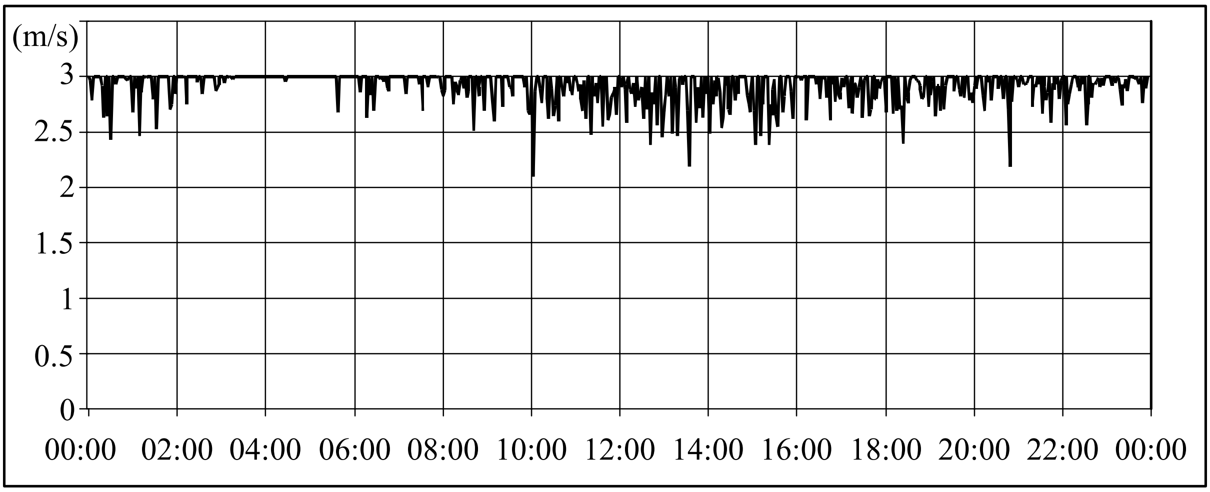

Figure 3. Raw (unprocessed) velocity data in pipe

Based on continuous measurements (most often) of flow rates and pressure, the existence of some significant local problems can be observed during a model calibration (significant grade of pressure along a pipe as a result of certain half-opened valve, significant leakages along pipelines) or significant deviation of characteristics from expected (a pipe diameter is not as designed, a significant degradation of a pump characteristics etc.). With such notices, planning and performing diagnosis of those details is necessary.

3.2. *System details diagnosis*

There is a long list of possible diagnostic measurements regarding assessment of particular detail characteristics of WSS. Some of them are: pump characteristic assessment, calibration of installed flow meters in nonstandard conditions, filter fields performance analysis in regular and overload conditions, pressure fluctuation after a pump failure (water hammer), the location determination of half-opened valve that is somewhere buried, based on a disturbance wave propagation, etc.

As an example, Figures 4 and 5 present results of a pump characteristic recording. Within most WSSs, where the authors took measurements, a flow rate and a water balance in the system was estimated based on number of hours that pumps were running, with assumption that characteristics are the same as in the pump catalogue. Only true pump characteristic measurement can show how big an error is made with that kind of water balance calculation. Figure 4. presents the deterioration of pump characteristics during the time (or pump aging) for a sludge pump (Prodanovic, Ivetic and Pavlovic, 1996), and Figure 5 presents characteristics of pump running in a cavitations regime, producing significantly lowered flow rates than expected (Prodanovic, Pavlovic and Jacimovic, 2001).

A choice of measurement methods and measurement equipment is directly related to a problem that is to be explored, as well as to conditions at the site. It could be taken as a rule that it is necessary to obtain accuracy of measurements in the order of the scale higher than for continuous measurements, so that factor has to be considered. For example, during a calibration process of existing flow meters (which are in accuracy category of 0.5 or 1%), it is not possible to use ultrasonic flow meter equipment, which is very handy, but with accuracy of 5 % or even worse.

