

# Vyškov - Hydraulic Analysis of Water Supply Network

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## ABSTRACT

Water distribution and supply network in Vyškov with approximately 20,000 inhabitants was built gradually with development of residential districts since the year 1936 and its length represents nearly 100 km of pipelines with diameter from DN 50 to DN 500. Dominant materials of pipelines are cast iron and PVC. There are four main water sources and they supply the whole area together. With a respect to the great terrain elevation differences hydrostatic pressure reaches up to the value of 7,5 bar on a relatively extensive area. A high pressure evokes redundant big loss of water in both the main pipe network and at single attached consumers. The objectives of the hydraulic analysis are focused on development, calibration and verification of a mathematical model of water distribution and supply network. Simulations covered different alternatives of the given network under steady state and extended period conditions. Based on the simulation results, the existing water supply network was divided into several pressure zones. This led to optimum hydraulic grade line distribution, decrease of water losses and savings of electricity consumption required in pumping stations. Modelling real time control scenarios of the water distribution and supply network will help the network operator to model its breakdown, reconstruction and/or planning new pipes, cover new consumers demands etc.

## INTRODUCION

Vyškov is a district city with app. 20,000 inhabitants. Its water distribution system has been built since 1936 and nowadays represents nearly 100 km of pipeline with diameter ranging between 50 and 500 mm. Dominant pipeline materials are cast and PVC. There are four main water sources supplying the whole area. Great terrain elevation results in high-pressure changes in a network that reach 7.5 bar. This high pressure causes excess leakage in the network.

Evaluation of the existing water supply systems and the aim to meet future requirements can be efficiently achieved by performing hydraulic analysis. The objectives of the hydraulic analysis are focused on:

Development, calibration and verification of a mathematical model of water distribution and supply network, simulation of different alternatives under steady state and extended period conditions.

Dividing the existing water supply network into several pressure zones. This should lead to optimum pressure distribution, and hence the decrease of water losses and savings of electricity consumption required by pumping stations.

Proper use of simulation tools helps the engineer to foresee possible breakdown, to plan rehabilitation program and to gain benefit from it, [5].

### **ODULA MODELLING PACKAGE**

ODULA is a professional engineering software package for the simulation of steady flow and pressure distribution, extended period simulation and water quality problems in water supply and water distribution systems (HYDROINFORM a.s.), [3]. It tracks the flow of water in each pipe, the pressure at each junction, the height of water in each storage tank, and the concentration of a substance throughout a distribution system during a multi-period simulation. Water age and source tracking can also be performed. ODULA has been built to operate within the Windows 95 and Windows NT. Its modular system is based on powerful graphics for the definition and checking input data, provides fast numerical solvers and an engineering approach to presenting output data. Data management is based on InterBase Client-Server database system with full SQL facilities. ODULA computational modules are based upon EPANET numerical algorithm, Environmental Protection Agency (EPA), [4]. The hydraulic model is an extended period hydraulic simulator that solves the following set of equations for each storage node  $s$  (tank or reservoir) in the system:

$$\partial y_s / \partial t = Q_s / S_v \quad (1)$$

$$Q_s = \sum_i Q_{is} - \sum_j Q_{sj} \quad (2)$$

$$h_s = E_s + y_s \quad (3)$$

along with the following equations for each link (between nodes  $i$  and  $j$ ) and each node  $k$ :

$$h_i - h_j = f(Q_{ij}) \quad (4)$$

$$\sum_i Q_{ik} - \sum_j Q_{kj} - Q_k = 0 \quad (5)$$

where the unknown quantities are:

$y_s$  = height of water stored at node s,  
 $Q_s$  = flow into storage node s,  
 $Q_{ij}$  = flow in link connecting nodes i and j,  
 $h_i$  = hydraulic grade line elevation at node i (equal to elevation head plus pressure head),  
 and the known constants are:  
 $A_s$  = cross-sectional area of storage node s (taken as infinite for reservoirs),  
 $E_s$  = elevation of node s,  
 $Q_k$  = flow consumed (+) or supplied (-) at node k,  
 $f(Q_{ij})$  = functional relation between head loss and flow in a link

Equation (1) expresses conservation of water volume at a storage node while Equations (2) and (5) do the same for pipe junctions. Equation (4) represents the energy loss or gain due to flow within a link. For known initial storage node levels  $y_s$  at time zero, Equations (4) and (5) are solved for all flows  $q_{ij}$  and heads  $h_i$  using Equation (3) as a boundary condition. This step is called "hydraulically balancing" the network, and is accomplished by using an iterative technique to solve the non-linear equations involved.

The method used by EPANET to solve this system of equations is known as the "gradient algorithm", Todini, E. and Pilati, S.(1987) [7], and has several attractive features. First, the system of linear equations to be solved at each iteration of the algorithm is sparse, symmetric, and positive-definite. This allows highly efficient sparse matrix techniques to be used for their solution, George-Liu (1981). Second, the method maintains flow continuity at all nodes after its first iteration. And third, it can readily handle pumps and valves without having to change the structure of the equation matrix when the status of these components changes.

