BEHAVIOUR OF A WATER SUPPLY SYSTEM: A MODELLING AND SIMULATION STUDY OF ACTIVITIES WITH SOME EXPERIMENTS

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ABSTRACT
Modelling and simulation is rapidly becoming a mainstream approach in determination of dynamical behaviour and management of operation of physical systems. This paper presents a study of nonlinear modelling and simulation of city of Gaziantep water supply system, and some experiments on the real system. The nonlinear model is obtained using active and passive dynamical elements. Validation of the simulation model is accomplished through comparison with system observations and using data validation and face validity approaches. The nonlinear system is simulated for comparison with the real-system measurements. Results demonstrate the dynamical behaviour of the real system about flow stability, water heads in the reservoirs and a measure of the friction at different sections of the water supply system.

I. INTRODUCTION
Physical systems in industry involve continuous material flows, such as liquid, gas or solid. Because of the operational complexities and stochastic nature, it is difficult to reach definite analytical solutions [1]. Simulation is widely used for performance evaluation of systems behaviour [2]. It is the imitation of the operation of a real process or system with a surrogate process or model, and provides feasibility to study complex systems [1, 3]. The simulation also provides some scenarios for different system variables to evaluate various alternatives and to generate several useful operational studies [1]. The models for a simulation do not only provide quantitative information but also increase the level of understanding of how the system works.

Water supply systems are becoming more important, since water demand has increased rapidly in the developing countries as a result of high population growth, improvement of living standards, rapid urbanization, industrialization and improvement of economic conditions while accessible sources of water keep decreasing in number and capacity [4]. During the last two decades, there have been increasing requirements to improve operation of water supply systems while improving the environment so that their behaviour can be fully understood and the total process is optimised [5]. These are exerting increasing pressure on local water authorities and water planners to satisfy the growing water demands [6, 7]. For example, populations of cities have increased substantially due to economical and social conditions after 1980s in Turkey. Fresh water resources, however, are far away from most of the city centers and towns. This requires modelling and simulation of the system to manage the water transfer [5, 8]. Understanding the technical side of these systems with their prospective behavior in case of a disturbance occuring at any point of the system is a crucial problem to improve the operation [9-11]. Pipes, reservoirs, pumps, valves and other hydraulic elements that play important roles in system dynamic behaviour, can be classified into two categories: active and passive [12].

Simulation of these systems have been indispensable work to understand behaviour of the system in order to consistently meet the demand and generate ideas for flexible management and design schemes [11-13]. This paper deals with nonlinear modelling, simulation and some real-system experiments performed on the city of Gaziantep water supply system to practice water management. Measurements obtained on the real system and simulation results obtained from the nonlinear system provide the feasibility of our configuration to evaluate various alternatives and scenarios about the real water supply system.

II. WATER SUPPLY SYSTEM
Water is taken from Kartalkaya dam, which is 53 km. away from the city of Gaziantep. Figure 1 illustrates the rough diagram of the water supply system along which exist three pumping stations (PST-1, PST-2, PST-3) and three reservoirs (RS-1, RS-2, RS-3). The system has a single line property, and no water is added or distributed along the supply system. The gravity helps flow of water

from the reservoir down to the next pumping station. Pumps are used to elevate water to the reservoirs. The position of PST-1 is taken as the reference point. $h_{ti}(t)$, h_{si}, l_{pi} denote the variable heads (*m*) in the reservoirs, static heads (*m*) and the lengths of pipes (*m*), respectively. The variables $Q_a(t)$, $Q_b(t)$, and $Q_c(t)$ designate the water flow rates through pipes. The pipelines are buried underground and are assumed to be free of chemical reaction, biochemical, thermal and noise pollution, and the system does not include cavitation. The flow rates, reservoir heads and speed of pumps represent deviations from their nominal steady-state operating values to obtain behaviour of the overall system. Uniform flows can be assumed for such a single line water supply system and the variations around nominal operating values do not deteriorate this generality [14]. Distributed flow is not taken into account, which is considered for complex piping systems having high flow velocities, especially for water distribution systems, and for the systems having small and different pipe sections [15]. It is assumed that water has uniform density in the pipe and is an incompressible liquid. The system and its individual components are stationary. Three pumps work in parallel in each pump station with a nominal speed (N_{so}) of 985 rpm. The pipes are concrete type with an inner diameter (*D*) of 1.4 m and a cross-sectional area (A_p) of 1.5394 m^2 and 15 years old. The reservoirs have a cross-sectional area (A_t) of 475 m^2. Bending curvatures of the pipes along the supply system are measured to be larger than the pipe inner diameter (*D*). The numerical data about the water supply system of the city of Gaziantep are presented in [5].