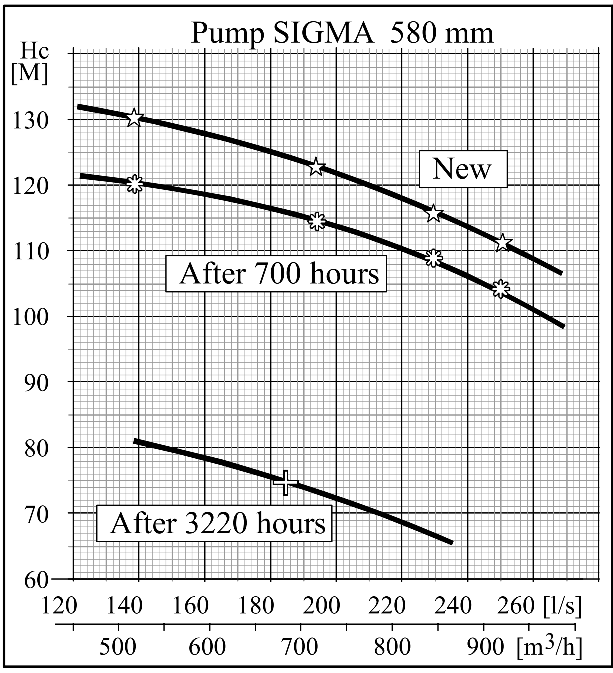

Figure 4. Pump aging diagram

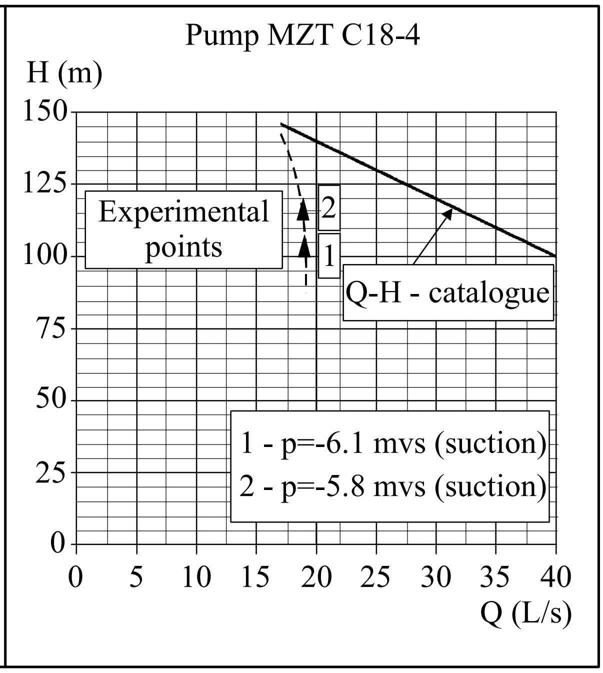

Figure 5. Buster pump working in cavitations regime

3.3 *Diagnosis of leakage losses*

Estimation of real water losses on a WSS is very difficult task. Since almost no WSS in Ex-Yu region has reliable measurements regarding water production and water distribution, information about water leakage is more political category and the result of analytical methods. Water Supply companies are mostly occupied with local urgent repair works in the case of a pipe break or if water appears at the surface in significant quantity. Some WS Companies are supplied with equipment for detection of water losses that is very helpful.

