Rural water distribution system with groundwater supply and water tower: Numerical modelling in EPANET 2.2

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Abstract. The paper focuses on the numerical modelling of a rural Water Distribution System (WDS), supplied from a deep well, from which the water is pumped in a water tower (storage tank). Consumers are fed gravitationally from the water tower, with variable demand over 24 hours. Simulations were carried out in EPANET 2.2 using two methods: Demand Driven Analysis (DDA) with outflow issuing from emitters, and Pressure Driven Analysis (PDA). To minimize numerical instabilities, a particular attention was paid to the groundwater well (modelled both with variable, and constant hydrodynamic level), as well as to the connection of the water tower to WDS (where the connection was made either using 2 pipes, or a single pipe). By applying the DDA and PDA methods to the resulting 2×2 configurations of the hydraulic system, a total of 8 sets of simulations (solutions) were obtained and compared. The most advantageous pair of method and configuration is recommended to be considered when modelling a complex (e.g. urban size) WDS with groundwater supply and storage tanks.

1. Introduction

The present study concerns the operation of the Water Distribution System (WDS) of Tirișneag village – a small village with a population of about 700 inhabitants, located in Olt County, on the right side of the Vedea River, in southern Romania. The village benefits from a groundwater source – a well from which water is pumped towards a Water Tower (WT) placed in the middle of the village. The consumers (mostly domestic end-users, e.g. houses and farms) are gravitationally supplied from the WT, with variable demand over a period of 24 hours. Operating costs are low, because the pump submerged in the well is operated mainly at predetermined time intervals, when the price of electricity is low. There is no need of water treatment station within the above WDS because the drinking water is of good quality, being pumped from a deep aquifer (the groundwater well is more than 90 m deep).

The water distribution network has 403 main pipes with a total length of 9.44 km, and 394 junctions, most of them at an elevation of 235 m.a.s.l. (meters above the Black Sea level); 238 out of 394 junctions are end-users. Water storage involves choosing the location, selecting the shape and assessing the active capacity of the storage chamber. The height of the WT was set so that consumers are supplied with a pressure higher than 2 bar at peak hours. The considered WT is of mushroom-shaped type; the bottom of its storage chamber is at 260 m.a.s.l. The quasi-conical shaped storage chamber has an active capacity of 24.4 m³ when the water reaches the maximum level of 264 m.a.s.l.

The above rural WDS was modelled here in EPANET 2.2 [1], considering two types of hydraulic analyses: Demand Driven Analysis (DDA) with outflow issuing from emitters, and Pressure Driven...
Analysis (PDA). DDA with emitters was also available in EPANET 2.0 [2]; PDA was implemented in the new version of the software, EPANET 2.2.

The studied system operates under a variable demand over a 24 hours period, so an extended period simulation was performed [3], [4], following a rural type demand pattern. A particular attention was paid to the groundwater well, which was modelled in EPANET, firstly with variable hydrodynamic level, as proposed by Iancu et al [5] and Georgescu et al [6], and then with constant hydrodynamic level [7]. Another concern pointed on the connection of the water tower to the WDS, because the connection through 2 pipes (one for filling and another one for emptying, as in the real WT) induces some numerical instabilities; in the attempt to diminish the instabilities, a configuration with WT connected to WDS through a single pipe (used for filling or emptying) [3], [8] was also investigated.

Accordingly, applying the DDA and PDA methods to the resulting 4 configurations of the hydraulic system (where the well has a variable/constant level, and the WT is connected by two pipes/one pipe to the remaining network), a total of 8 sets of simulations/solutions were obtained and compared in the present paper. Obviously, the best configuration, able to reproduce the WDS operation and to satisfy the demands with minimal numerical instabilities, will be the recommended one to model water distribution systems based on groundwater supply and storage tanks.

2. Numerical approach

2.1. DDA with emitters versus PDA

WDS simulation models are developed based on two different approaches, namely:

- demand driven approach, attached to demand driven analysis – DDA, where nodal outflows (demands) are provided irrespective of the available nodal pressure;
- pressure driven approach, attached to pressure driven analysis – PDA, where nodal outflows depend on the available nodal pressure, according to different relationships between demand and pressure (or pressure head) [9]-[11].