III. DYNAMIC MODELS OF SYSTEM

Hydraulic systems generally lead to complex models. Solution of these complex models is difficult, since many parameters are included that may be negligible in operation [7]. For these reasons, the system model should be obtained using dominant variables to reflect the dynamical behaviour of the plant [10]. Head developed by a variable-speed pump that is running in parallel with other pumps in a pump station varies nonlinearly with its speed *N* (rpm) and output water flow rate $Q_p(t)$ (m^{3}s^{-1}) [5,12,15]:

$$h_{\mathrm{p}}(N, Q_{\mathrm{p}}) = A_o N^2 + \frac{B_o}{n} N Q_{\mathrm{p}} - \frac{C_o}{n^2} Q_{\mathrm{p}}^2 \qquad (1)$$

where A_o, B_o, C_o are the constants for a particular pump depending on component characteristics and *n* is the number of the pumps running in parallel in the pump station. These constants can also be calculated using appropriate manufacturer's specifications [5].

For the pipes, consider a pipe section with length l_p (m) and of area A_p (m^2). If the head difference between two ends of the pipe section, Δh is considered, the following differential equation can be given [12,15,16]:

$$\frac{dQ(t)}{dt} = \frac{gA_{\mathrm{p}}}{l_{\mathrm{p}}}\left(\Delta h - h_{\mathrm{loss}}(t)\right) \qquad (2)$$

where h_{loss} denotes the total head loss caused by friction along the piping system, *g* is the acceleration due to gravity.

Reservoirs are dynamical elements for the water storage. When a reservoir discharges under its own head without external pressure, the continuity equation can be applied as [7]:

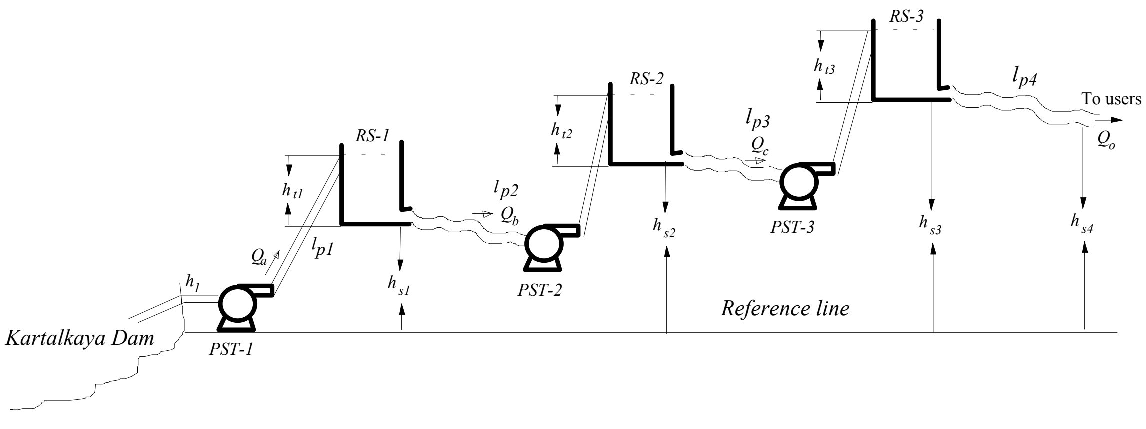
$$\frac{d(\rho V(t))}{dt} = \rho_{\mathrm{i}} Q_{\mathrm{i}}(t) - \rho_{\mathrm{o}} Q_{\mathrm{o}}(t) \qquad (3)$$

where ρ, ρ_i, ρ_o represent the water densities inside the reservoir, water inflow and outflow, respectively, that are assumed to be constant and equal ($\rho=\rho_i=\rho_o$). $Q_i(t)$ (m^{3}s^{-1}) and $Q_o(t)$ (m^{3}s^{-1}) denote reservoir input and output water flow rates, respectively, and $V(t)$ (m^3) is the volume of a particular reservoir.