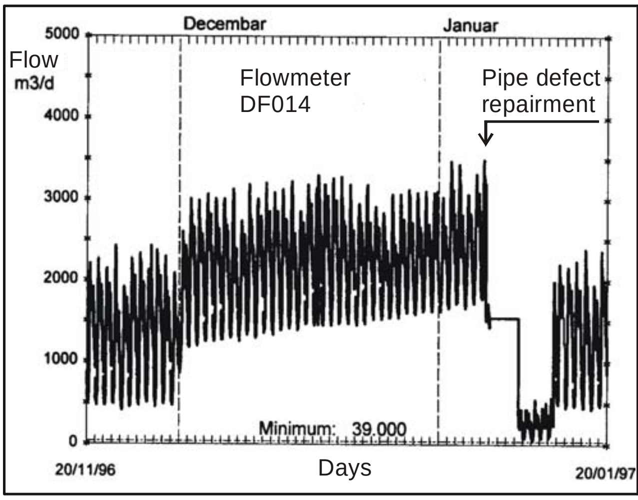

Figure 6. Two month flow rate record from section flowmeter

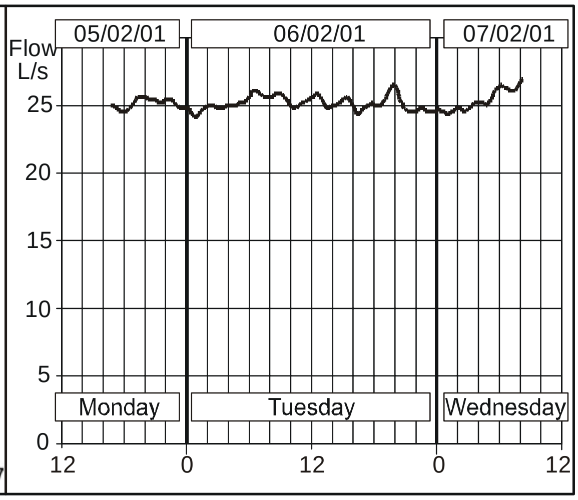

Figure 7. Flow without daily irregularities shows that losses are substantial

In order to keep the water losses as minimal as possible, continuous measurements of flow rate on all mains are necessary. The Figure 6 presents an example, taken from the literature (Obradovic, 1999), of continuous flow rate recorded on a sector flowmeter. It can be seen that in first 10 days daily diagram of flow non-uniformity is quite normal (ratio between daily maximum and minimum is aprox. 5:1), but afterwards in December, night flow rate has suddenly started to rise with decrease of daily maximum to minimum ratio (Thornton, 2002). Such continuous record clearly indicates the gradual spreading of pipe rupture. After repair work, in the middle of January, daily flow diagram is restored to a primary shape. Based on this kind of recording, it is possible to estimate the real quantity of water losses, to estimate required investments for rehabilitation, and also to make a cost benefit analysis when to start with pipe rehabilitation.

Figure 7 presents a somewhat different result – a flow rate during two days period is recorded in 300 mm pipe, at the entrance to a small coastal settlement, during a winter period and without tourists and commercial working. What were water losses on that pipe when there was almost perfect daily uniformity of flow rate? 90 % or 95 %? How to estimate what was the normal flow rate through a pipe, if this was the only, ever made measurement in the system? And can we call it "the water losses" when some of the valves are purposely left opened and water runs into the sea, just to reduce the piezometer level so that the next village doesn't get the water? Naturally, the illustrated example is an extreme case (but one which does sometimes occur). More often the result of diagnostic measurement is the daily flow rate diagram with maximum/minimum rate of 2:1 up to 3:1 that indicates the existence of water losses at downstream part of a water supply network, but doesn't allows their better estimation.

Currently, it seems to be a common view that it is enough to make a few diagnostics measurements in order to reduce water losses. The truth is somewhat different: leakage reduction is acomplex process, which requires permanent WS Company engagement and effort on monitoring, as well as the persistence in maintenance of all potential locations for water losses (WHO, 2001).

3.4. *Diagnosis in accidental regime*

Diagnosis of accidental regimes in WSS, in general, obtains a lot of significant information about real system conditions. At the systems with continuous monitoring, diagnosis is reduced to analysis of collected information before and after accident, where measurement data should be linked with data about system manipulation (which valves and when they are closed/opened, pump work regimes, etc.)