EPANET allows implementing pressure driven nodal demands in DDA by setting the consumers as emitters [1], [2]. For a node of emitter type, the available demand \( Q \) is related to the available nodal pressure \( p \) as follows:

\[
Q_{\text{DDA}} = \frac{a}{p} = \frac{Q_r}{\sqrt{p/p_r}} \quad \text{for} \quad a = Q_r/\sqrt{p_r} \tag{1}
\]

where \( a \) is the emitter coefficient, computed here based on the requested demand \( Q_r \) and the requested nodal pressure \( p_r \). According to (1), the available demand will be:

\[
Q_{\text{DDA}} \geq Q_r \quad \text{for} \quad p \geq p_r \\
Q_{\text{DDA}} < Q_r \quad \text{for} \quad p < p_r \tag{2}
\]

When PDA is set in EPANET 2.2, the available demand \( Q \) is related to the available nodal pressure \( p \) as follows [12]:

\[
Q_{\text{PDA}} = \begin{cases} 
Q_r & \text{for} \quad p \geq p_r \\
\frac{Q_r}{\sqrt{p/p_{\text{min}}}} & < Q_r \quad \text{for} \quad p_{\text{min}} \leq p < p_r \\
0 & \text{for} \quad p < p_{\text{min}} \end{cases} \tag{3}
\]

where \( p_{\text{min}} \) is the minimal value of the nodal gauge pressure that ensures an outflow at the consumer.

Although the second relation in (3) reduces to (1) for \( p_{\text{min}} = 0 \), a comparison of the first conditions in (2) and (3) shows that when \( p > p_r \), the outflow computed with DDA is greater than \( Q_r \) while the outflow computed with PDA is limited to \( Q_r \).
For the WDS studied in this paper, the design value of the total demand is about 21 litres/s; that value is divided among 238 consumers, which request a demand $Q_r$ varying from 0.077 to 0.118 litres/s, at a gauge pressure $p_r$ of 20 mWC. For the above $Q_r$ and $p_r$ values, the emitter coefficients $a$ from (1) vary from 0.0172 to 0.0263.

The following options were set in EPANET 2.2:

- **Hydraulics Options** – flow rate in litres/s (with the corresponding default units for the remaining hydraulic and geometric parameters [1], [2]); Darcy-Weisbach headloss formula; required pressure $p_r = 20$ mWC and minimal pressure $p_{min} = 0$; demand model selected as DDA or PDA, upon choice;
- **Times Options** – total duration of 24 hours; hydraulic time step of 1 minute, and pattern time step of 15 minutes.

DDA simulations were performed by setting all 238 consumers as emitters; to mimic the rural demand pattern, minor losses were added (using control structures) to a throttling control valve (V) placed between WT and the distribution network; minor loss coefficients added to V vary from 0 to 8500 at peak hours, and from 42500 up to 297000 at off-peak hours.

PDA simulations were performed by setting for each consumer its $Q_r$ value, together with a demand pattern appropriate for the entire rural WDS. The demand pattern coefficients $c$ vary over 24 hours as presented in figure 1: the mean value of $c$ is 0.67, which gives a mean value of the daily total demand equal to 14.07 litres/s; $c_{max}$ of 1.173 gives a maximum demand of 24.52 l/s, while $c_{min}$ of 0.257 gives a minimum demand of 5.37 litres/s.

### Figure 1. Demand Pattern set in PDA.

### Figure 2. Groundwater well scheme [5], [13].

### Figure 3. Well's curve $\Delta H = \Delta H(Q)$.

### Figure 4. Well models: (a) W1 [5]; (b) W2 [7].

#### 2.2. Groundwater well modelling in EPANET

When dealing with a groundwater supply source, the simulation of the WDS operation depends on the description and insertion of the groundwater well into the numerical model of the entire hydraulic system. The well scheme in a cross-section of an unconfined aquifer is presented in figure 2 [5]. The well of the studied WDS is characterized by the following parameters: well's radius $r = 0.15$ m; hydrostatic level $H_i = 153$ m.a.s.l.; bottom of the well at 137 m.a.s.l.; hydraulic conductivity of the
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aquifer \( K = 2.15 \times 10^{-5} \) m/s; hydrodynamic level \( H_d \) with an optimal value of 145 m.a.s.l. for the optimal extraction flow rate of 21 litres/s. The flow rate \( Q \) that can be extracted from the well depends on the drawdown \( \Delta H = (H_s - H_d) \), in accordance with the Dupuit formula [5]:

\[
Q = Q(\Delta H) = \pi K \frac{H_s^2 - (H_s - \Delta H)^2}{\ln(575\Delta H / KH_s / r)}
\]  

(4)

Equation (4) allows generating pairs of values \( \{\Delta H, Q\} \), which define the curve \( Q = Q(\Delta H) \). The resulting curve can be inserted in EPANET (figure 3) as headloss – flow rate curve, \( \Delta H = \Delta H(Q) \), a curve that describes the operation of a General Purpose Valve (GPV).