Total head loss and water flow rate in a supply system can be given as [5,12]:

$$h_{\mathrm{loss}}(t) = h^{\mathrm{o}}_{\mathrm{loss}} + \Delta h_{\mathrm{loss}}(t)\,, Q(t) = Q^{o} + \Delta Q(t) \qquad (4)$$

where ($.^o$) denotes nominal steady-state value and $\Delta h_{\mathrm{loss}}(t)$ designates the variable head loss caused by the variable water flow rate $\Delta Q(t)$. The head loss can be



categorised as the head loss caused by friction (major) losses and local (minor) losses [7,10]. The friction losses in pipelines of such a large water supply system dominate the local losses [7,8]. There are several approaches obtained from theoretical considerations and experimental data to calculate the friction loss in pipes [5,13-15]. The total loss in a pipeline can be given as [14]:

$$h_{\text{loss}}^{\text{pipe}}(t) = h_{\text{loss-f}_\text{p}}(t) + h_{\text{loss-l}}(t) \tag{5}$$

where $h_{\text{loss-fp}}$ denotes friction losses, $h_{\text{loss-l}}$ denotes local losses. Hazen-Williams [6] and Darcy-Weisbach approaches [14-16] have been frequently used in obtaining the head loss in piping systems [5,11]. Local (minor) losses are caused by expansions, contractions, and bends in pipelines, valves, flow at entrance and exit of reservoirs, rapid changes in the direction or magnitude of the velocity of water [14].

IV. EXPERIMENTS AND SIMULATIONS

The water leaving a reservoir flows through the pipelines by gravity down to the next pump station. The present system runs in conventional open-loop conditions and is controlled manually. The output water flow rate ($Q_o(t)$) and reservoir heads were measured on the real system at hourly intervals throughout a day, and 24 measurements were taken at the nominal speed of the pumps as shown in Figure 2 and Figure 3. Using the data obtained, the average water flow rate was calculated to be about Q_{so}= 2.83 m^3/s. (10188 m^3/h), and observed to vary between 10175 m^3/h and 10203 m^3/h. Heads of the reservoirs that were measured vary around 4.2 m in RS-1, 2.15 m in RS-2 and 3.2 m in RS-3, respectively. For the simulation studies, the block diagram of the nonlinear overall system, illustrated in Figure 4, was implemented in Matlab-Simulink. The pump characteristics were obtained from the manufacturer. The nonlinear head developed by the pump was calculated around the nominal operating point (Q_{so}=985 rpm;Q_{so}=2.83 m^3/s) using the characteristic curve [5, 12]:

$$h_\text{p}(N, Q_\text{p}) = 0.0001433N^2 + 0.005015NQ_\text{p} - 3.98Q_\text{p}^2$$

Simulation results show that the reservoir heads are around 4.15 m in RS-1, 2.07 m in RS-2 and 3.15 m in RS-3 of the steady-state, respectively.

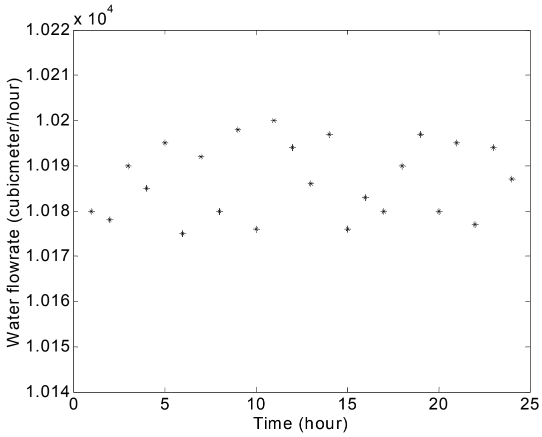


Figure 2. Measured output water flow rate ($Q_o(t)$).

