Modelling of a drip irrigation system operation for greenhouses rose cultivation using PDD in EPANET 2.2

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Abstract. The present study focuses on the operation of a drip irrigation system for greenhouses rose cultivation in Adunatii-Copaceni, Giurgiu County, Romania. The numerical modelling of the irrigation system was performed in EPANET 2.2, using the pressure driven demand model. The pumping schedule fits the real operation, where five greenhouses are irrigated successively each morning, directly through pumping from a groundwater source. Fertigation is applied for each greenhouse every 5 days, in the evening, through pumping from a storage tank. Despite the hydraulic assumptions adopted to model the groundwater well and dripper lines, the computed results match the values of the outflow rates measured for the dripper lines of the real drip irrigation system. Simulations are useful to investigate, at no cost, different scenarios attached to the operation of the studied drip irrigation system.

1. Introduction

The paper focuses on the numerical modelling of the operation of a drip irrigation system for greenhouses rose cultivation. The case study is a drip irrigation system built for 5 greenhouses of roses; the system is located in southern Romania, in Adunatii-Copaceni, Giurgiu County.

Greenhouses irrigation relies on watering scheduling that must be properly established, to improve both crop production and quality [1], [2]. With respect to other irrigation methods, drip irrigation increases the water use efficiency, while fertigation (the injection of fertilizers into the irrigation system) reduces the required amount of fertilizers [3], [4]. Based on prescriptions for the soil-grown rose crop in drip irrigated greenhouses [4], [5], and on the experience validated for the targeted local climate and local sand-based soil, for the above case study the daily watering schedule corresponds to the irrigation of each greenhouse one hour, each morning. Fertigation is scheduled each evening for a single greenhouse; a 5 days cycle is needed to provide the selected fertilizer to all greenhouses.

The operation of the above drip irrigation system was modelled in EPANET 2.2 [6]. The case study is described in Section 2, the proposed numerical model is presented in Section 3, while results are discussed in Section 4.

2. Case study description

The studied drip irrigation system is located at an elevation of 91 m.a.s.l. The system incorporates most of the usual components listed in the literature [7], namely (figures 1 and 2):
• a pumping station (PS), with two pumps – a submersible borehole pump denoted P1 (rated parameters: 7 m³/h (1.94 litres/s) flow rate; 31 m pumping head; 65.5% efficiency; 0.9 kW absorbed power) and a self-priming pump denoted P2 (rated parameters: 7 m³/h flow rate; 15 m pumping head, 53% efficiency, 0.54 kW absorbed power);
• a groundwater well denoted W (15 m deep to the hydrodynamic water level), from where the water is pumped by P1;
• a storage tank denoted T (a horizontal cylinder 2.2 m long, of 1.52 m inner diameter; 4 m³ total active capacity), placed aboveground, from where water is pumped by P2;
• main pipes (of 32 mm nominal diameter) that connect PS to a distributor (D) with 2 inlets and 3 outlets, from where the water is conducted to the greenhouses by branched sub-main pipes (of 32 mm diameter); all main/sub-main pipes and D are made from high-density polyethylene (HDPE);
• different valves (non inserted in figure 2) that control the system operation;
• five greenhouses, of different sizes: three of medium length (60 meters long and 8 m wide, denoted GH1, GH3 and GH4), then a longer one (70 m long and 8 m wide, denoted GH2) and a shorter one (50 m long and 8 m wide, denoted GH5);
• a total number of 50 dripper lines (flexible drip pipes of 16 mm diameter, and same length as the greenhouse); within each greenhouse, the roses are irrigated through 10 parallel dripper lines, supplied upstream by a HDPE distribution line; each dripper line has drip holes every 10 centimetres; the rated demand of 1 litre/h per hole leads to 3 different values of the total demand for the greenhouses; thus, for the longest one (GH2) the total demand is 7 m³/h (1.94 l/s), for each of the medium ones (GH1, GH3, GH4) the total demand is 6 m³/h (1.67 l/s), while for de shortest one (GH5), the total demand is 5 m³/h (1.39 l/s).

To reduce the PS size and benefit of the optimal flow rate provided by the existing groundwater well, the irrigation with fresh water (pumped directly from the well by pump P1) is not performed simultaneously for all 5 greenhouses.

**Figure 1.** Irrigation system top view: pumping station PS and five greenhouses of roses, denoted from GH1 to GH5 (depicted from Google Earth [8] – Giurgiu, Romania, 44°17’02”N 26°00’16”E).