Two models can be implemented in EPANET to mimic the pumping from a groundwater well:

- the first well's model, denoted W1 (figure 4a), allows modelling the variable water level in the well; W1 consists of 5 successive objects [5], [6], namely a reservoir R (with constant head equal to the hydrostatic head \( H_s \)), a GPV (with the same diameter, 0.3 m, as the well, operating upon the curve plotted in figure 3), a short pipe with check valve (CV) with the same diameter as the well, a tank labelled as W (with a bottom level as the one of the well, an initial level equal to 145 m.a.s.l. – the optimal hydrodynamic level \( H_d \); the tank has the same diameter and active capacity as the well); finally, the submersible pump P operates upon the head – flow rate curve \( H = H(Q) \) from figure 5, as well as upon the efficiency – flow rate curve;

- the second well's model, a simplified model, denoted W2, allows modelling the water pumped from a well at a constant hydrodynamic level [6], [7]; it consists of an emitter labelled as W (set to an elevation equal to the optimal \( H_d \) value of 145 m.a.s.l.; a high value of the emitter coefficient, e.g. \( 10^5 \) [6] will ensure the desired inflow into WDS); the emitter is followed by the same pump P, which run upon the performance curves previously mentioned.

\[\text{Figure 5. Pump curve } H = H(Q).\]

\[\text{Figure 6. WT capacity curve } V = V(h).\]

2.3. Water tower connection to the network
When modelling tanks in EPANET, numerical instabilities can appear [3], [8]. Modelling groundwater wells as in configuration W1, which includes a tank, leads to instabilities, reflected in oscillations of the water level in tank (of the well's hydrodynamic level) and subsequently oscillations of the flow rate pumped from the well, as proved by the comparison of the results [6] obtained using two different software, namely: EPANET 2.0 and WDNNetXL [14].

For the studied rural WDS, the mushroom-shaped water tower (described in Section 1) operates in EPANET 2.2 upon the capacity curve \( V = V(h) \) plotted in figure 6, where the volume \( V \) depends on the water height \( h \) in the conical storage chamber. As already mentioned, the water tower, modelled in EPANET by a tank, is connected to the WDS using two different configurations:

- the first one, denoted further as WTa (figure 7), contains 2 pipes, one for filling the tank (the discharge pipe with CV, for pumping water into WT) and another one from WT to the network, labelled as Pipe 1 (77 m long, 400 mm diameter, with CV), for emptying the tank;
• the second configuration, denoted further as WTb (figure 8), contains a single pipe connected to WDS by a tee fitting; that filling/emptying single pipe (25 m long, Ø400 mm) represents the vertical part of the previous Pipe 1 from WTa; thus, in WTb the resulting Pipe 1, supplying water from WT to the network, is only 52 m long (it also contains a CV).

![Figure 7. WTa configuration (2 pipes).](image1)

![Figure 8. WTb configuration (a single pipe).](image2)

2.4. Resulting WDS configurations: W1&WTa; W2&WTa; W1&WTb and W2&WTb

Tirșineag WDS is modelled based on the following 4 configurations, obtained by combining 2 types of well models (W1; W2) with 2 types of connections of the WT to the system (WTa; WTb):

- W1&WTa (figure 9) – full well model (W1) with WT connected by 2 pipes (WTa);
- W2&WTa (figure 10) – simplified well model (W2) with WT connected by 2 pipes;
- W1&WTb (figure 11) – full well model with WT connected by a single pipe (WTb);
- W2&WTb (figure 12) – simplified well model with WT connected by a single pipe.

Figure 9 displays the distribution of the requested demand $Q_r$ in litres/s, set at consumers only when running PDA. Starting from valve V (of 400 mm diameter), all pipes are the same for all 4 configurations, with lengths from 0.5 to 192.7 m and diameters from 15 mm (near end-users) to 300 mm. For all runs, the most disadvantaged consumer is the same: the one denoted as C in figure 9.

![Figure 9. Requested demands $Q_r$ for PDA simulations only – W1&WTa case, with the full well model W1 (reservoir R, general purpose valve GPV, tank W, pump P) and water tower WT connected by 2 pipes (WTa); check valves CV are placed on the discharge pipe of pump P, and on Pipe 1.](image3)
3. Results and discussions

The WDS operation was simulated for all 4 configurations (listed in subsection 2.4) firstly by setting DDA with emitters and minor losses at the control valve V (to ensure a variable demand), then by setting the PDA with demand pattern and no minor losses at the valve V.