ODULA's dynamic water quality simulator tracks the fate of a dissolved substance flowing through the network over time. It uses the flows from the hydraulic simulation to solve a conservation of mass equation for the substance within each link connecting nodes i and j:

$$\partial c_{ij} / \partial t = -(Q_{ij} / S_{ij}) (\partial c_{ij} / \partial x_{ij}) + \theta(c_{ij}) \quad (6)$$

where:

$c_{ij}$  = concentration of substance in link i,j as a function of distance and time (i.e.,  $c_{ij} = c_{ij}(x_{ij},t)$ ),  
 $x_{ij}$  = distance along link i,j,  
 $Q_{ij}$  = flow rate in link i,j at time t,

$S_{ij}$  = cross-sectional area of link i,j,  
 $\theta(c_{ij})$  = rate of reaction of constituent within link i,j,

Equation (6) of ODULA's water quality model provides a mechanism for considering the loss (or growth) of a substance by reaction as it travels through the distribution system, solved by a numerical scheme called the Discrete Volume Element Method (DVEM), Rossmann et al.(1983). Reaction can occur both within the bulk flow and with material along the pipe wall. ODULA models both types of reactions using first order kinetics. In general, within any given pipe, material in the bulk flow will decrease at a rate equal to:

$$\theta(c) = -k_b c - (k_f / R_H) (c - c_w) \quad (8)$$

where:

$k_b$  = first-order bulk reaction rate constant,  
 $c$  = substance concentration in bulk flow,  
 $k_f$  = mass transfer coefficient between bulk flow and pipe wall,  
 $R_H$  = hydraulic radius of pipe (pipe radius/2),  
 $c_w$  = substance concentration at the wall,

In addition to chemical transport, ODULA can also model the changes in age of water over time throughout a network. To accomplish this, the program interprets the variable  $c$  in Equation (6) as the age of water and sets the reaction term  $q(c)$  in the equation to a constant value of 1.0. During the simulation, any new water entering the network from reservoirs or source nodes enters with age of zero. Water age provides a simple, non-specific measure of the overall quality of delivered drinking water. When the model is run under constant hydraulic conditions, the age of water at any node in the network can also be interpreted as the time of travel to the node. ODULA can also track over time what percent of water reaching any node in the network had its origin at a particular node. In this case the variable  $c$  in Equation (6) becomes the percentage of flow from the node in question and the reaction term is set to zero. The  $c$ -value of the source node is kept at 100 percent throughout the duration of the simulation.

#### **DATA ACQUISITION AND USE OF GIS MODELS**

The basic data describing the water supply and distribution network was collected in MAPA 2 geographical information system. Thematic maps were created in MicroStation. This is namely:

Junction node X, Y and Z co-ordinates.

Pipe length, material, residential coefficient, list of pipe vertices, beginning and ending junction node.

The data was imported into Vak Base, which is the general database system for water distribution and sewer networks (HYDROINFORM a.s.), [3]. The data was after completing and processing exported into the ODULA modelling package.

### MATHEMATICAL MODEL OF WATER SUPPLY NETWORK

The mathematical model of the water distribution and supply network was build-up in the ODULA modelling package from the base network data imported from the VakBase information tool. The model was then extended by the detailed description of hydraulic structures such as tanks, pumping stations and nodal demand values and their time variation, Fig.1.



*Fig.1. Computational scheme of the water supply network of Vyškov - ODULA modelling package*

Specifications covered tank size and elevation, minimum, maximum and initial water depth, characteristics Q-H curves for pumping stations and the elevation of the pumping station and/or water elevation in the water source.

The observation of the six main locations (two tanks and four pumping stations) was performed by telemetry RADOM readings. The measured data was collected over an extended period of time (24 hours with the time step of 15 minutes). The total water demand was calculated as the difference between the water inflow (tanks outflow, pumping stations delivery) and water transfer outside the network. This total water demand was then used in nodal demand distribution. The nodal demands were distributed by the method of reduced lengths, residential type coefficient  $k_{1i}$  assigned to each link, value of water consumer assigned to the particular nodes and a total water demand is specified:

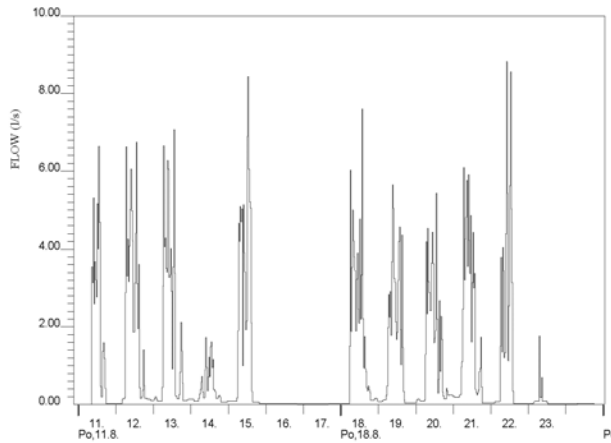
$$q_{pi} = (Q - \sum O_i) l_i k_{1i} / \sum (k_{1i} l_i)$$

The recalculation takes into account a sum of water consumers  $\sum O_i$  and in accordance with the weighted average method sets a particular demand  $q_{pi}$  to each link. The water demands of adjacent nodes are increased by 1/2 value of  $q_{pi}$ .