**Figure 2.** Irrigation system scheme [9] (dimensions in meters): groundwater well W; pumps P1 and P2; storage tank T; distributor D; greenhouses of roses GH1-GH5, with 10 dripper lines each.
Thus, the irrigation with fresh water is performed daily in the morning, successively for each greenhouse during one hour, starting with GH1 up to GH5. The following pumping schedule is set to irrigate the studied system with the pump P1: watering starts at dawn for GH1 (from 6 am to 7 am), continues with GH2 (from 7 am to 8 am), and so forth up to GH5 (from 10 am to 11 am).

The pumped water is directed to a certain greenhouse using shutoff valves, placed downstream on the sub-main pipes, at the inlet of each greenhouse; secondary shutoff valves are also installed upstream of each dripper line, but they are kept open (figure 3).

Figure 3. Photos of the system: (a) HDPE distribution line (supplied left side by a sub-main pipe) feeding parallel dripper lines (upstream on each dripper line, the secondary shutoff valve is open); (b) zoom on the tee fitting connecting the sub-main pipe to the distribution line; (c) parallel dripper lines.

As previously stated, roses need nutrient supply: each plant needs 1 gram of nutrient substance once per day [4]. For the selected case study, roses fertilization is done with one of the following 5 essential substances: ammonium nitrate; calcium; magnesium; potassium sulphate; urea. Each greenhouse contains in average about 1500 plants, so 1.5 kg of the selected fertilizer must be dissolved in water (in the storage tank T) and spread through greenhouse's dripper lines. Due to the limited capacity of tank T, the selected fertilizer is spread within a single greenhouse per day, starting with GH1 up to GH5, so a period of 5 days corresponds to a single type of fertilizer. A cycle of 25 days is needed to spread all 5 substances.

It must be highlighted that any water quality analysis (related to the fertilizer rate of reaction) is beyond the purpose of the present paper. Thus, the fertigation will be analysed here only from the hydraulic point of view, for a total duration of 120 hours (meaning 5 days).

Within the studied system, the fertigation starts in the evening, at 7 pm. Before fertigation, at 6 pm, the pump P1 starts to fill the storage tank T (28 minutes of pumping are enough to fill the entire tank, of 4000 litres active capacity). Starting from 7 pm, the water with dissolved nutrient substance is pumped by P2 from the tank T, up to the targeted greenhouse; depending on the greenhouse size and position with respect to PS, 35 to 49 minutes of pumping are needed to spread by dripping the entire content of tank T.

3. Drip irrigation system numerical model

Within this paper, the hydraulic analysis of the above drip irrigation system was performed in EPANET 2.2 [6], using the pressure driven demand model. This new version of EPANET, released in May 2020, includes two nodal demand models, each attached to a certain type of hydraulic analysis:

- a fixed demand model, allowing to run a demand driven analysis (DDA), where a fixed (imposed) value of the nodal demand is ensured irrespective of the nodal pressure;
- a pressure driven demand (PDD) model, allowing to run a pressure driven analysis (PDA), where the delivered nodal demand depends on the nodal pressure [10]-[12].

DDA was the only hydraulic analysis implemented in the previous version: EPANET 2.0, officially released in 2000 [13]. It must be highlighted that DDA allows to model the pressure driven outflow rate at orifices/nozzles/sprinklers, using emitters.

DDA with emitters is usually used to model sprinkler-based irrigation systems (e.g. centre pivot irrigation systems [14]), as well as drip irrigation systems, where orifices (drip holes) deliver pressure-dependent outflows. Due to specific operating conditions, the drip irrigation system considered in this paper was modelled using PDA. Within PDA, the available nodal demand $Q$ depends on the available nodal gauge pressure $p$ as follows [15]:

$$
Q = Q_r \text{ for } p \geq p_r
$$

$$
Q = Q_r \sqrt{\frac{p - p_{\text{min}}}{p_r - p_{\text{min}}}} < Q_r \text{ for } p_{\text{min}} \leq p < p_r
$$

$$
Q = 0 \text{ for } p < p_{\text{min}}
$$

where $Q_r$ is the required nodal demand (full demand), $p_r$ is the required nodal gauge pressure allowing to deliver $Q_r$ (for the case study, $p_r = 2$ mWC) and $p_{\text{min}}$ is the minimal nodal gauge pressure ensuring an outflow rate (for the case study, $p_{\text{min}} = 0.1$ mWC); below $p_{\text{min}}$ there is no outflow.