To facilitate comparison, the results attached to all 8 type of simulations are presented further within tables built as matrices of images.

The resulted variation of the total flow rate provided to the distribution network through Pipe 1 is presented in table 1, in litres/s. When comparing the results from table 1, PDA runs lead to the same results for all 4 configurations (a daily averaged value of the total demand $Q_m$ of 14.07 litres/s). DDA runs are comparable for W1&WTa (where $Q_m = 14.47\ l/s$) and W2&WTa (where $Q_m = 14.56\ l/s$). For the other DDA runs, the maximum total demand reaches 29.42 l/s for W1&WTb (where $Q_m = 17.37\ l/s$) and exceeds 31 l/s for W2&WTb (where $Q_m = 20.7\ l/s$). Moreover, DDA run for W1&WTb shows few sudden peaks and drops, possible due to instabilities.

The resulted head variation at the water tower is presented in table 2, in meters. Then, the variation of the available demand at the most disadvantaged consumer, C, is presented in table 3, in litres/s.

Table 1. Total flow rate [litres/s] provided to the distribution network through Pipe 1.
Table 2. Water tower head [m], illustrating the water level variation.

| DDA with emitters | PDA |
|-------------------|-----|
| W1 & WT\text{a}   |     |
| W2 & WT\text{a}   |     |
| W1 & WT\text{b}   |     |
| W2 & WT\text{b}   |     |

Table 3. Available demand [litres/s] at the most disadvantaged consumer, denoted C.

| DDA with emitters | PDA |
|-------------------|-----|
| W1 & WT\text{a}   |     |
| W2 & WT\text{a}   |     |
| W1 & WT\text{b}   |     |
| W2 & WT\text{b}   |     |
The WT head variation from table 2 shows that for the full well model W1, the water tower is emptied at peak hours and filled up to its maximum level (264 m.a.s.l.) outside peak hours; PDA runs give a shortage in the emptying process with respect to DDA runs. For the simplified well model W2, the water level in WT is kept almost constant (at its maximum value); there is a slight level oscillation at peak hours for WTa (2 pipes connection), while the WT level is unchanged for WTb (single pipe connection) after a sudden initial filling. It must be highlighted that for W2&WTb, excepting the initial time moments, the water pumped is sent directly to the network, through Pipe 1. Thus, for W2&WTb, the WT loses its buffer role (its presence in WDS becomes unnecessary), meaning that the WDS losses the water tower main advantages in overtaking the peak flows and reducing the operating costs through pumping for storage purposes at off-peak hours.

In table 3, the trend of the available demand at node C follows the total flow rate $Q_1$ from table 1. The pressure variation at the consumer C is presented in table 4, in mWC. A comparison of the mean, maximum and minimum values of $Q_1$ and $Q$ for all 8 simulations is presented in table 5.

Table 4. Available pressure [mWC] at the most disadvantaged consumer, denoted C.

|          | DDA with emitters | PDA |
|----------|-------------------|-----|
| W1&WTa  | ![Graph](image1)  | ![Graph](image2) |
| W2&WTa  | ![Graph](image3)  | ![Graph](image4) |
| W1&WTb  | ![Graph](image5)  | ![Graph](image6) |
| W2&WTb  | ![Graph](image7)  | ![Graph](image8) |

Table 5. Mean, maximum and minimum total flow rate $Q_1$ and available demand $Q$ at node C, in l/s.

|          | DDA with emitters | PDA |
|----------|-------------------|-----|
| W1&WTa  | 14.47 24.58 5.37 0.080 0.14 0.03 | 14.07 24.52 5.37 0.08 0.14 0.03 |
| W2&WTa  | 14.56 24.79 5.37 0.081 0.14 0.03 | 14.07 24.52 5.37 0.08 0.14 0.03 |
| W1&WTb  | 17.37 29.42 6.23 0.097 0.16 0.03 | 14.07 24.53 5.38 0.08 0.14 0.03 |
| W2&WTb  | 20.70 31.1 6.23 0.114 0.17 0.03 | 14.08 24.53 5.38 0.08 0.14 0.03 |

In accordance with the total flow rate from table 1, all PDA runs lead to similar values of the available demand at the end-users (table 3). The results provided for WTa (2 pipes connection) using
DDA and PDA are comparable with respect to the available demand (which varies according to the demand pattern), while differences are visible in table 3 for WTb (single pipe connection).