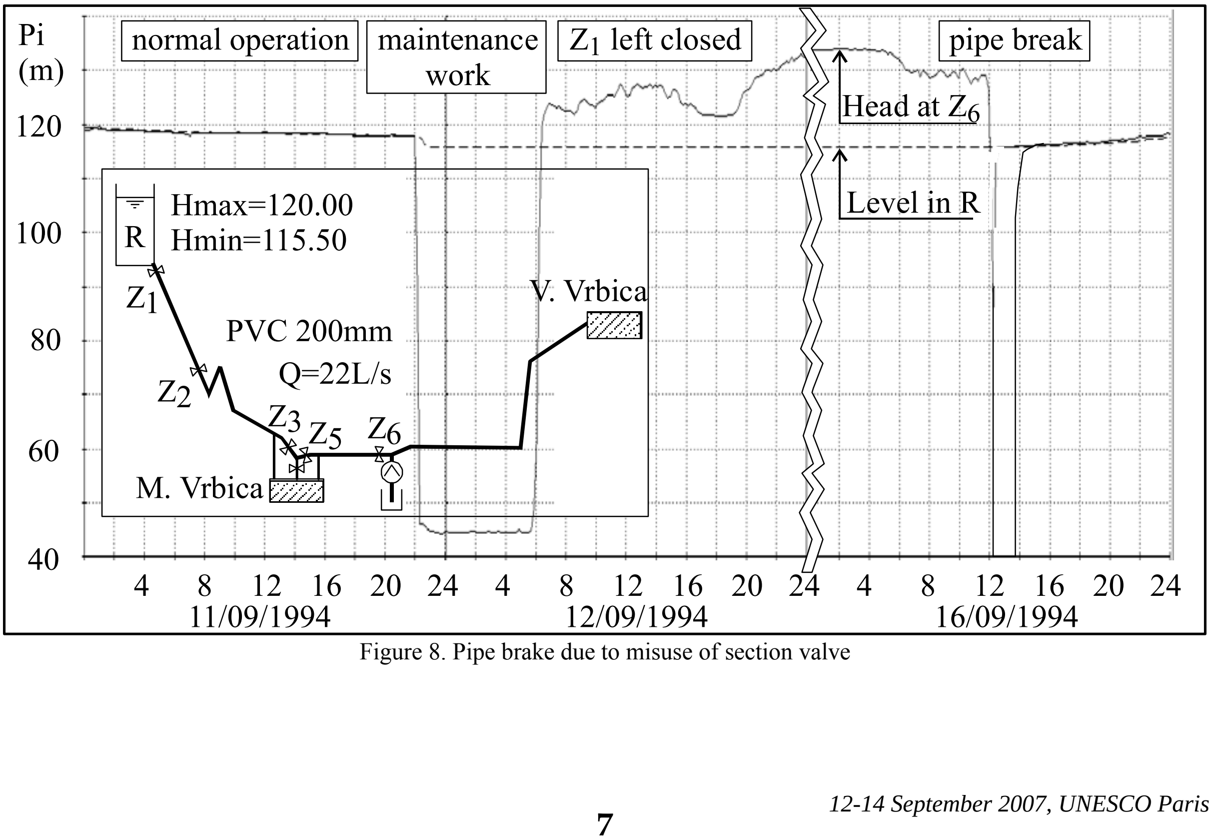

Figure 8. Pipe brake due to misuse of section valve

On the systems without continuous measurements, this kind of diagnosis is possible only if during the measurement campaign either accident is simulated or it randomly happens. The Figure 8 presents a recorded pipe break (Prodanovic, Ivetic and Pavlovic, 1994) in Mala Vrbica, nearby Kladovo (Serbia). On the pipeline segment that has been positioned along the valley, failures occurred rather often. A 10 day measurement campaign, as well as a series of induced water hammer measurements, showed that all system parameters were within designed limits. After that, a “simulation” of equipment removal was done, but with one data logger left to record the pressure at a well pump. A few days later, the pipe was broken (presented as a rapidly pressure drop on the Figure 8). The recorded diagram on the figure 10 presents a pressure increase, starting from 12/09 till the pipe failure on 16/09. After contacting local people at the site, the reason was found: some local plumber during some home repairs, closed the valves on pipeline (Z1 and Z2 on the figure). When a repair was over, he forgot to open valve Z2, thus leaving the pump without the reservoir, which limits the pump pressures.

4. DIAGNOSIS ORGANIZATION

Diagnostic measurements should be the integral part of every WSS activities. A special team should be established with following jobs:

- maintenance of installed measurement equipment
- regular equipment calibration;
- keeping of logbook of all measurement works and readings (manual or automatic);
- primary results processing;
- reliability control (if any of devices shows significantly increased / decreased values);
- permanently storing the results with comments;
- making regular reports in form of weekly/monthly/seasonally diagrams;
- making reports about exceptional events, etc.

Diagnosis equipment should be undertaken using modern electronic measurement equipment with a possibility for several days or weeks of continuous recording of pressure and flow rate, as well as water levels in reservoirs. However, ordinary manometers and flowmeters could be useful too, if regularly calibrated and manually recorded.

A situation in a majority of companies in this region is such that there is no organized diagnosis approach. On demand, another company is involved for measuring campaign and only if it is necessary. Fundamental system parameters are usually unknown, even location of pipes, pipe diameters and valve locations. Every requirement for a pipe excavation and a manhole construction on a straight pipeline section, in order to establish a reliable flow rate measurement location, is considered as a wasteful luxury (*it would be perfect if measurements could be accomplished in the office*).

In such conditions, it is difficult to obtain reliable diagnostic measurements. When presented with an unknown system, it is necessary first to identify a distribution network. Details of node connections (not important for a regular system performance as long as there is enough water) are essential in measurement and data analysis. If a numerical model exists, it is necessary to check a planned measurement strategy (opening/closing of some reservoir chambers, system performance in various pumping regimes, exclusion of particularly network sections etc.) in order to maximize the measured data reliability with minimal effects on a regular consumption. Using simulation model, measurement locations also should be selected, in order to obtain more system information from fewer locations.

In situation where there are no previous measurements, nor a numerical model, as the rule of thumb, two campaigns of diagnostic measurements should be planned. The first measurement campaign will obtain the fundamental system information as the base for system problem identification. Then, a selection of a new measurement location and sampling criteria can be done, in order to better enlighten the noticed system problems. The second campaign can be focused on specific system details, same as on continuous system performance monitoring during longer period of time (24 hours at least, but 7 days is recommendable).