The layout of the drip irrigation system built in EPANET 2.2 is presented in figure 4. The configuration of the numerical layout corresponds to the real one (figure 2), within some assumptions (further described) with respect to the dripper lines and to the groundwater well. The numerical model from figure 4 includes the following valves: check valves (CV) on the discharge pipes inside the pumping station PS; shutoff valves V and VT that control the discharge of pump P1, either directly to the network (V open & VT closed), or to the storage tank T (V closed & VT open); shutoff valves denoted from V1 to V5, attached to the distribution line of each greenhouse, from GH1 to GH5. Valves V1-V5, V and VT are set as throttle control valves in EPANET, operating fully open or closed, upon time-based commands implemented through control structures (“simple controls” [6], [13]).

![Figure 4. Irrigation system numerical model](image)

The studied system contains 50 dripper lines (10 per greenhouse), with many drip holes, namely: 600 orifices per dripper line within GH1, GH3 and GH4; 700 orifices per dripper line within GH2, and
500 orifices per dripper line within GH5. The rated demand of 1 litre/h per hole leads to a total demand per dripper line of: 600 litres/h in GH1, GH3, GH4; 700 litres/h in GH2; 500 litres/h in GH5. The total demand per dripper line (denoted \( Q_d \)) is uniformly distributed along the pipe, so by lumping half of \( Q_d \) at the two terminal nodes of the pipe, the dripper line can be modelled by an equivalent common pipe (without drip holes) with 0.5\( Q_d \) set as nodal demand at each of its two extremities [16]. Based on this simplified assumption, each dripper line is modelled in EPANET as an equivalent pipe, for which a required nodal demand \( Q_r \) (base demand [6]) is set at both start-node and end-node: \( Q_r = 0.0833 \text{ l/s at GH1, GH3, GH4; } Q_r = 0.0972 \text{ l/s at GH2 and 0.0694 l/s at GH5 (figure 4).} \)

To simulate the variable water level of the groundwater source, an equivalent model is adopted for the well, by replacing the real well with the following 3 components [17], [18] (figure 4):

- a reservoir \( R \) of 78 m constant head; this head value equals the hydrostatic level \( H_s \) of the aquifer (for the case study, \( H_s = 78 \text{ m.a.s.l.} \));
- a general purpose valve GPV, of 0.5 m diameter (as the real well), operating upon the drawdown – flow rate curve \( \Delta H = f(Q) \) plotted in figure 5, derived from Dupuit formula [17]:

\[
Q = \pi K \left( H_s - \sqrt{K H_s} \cdot \Delta H \right) \ln \left( \frac{575 \Delta H \sqrt{KH_s}}{r} \right)
\]  

(2)

where the extracted flow rate \( Q \) is related to the drawdown \( \Delta H = (H_s - H_d) \), defined as difference between the hydrostatic level \( H_s \) and the hydrodynamic level \( H_d \); the hydraulic conductivity of the aquifer is \( K = 8.2 \times 10^{-6} \text{ m/s} \); the optimal value of \( H_d \) is 76 m.a.s.l. (15 m below the ground level) for the optimal extracted flow rate of 1.67 litres/s;

- a water tank denoted \( W \), with the initial water level set 15 m above the bottom of the tank; this initial water level in the tank corresponds to the optimal value of \( H_d \) in the well; the diameter of 0.5 m, and the active capacity of the tank \( W \) match the values of the real well.

![Figure 5. Drawdown – flow rate curve \( \Delta H(Q) \).](image)

![Figure 6. Capacity curve of storage tank T.](image)

![Figure 7. Head – flow rate curve of pump P1.](image)

![Figure 8. Head – flow rate curve of pump P2.](image)
As previously mentioned, the storage tank T has a cylindrical shape and is installed horizontally. The available water volume inside the tank T depends on the water height with respect to the bottom of the tank – the resulting capacity curve is presented in figure 6. When the water level reaches its maximum value (of 1.52 m), the total active capacity of $4 \text{ m}^3$ is attained. At the beginning of the simulation, the tank is empty, thus the initial water height is set equal to 0. The tank is filled daily using the pump P1, set open from 6 pm to 6:28 pm.

The head - flow rate curves of pumps P1 and P2 are presented in figures 7 and 8. As already stated, to perform the daily irrigation with fresh water, the pump P1 is set open each morning, from 6 am to 11 am. The pump P2 is set open less than one hour per day, to perform fertigation each evening, starting at 7 pm; the pump P2 stops when the tank T is emptied, namely at 7:40 pm for GH1, GH3 and GH4, at 7:35 pm for GH2, and at 7:49 pm for GH5.