A comparison of the mean, maximum and minimum values of the available pressure at the most disadvantaged consumer C is presented in table 6 for all 8 runs. With respect to the DDA results, it must be pointed out that the available pressure varies according to the pressure variation at the control valve V, where minor losses were added (to mimic the demand pattern). The minimum available pressure for DDA is greater than the value $p_{\text{min}} = 0$ set for PDA, so a minimal available demand of 0.03 litres/s is ensured through emitters at off-peak hours.

As already mentioned when discussing about the water tower head (table 2), for W2&WTb case the water is no more pumped into WT, but sent directly to Pipe 1. Moreover, for both WTb cases, the value of the maximum pressure computed using PDA is far too increased, reaching about 7.6 bar. Obviously, the pump must be changed for WTb, to decrease the discharge pressure by more than 4.6 bar (46 mWC). High instabilities appear for W1&WTb, where PDA run leads to successive drops of the available pressure, while DDA leads to few sudden high peaks and drops of the available pressure.

| Table 6. Available pressure $p$ [mWC] at node C: mean, maximum and minimum values. |
|----------------------------------------|-------|--------|-------|-------|--------|-------|
| DDA with emitters                      | PDA   |        |       |       |        |       |
|                                       | $p_m$ | $p_{\text{max}}$ | $p_{\text{min}}$ | $p_m$ | $p_{\text{max}}$ | $p_{\text{min}}$ |
| W1&WTa                                | 10.89 | 26.52  | 1.26  | 27.88 | 28.92  | 26.05 |
| W2&WTa                                | 11.07 | 26.97  | 1.26  | 28.11 | 28.89  | 26.81 |
| W1&WTb                                | 14.57 | 38.02  | 1.69  | 54.34 | 76.55  | 26.54 |
| W2&WTb                                | 21.45 | 42.50  | 1.69  | 70.17 | 76.55  | 26.88 |

Further, the daily cost $C$ of the energy consumed for pumping is computed (in EUR) based on a daily mean price of 0.08 €/kWh [15], [16]. The values computed for the total daily energy $E$ (in kWh) consumed for pumping and its cost $C$ are compared for all 8 runs in table 7; the percents of pump utilization during 24 hours are also inserted. For all configurations, PDA gives lower values of $E$ and $C$, with respect to DDA. The greatest energy and cost values correspond to WTb. The most expensive configuration is W2&WTb (the simplified well model & WT linked to WDS by a single pipe).

| Table 7. Pump utilization [%], total daily energy $E$ [kWh] consumed for pumping and cost $C$ [€]. |
|----------------------------------------|-------|--------|-------|--------|-------|-------|
| DDA with emitters                      | PDA   |        |       |       |        |       |
|                                       | Pumping (%) | $E$ (kWh) | $C$ (€) | Pumping (%) | $E$ (kWh) | $C$ (€) |
| W1&WTa                                | 68.2  | 606.2  | 48.5  | 68.6  | 600.7  | 48.1  |
| W2&WTa                                | 100   | 530.5  | 42.4  | 100   | 513.3  | 41.1  |
| W1&WTb                                | 76.8  | 819.2  | 65.5  | 79.5  | 771.7  | 61.7  |
| W2&WTb                                | 100   | 1058.1 | 84.7  | 100   | 913.3  | 73.1  |

4. Conclusions

The operation of a rural water distribution system was modelled in EPANET 2.2, using two methods: Demand Driven Analysis with emitters, and Pressure Driven Analysis. In the attempt to minimize numerical instabilities, the groundwater well (the water source) was modelled both with variable (W1), and with constant hydrodynamic level (W2); also, the water tower (that feeds gravitationally the system) was connected to the WDS either using 2 pipes (WTa), or a single pipe (WTb).

Despite the numerical advantages in reducing instabilities provided by the connection of the WT to the WDS through a single pipe, there is no interest in using the WTb solution, where the water tower plays no role in the supply process for both DDA and PDA runs (the pump operates non-stop to feed the network directly); moreover, the pump must be changed for PDA to decrease the discharge pressure. The values of the energy consumed for pumping and cost sustain the above conclusion.

The simplified configuration W2&WTa is less realistic, although it seems to be appealing: it ensures the lowest cost, despite the fact that the pump runs 24 hours (but it runs at high efficiency).
Obviously, the configuration W1&WTa (where the well operates with variable level and the water tower is linked by 2 pipes to the system) is trustworthy, thus recommended to be adopted to model the WDS, preferably using PDA. Solutions like W1&WTa can be considered when modelling more complex WDS, e.g. urban size networks, based on groundwater supply and storage tanks.

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