Several large water users were selected and the flow metering was performed over a period of 14 days by DATALOGGER. These readings were not done in the same time, as there was a lack of flow meters.

#### **MODEL CALIBRATION UNDER STEADY STATE AND QUASI-STEADY BOUNDARY CONDITIONS**

The validity of water distribution and supply network modelling depends largely on the accuracy of the input data. Models for steady-state applications can be calibrated using multiple static flow and pressure observations collected at different times of day under varying operational conditions. In addition, simulation models for extended-period applications, such as Krnov water supply network, require field data collected over an extended period (e.g., one to seven days). The first step in calibrating a hydraulic model was to determine initial estimates of the primary parameters, such as pipe roughness coefficients and demands to be assigned to each junction node. This was done by executing the model using the estimated parameter values and observed boundary conditions and then comparing the model results with the results from actual field observations - data from pump station flow meter readings and tank telemetry data, Fig.2.



*Fig.2. Flow measurements obtained by RADOM*

Model accuracy was evaluated using a relative pressure difference, a maximum state variable (i.e., pressure grade, water level, flow rate) deviation between 5-10 percent is generally regarded as satisfactory. After model results and field observations were in reasonable agreement, a micro-level model calibration was performed. The parameters to be adjusted during this final phase of calibration are pipe roughness and nodal demands.

#### **STEADY STATE CALIBRATION**

Steady state calibration was based upon a selected time level containing the most important operating conditions including pumping stations. The model results and the field observations were compared for the main network components:

Pumping stations: reasonable agreement between measured and calculated parameters was achieved for every pumping station. The accuracy was about 2.3% of the total flow within the particular time level.

Tanks: the difference between measured and calculated values in the Lhota and Drnovice tanks varied from 0 to 13.7% of the total flow within some of the time levels. The differences are probable caused by undefined water users.

## **EXTENDED PERIOD CALIBRATION**

Time series graphs of water inflows were created from the observed values in the main network locations by the RADOM telemetry. Each time series consists of successive multiplier values within the time step of 15 minutes related to the initial flow value. Time series graphs of the main water users were also created from the DATALOGGER readings. The total simulation time of each extended period analysis was 24 hours.

## **HYDRAULIC AND WATER QUALITY SIMULATION**

Hydraulic simulations were focused on calibrating the network under the steady state and extended period conditions, an analysis of multiple operational scenarios and on water quality analysis of source tracing. Source tracing analyses was performed in order what degree water from a given source blends with that from other sources, and how the spatial pattern of this blending changes over time.

## **DIVIDING THE NETWORK INTO SEPARATE PRESSURE ZONES**

Water distribution and supply network was divided into three main pressure zones. This division was achieved by disconnecting the adjacent pipes and creating the independent networks. The mathematical model of the network was preliminary split into three separate sub-models. Later on, the model schematisation of the total network area allowed us to model three pressure zones within one simulation run. Hydraulic analysis of new zones was performed with respect to the design water demands. The estimate of the designed total water demand was based on the following criterion:

The initial estimate was based on maximum daily demand observed by RADOM readings within the period of 1996-1997.

The total water demand was divided into the new pressure zones based on the results of the method of reduced pipe lengths and the ratio of the invoiced water for each zone.

Each pressure zone water demand was corrected by the coefficient of future development based on the increase of the industry, population and specific water demands.



The simulation results were performed for the three pressure zones and carefully evaluated. The design of the second and third pressure zone proved its expectations while the first pressure zone had insufficient pressure distribution. New tank was added to the network (it was the existing disconnected tank) and the simulation runs were performed again, Fig.3. The required pressure values were reached within the network, and only a small part of the network was supplied by AT-station with the frequency regulation.



*Fig.3. First pressure zone - source tracing*

## **RESULTS PRESENTATION**

The simulation results were presented in the form of multiple horizontal plan plots, longitudinal profile plots (either of which can be animated for extended period simulations), and time series plots. ODULA automatically generates animation of extended period simulations for both horizontal plan plots and profile plots, including the creation of Microsoft AVI files. Animation of results is synchronised within multiple active windows. This is highly efficient tool for displaying extended period simulation results and showing the control linkage among the network elements.

Longitudinal profile plots can be plotted along any user-selected route. For the horizontal plan plot, contouring of analysis results was performed for the hydraulic grade line, directional flow arrows were plotted alongside the pipes to show the flow direction for any time step. Tabular printed reports were generated for the simulation results directly from the database report generator.

The model results can be exported into GIS models such as MapInfo, Arc/View and/or MicroStation Outlook and graphical output can be saved in DXF files. It is possible to deliver the simulation results together with the ODULA Analyses Viewer to the client. This option seems to be very promising for the results interpretation.

## CONCLUSION

The owner of Vyškov water supply and water distribution network has started preparation of project documentation related to dividing the network into separate pressure zones on the basis of hydraulic analysis results. Designed improvements will bring benefits within the time period 1998-1999.

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