4. Results and discussions

The pressure driven analysis of the studied drip irrigation system was performed for 5 days, a period that corresponds to the fertigation of all 5 greenhouses using a single type of nutrient substance. The following time settings were applied in EPANET 2.2: total duration of 120 hours, hydraulic time step of 1 minute, and clock start time 0:00 (midnight).

The pumping schedule (start/stop commands for each pump), together with the shutoff valves status (open or closed), were defined using time dependent if-then statements – a total of 114 “simple controls” were set in EPANET to model the operation of the studied hydraulic system.

To exemplify the results, the variation of the following hydraulic parameters versus time is plotted further, namely:

- the pumping head of both pumps P1 and P2 (figure 9) and their discharge (figure 10);
- the head of the tank W that models the well (figure 11), corresponding to well's water level;
- the head of the storage tank T used for fertigation each evening (figure 12);
- the total flow rate delivered to each greenhouse GH1-GH5 through the corresponding shutoff valve V1-V5 (figure 13);
- the available demand at the end-nodes of the dripper lines within each greenhouse GH1-GH5 (figure 14).

![Figure 9. Pumping head variation for pump P1 (blue lines) and pump P2 (green lines).](image-url)
Figure 10. Discharge variation for pump P1 (blue lines) and pump P2 (green lines).

Figure 11. Head variation for the tank W that models the groundwater well: the water level decreases below the optimal hydrodynamic level when the pump P1 operates.

Figure 12. Head variation for the storage tank T: the tank is filled just before the fertigation, then is emptied when the pump P2 operates.
As seen in the graphics from figures 9-14, the numerical model mimics the pattern of the operation of the studied drip irrigation system, as it was described in Section 2. The numerical results match the limited amount of data measured in situ.

For example, during the morning irrigation performed with pump P1, the delivered flow rate (available demand) was measured in situ (using the volumetric method) for several drip holes on a mid-dripper line inside the greenhouse GH5: the measured outflow rate varied from 0.9 to 1 litre/h (1 litre/h mostly). It must be pointed out that GH5 is the most remote greenhouse with respect to the pumping station, so its end-nodes are viewed as the most disadvantaged consumers – nevertheless, the available nodal pressure is sufficient to deliver the required nodal demand.

For the greenhouse GH5, the available demand computed in EPANET 2.2 at the start-node, as well as at the end-node of any dripper line equals 0.0694 litres/s, yielding a total value of 0.139 l/s (500 litres/h) delivered per dripper line. By distributing the total computed value of 500 litres/h along the dripper line with 500 drip holes, one get 1 litre/h per hole, which fits the measured values.

We recall that each dripper line was modelled based on the assumption that the demands distributed along the pipe are replaced by two lumped demands at the terminal nodes of the pipe. Despite the encouraging concordance between the computed results and in situ measurements, the numerical equivalence adopted for the dripper lines must be thoroughly studied further, because it was proved that errors affect the computed head losses for the above assumption [19].

Figure 13. Total flow rate variation at valves V1-V5, at the inlet of greenhouses GH1-GH5.

Figure 14. Available demand variation at the end-nodes of dripper lines in greenhouses GH1-GH5.
5. Conclusions
The paper focuses on the operation of a drip irrigation system for soil-grown rose cultivation in greenhouses. The case study is a drip irrigation system built for 5 greenhouses of roses in Romania. The hydraulic analysis of the studied system was performed in EPANET 2.2, using the pressure driven demand model, over a period of 5 days (120 hours duration), with a hydraulic time step of 1 minute.

The pumping schedule fits the real operation, where 5 greenhouses are irrigated with fresh water successively each morning (through pumping from a groundwater well), while fertigation is applied for each greenhouse every 5 days, in the evening (through pumping from a storage tank, where a fertilizer is dissolved in water). Although hydraulic assumptions were adopted to model the groundwater well and dripper lines, the computed results match the values of the outflow rates measured for the dripper lines inside the greenhouses of the real system.

Simulations can be used to investigate, at no cost, different scenarios attached to the operation of the studied drip irrigation system. Further research can be conducted, for example, to depict the system behaviour for different values of the initial water level in the groundwater well (which is the single water source of the system). The influence of an initial water level lower than the one corresponding to the optimal hydrodynamic level is important, knowing that drought is a serious threat for the rose crop.

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