5. IS THE DIAGNOSIS EXPENSIVE?

As the answer to that question, there are two novel examples from the authors practice:

- Diagnostic measurements were performed on a WSS in a small seaside town (some of the results were given in Figures 3 and 7). The system had neither measurement equipment nor any previous measurement results. Measurements were accomplished in order to obtain data for a numerical simulation model calibration, and no detailed diagnostic measurements of water losses were contracted. However, based on obtained data, a rough estimation showed that water losses were about 400 L/s, and with water price of 0.25 €/m^3 made 8,500 € of losses per day (the price of an compact flow rate and pressure logger is about 5,000-7,000 €, and only for pressure 1,000-2,000 €).
- WSS Laktasi (RS), extensive diagnostic measurements were done. Firstly, the two well pumps and one buster pump for Slatina settlement were analyzed, and then, 24 hours continuous flow rate and pressure measurements in the system was performed using the built in flowmeters, pressure loggers and manometers. Analysis of well pumps characteristics showed a significant difference between the pumps at the first and the second well: the first pump gives 27 L/s and the second one 40 L/s, where the first pump has almost 10m higher head than the second one (the first pump was from donation program in May 2001.) Obvious incompability between pumps results in reduction of performance of the first pump and an insufficient well utilization. If there were diagnostic measurements on the old pump before it was changed in May 2001, along with analysis of dynamic water levels in both wells, as well as coupled pump performance, the pump with better system conformation would be chosen, and higher flow rate could be distributed in the network of the Laktasi settlement.

These two examples undoubtly show that diagnostic measurements are a good investment for a longer period. However, a heritable problem in almost all WSS in former Yugoslavia is the lack of money and a habit that any kind of saving, especially if it requires some direct investments, doesn't pay off (one must be rich enough to be able to save).

6. CONCLUSION

The paper objective was not to convince or persuade a reader if a water distribution system diagnosis is required or not. Diagnosis is necessary if the economic performance and system performance with full reliability are required. Using explanations of what the diagnosis comprise of, illustrated with practical examples, the idea of the authors was to provide guidance on appropriate methods and approaches to water system diagnosis. Managers and WSS owners need to realize the importance of a systematic and a precise system performance monitoring. In the WSS management a service should be provided that can deliver continuous measurements and data analysis. In the beginning, probably much of the work will have to be contracted to other specialized companies, to allow an active "knowledge transfer" and fast learning curve. A usual mistake made in WS companies is to buy expensive equipment rather then to educate workers: even ordinary manometers and flowmeters will do a significant part of the work if a diagnosis team is quality educated and motivated for the work.

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7. REFERENCES

Alegre, H., Hirner, W., Baptista, J., and Parena, R. 2000. *Performance Indicators for Water Supply Services; Manual of Best Practice*. International Water Association.

Gotoh, K., J. K. Jacobs, S. Hosoda and R. L. Gerstberg (1993). *Instrumentation and Computer Integration of Water Utility Operations*. American Water Works Association Research Foundation and Japan Water Works Association. Denver, USA and Tokyo, Japan

Maksimovic, C. (1993). *Measurements in Hydraulic*. Faculty of Civil Engineering, Belgrade (in Serbian)

Obradovic, D. (1999). *Contemporary Water Works. Informatics and operational management*. Yugoslav Association for Water Technology and Sanitation (in Serbian)

Prodanovic, D., M. Ivetic i D. Pavlovic (1994) Steady and unsteady flow in water supply system of Mala and Velika Vrbica, measurements and numerical model analysis (in Serbian)

Prodanovic, D., C. Maksimovic (1995) Diagnostic measurements on water purification station of Smederevska Palanka city (in Serbian)

Prodanovic, D., M. Ivetic i D. Pavlovic (1996) Measurements and analysis of sludge pump and hydraulic transport system characteristics at Thermal Power Plant TENT Obrenovac A (in Serbian)

Prodanovic, D. i M. Ivetic (2000). Continual measurements of flow distribution on filter plant Strand, Novi Sad with system performance evaluation (in Serbian)

Prodanovic, D., D. Pavlovic i N. Jacimovic (2001). The report on diagnostic measurements on Water Supply System Laktasi - Republika Srpska (in Serbian)

Simic M. (1994) *Electronics and Measurements in Civil Engineering and Geodesy*. Faculty of Civil Engineering, Belgrade (in Serbian)

Thornton, J. 2002. *Water Loss Control Manual*. The McGraw-Hill Companies.

WHO – World Health Organisation. 2001. Leakage Management and Control - A Best Practice Training Manual.