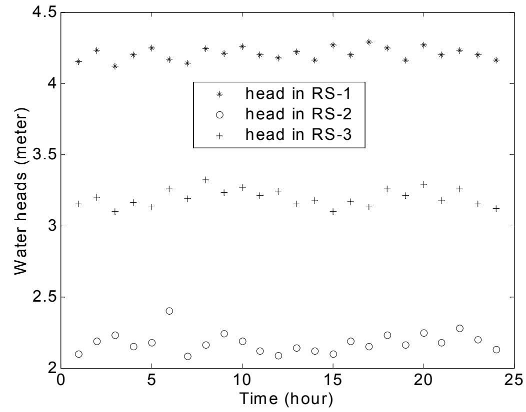


Figure 3. Measured water heads in the reservoirs.

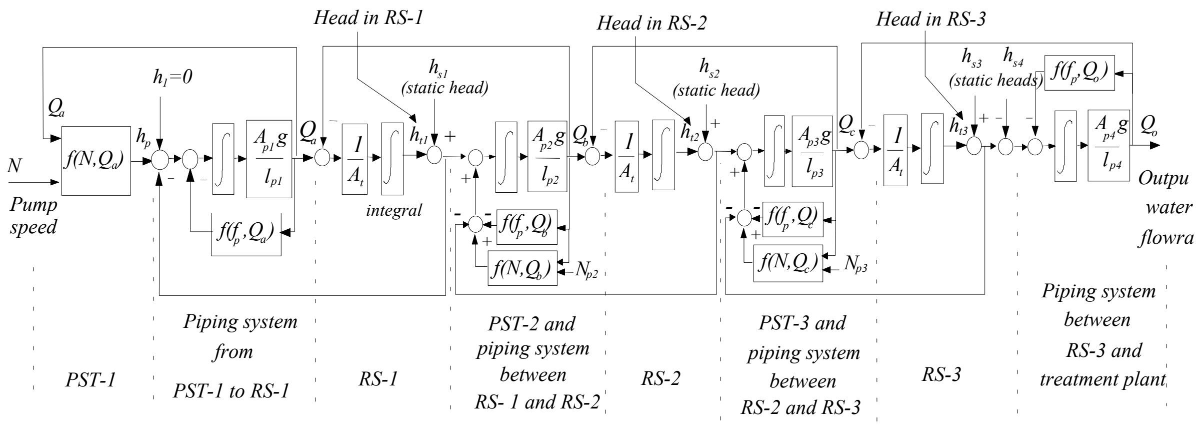


Figure 4. Nonlinear block diagram of the water supply system.

V. MODEL VALIDATION

Model validation should be performed to determine whether a simulation model is an accurate representation of the system or not. An approach is to use system observations and model results both to test model validity and to use simulation predictions for the system variables [17,18]. There are several methods to validate a simulation model such as historical data validation, face validity, internal validity, and extreme condition tests [17]. Data validation and face validity methods are used in the present paper.

To check the transient characteristics of the model, a test is performed on the real water supply system such that the speed of the pump in PST-1 is reduced 40 rpm (from 985 rpm to 945 rpm) by reducing the driving motor terminal voltage to obtain variations at the head in RS-1. The data are recorded at every half an hour, that is, a sample is recorded at every 30 minutes, and 30 measurements are obtained in 15 hours. The measured data (shown by stars) and simulation results (solid line) are illustrated in Fig. 6 that shows variations in the head of the RS-1. The results obtained from the normal conditions (steady-state) and transient response confirm the fact that the dynamical model used to represent the real water supply system can be used in the simulation of the system to generate some scenarios.

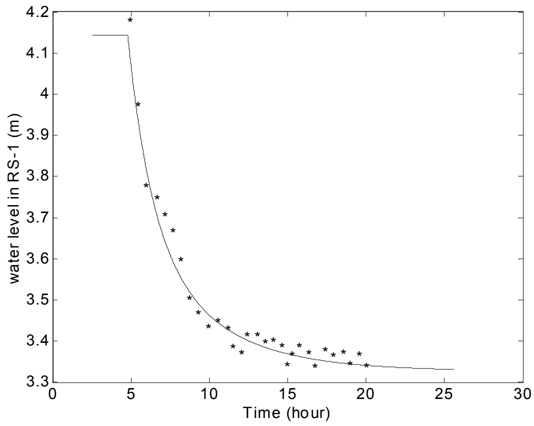


Figure 6. Water level in RS-1.

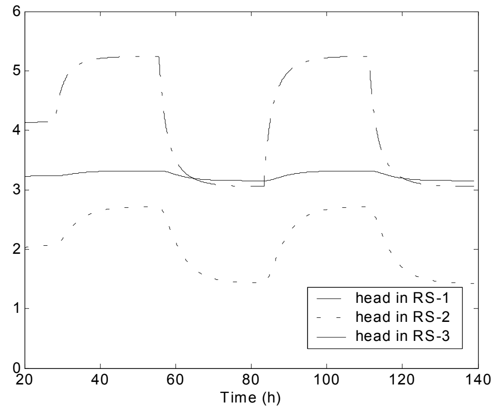


Figure 7. Heads in the reservoirs for a square wave flow disturbance $\Delta Q_a(t)$=0.425 m^3/s.

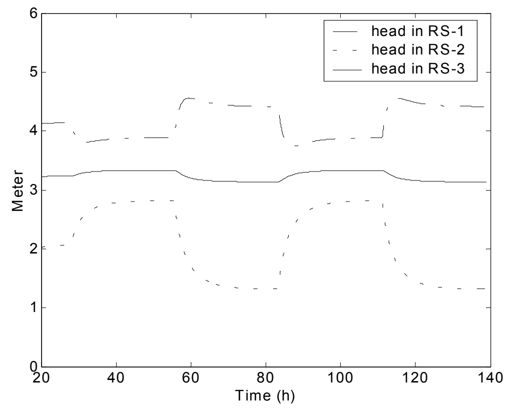


Figure 8. Heads in the reservoirs for a square wave flow disturbance $\Delta Q_b(t)$=0.425 m^3/s.

VI. LOAD DISTURBANCE TEST

The flow disturbances in water supply systems are common and should be taken into account in water management and control problems [7, 10, 12] since a section or a part of the pipeline might be broken. A series of tests was performed in this section to obtain the behaviour of the system in response to the water flow rate disturbances applied at different points along the pipeline. The responses were illustrated in Figure 7, Figure 8 and Figure 9. A flow rate disturbance of 15% ($\Delta Q_a(t)$=0.425 m^3/s square wave signal in magnitude with a frequency of 5.10^{-6} Hz) in the pipe section of length l_{p1} was applied to the system, and the corresponding heads at the reservoirs were illustrated in Figure 7. The flow rate disturbance signal was applied at t=10^5 s (t=27.7 h) after starting. The water head in the last reservoir RS-3 was not affected significantly, since the flow disturbance is self-regulated through the system. A flow rate disturbance of equal magnitude (15% of steady-state flow rate value) was applied at $\Delta Q_b(t)$=0.425 m^3/s and $\Delta Q_c(t)$=0.425 m^3/s, and the corresponding head responses of the reservoirs were illustrated in Figure 8 and Figure 9, respectively.

VII. CONCLUSIONS

Modelling and simulation are the key issues in physical water supply problems to determine behaviour of the system and range of operation for management goals and control purposes, such as flow regulation and cost minimisation. Sufficient technical information about a water supply system can be obtained by accurate modelling and a reasonable simulation. The study presented here seems to be effective in tackling the behaviour of the supply system and to generate various alternatives.

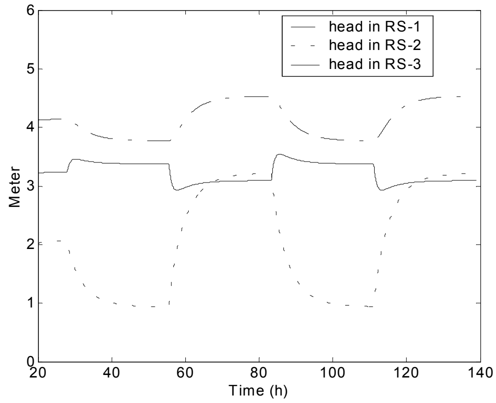


Figure 9. Heads in the reservoirs for a square wave flow disturbance $\Delta Q_c(t)$=0.425 m^3/s.

A modelling approach was chosen to enhance our understanding of the observed system. The approach uses active and passive dynamical elements in the modeling. This was not primarily to provide a highly accurate representation, but to enrich our understanding of the fundamental behaviour of the system. The hydraulic models, in particular, included the nonlinear coupling between flow rates and reservoir heads. The study revealed the dynamics of behaviour and interactions among active and passive elements in the water supply system. A good approximation for pumps was obtained using appropriate manufacturer's specifications.

Simulation model validation was performed. This basically included the comparison of the steady-state and transient characteristics of the system obtained from the simulations and experiments. The whole nonlinear system was simulated to obtain the flow rates, reservoir heads and head loss caused by the friction. This concept has allowed to produce some scenario for changes in the water flow rate disturbance that was assumed to occur at any point of the water supply system.

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REFERENCES

1. E. J. Chen, Y. M. Lee, P. L. Selikson, A simulation study of logistic activities in a chemical plant, Simulation Modelling Practice and Theory, Vol. 10, pp 235-245, 2002.
2. D. Anagnostopoulos, A methodologial approach for model validation in faster than real-time simulation, Simulation Modelling Practice and Theory, Vol. 10, pp 121-139, 2002
3. A. M. Law, W. D. Kelton, Simualtion Modelling and Analysis, 3rd Edition, McGraw-Hill, New York, USA., 2000.
4. W. A. Abderrahman, Urban water management in developing arid countries, Water Resour Dev., Vol. 16, no.1, pp 7-20, 2000
5. İ. Eker, T. Kara, Modelling and simulation of water supply systems for feedback control, in: Proceedings of UPEC'2001: 36th Universities Power Engineering Conference, Power Utilisation, Part-5C, University of Wales Swansea, 12-14 September, Swansea, U.K., 2001.
6. D.S. Brookshire, D. Whittington, Water resources issues in the developing countries, Water Resour Res., Vol. 29, No. 7, pp 1883-1888, 1993.
7. M.A. Brdys, B. Ulanicki, Operational Control of Water Systems, Prentice Hall International Ltd, U.K., 1994.
8. D. Obradovic, Modelling of demand and losses in real-life water distribution systems, Urban Water, Vol. 2, pp 131-139, 2000.
9. M. Elbelkacemi, A. Lachhab, M. Limouri, B. Dahhou, A. Essaid, Adaptive control of a water supply system, C. Eng Prac.,Vol.9,pp 343-349,2001.
10. D.B. Simons, Future trends and needs in hydraulics, J. Hydraul. Eng. 118 (12) (1992) 1608-1620.
11. G. Cembrano, G. Wells, J. Quevedo, R. Perez, R. Argelaguet, Optimal control of a water distribution network in a supervisory control syste, Cont. Eng. Prac., vol. 6, pp 1177-1188, 2000.
12. İ. Eker, T. Kara, Control of water supply systems, in: Proceedings of UPEC'2001: 36th Universities Power Engineering Conference, Power Utilisation, Part-8C, University of Wales Swansea, 12-14 September, Swansea, U.K; 2001.
13. İ. Eker, T. Kara, Water supply systems and friction factor: Case Study, in: Proceedings of GAP'2002: 4. International South-East Anatolian Project Engineering Congress, Harran Üniversity, 6-8 June, Urfa, Turkey, pp 1277-1282, 2002.
14. J. F. Douglas, J.M. Gasiorex, J.A. Swaffield, Fluid Mechanics, Longman, U.K., 1985.
15. J. A. Fox, Hydraulic Analysis of Unsteady Flow in Pipe Networks, MacMillan, London, U.K.,1977.
16. T. Kara, İ. Eker, Modelling of pipe sections for incompressible liquids, in: Proceedings of 8. Turkish Electrical, Electronic and Computer Engineering Conference, 5-7 September, Gaziantep, Turkey, pp 521-524, 1999.
17. R. G. Sargent, Varification, validation, and accreditation of simulation models, in: Proceedings of the Winter Simulation Conference, USA, pp 50-59, 2000.
18. N. Robertson, T. Perera, Automated data collection for simulation ?, Simulation Modelling Practice and Theory, Vol. 9, pp 349-364, 2002.