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ON THE WEAKNESSES AND LIMITATIONS OF EPANET AS REGARDS ENERGY

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ABSTRACT

With more than 1,500 citations in ranked journals and hundreds of thousands of downloads, EPANET is the benchmark software for analysis and design of pressurised water distribution networks. User-friendly, powerful, reliable and its public domain use has spread throughout the world. However, from an energy standpoint its capacity is limited to the point where, in certain circumstances it can supply erroneous results. This is understandable because on one hand its main aim was to model water quality, and on the other hand, because it was conceived and developed towards the end of the last century before people started talking about the water- energy nexus. Increases in the cost of energy and the need to limit greenhouse gas emissions, however, have made energy efficiency a primary and inescapable objective. As the transport of pressurised water is a big consumer of energy, it seems convenient for EPANET users, particularly for those who applied this software to pressurized irrigation networks, to understand, as far as energy is concerned, its weaknesses and limitations which, at the end, is the aim of this paper.

Keywords: water management; water supply systems; water network; hydraulic simulation; water and energy

INTRODUCTION

The first version of EPANET, version 1.1, was released in 1993 (Rossman, 1993) and seven years later, version 2.0 (Rossman, 2000) appeared which is still the latest version of this software package. Eleven years later, the imminent appearance of version 3.0 was announced (Rossman, 2011), which for whatever has not been released. In fact, there is a recent and very welcomed international attempt led by Dr. Boccelli (University of Cincinnati) who, is saddled with the responsibility to update EPANET has addressed an open letter to the international Water Distribution Systems Analysis (WDSA) community entitled “Announcement of an open source EPANET initiative”. If successful, it should be great news for all EPANET users.

The following analysis of the weaknesses and limitations of EPANET as regards energy, should therefore be referred to the present version 2.0. It must be said that, from an energy standpoint, few changes were added to the original for the second version of the software. The most important aspect being the inclusion of schedule patterns for the cost of energy, and allowing the study of total energy expenditure, based on pumping schedule arrangements. Neither does the awaited version 3.0 promises improvements as regards energy, despite thet, some enhancements was announced in the modelling of the evolution of water quality, in hydraulics and in the interface (Rossman, 2011). There is just one energy collateral enhancement, which is the possibility of pump behaviour modelling with third degree polynomials, an improvement that should be welcomed because minor errors (see Table 6, pump efficiencies, periods 2 and 3.2, with pump rotating at its nominal speed) could be avoided. This will overcome another well known EPANET’s drawback: positive slopes are not allowed along the head – flow characteristic pump curve, but they do happen often in practice (particularly in axial flow pumps).

In order to understand the lack of attention EPANET pays to energy-based analysis, it is important to place the program in its historical context. In fact, the first article to expressly cite the water-energy nexus (Gleick, 1994) is contemporary with version 1.1 of EPANET, while the first report quantifying energy linked to the urban water network (CEC, 2005) is later than the actual version of EPANET, a report which makes the water-energy nexus a primary objective. The activity of EPANET`s promoter, the Environmental Protection Agency (EPA), reflects this, because they develop programs and tools to this end. Those related directly to the water industry stays on its own (EPA, 2008; EPA, 2012), while the programs with a wider scope (e.g., the promotion of efficient energy devices with its corresponding labeling) are developed in collaboration with other institutions (EPA, 2009). One of its latest publications (EPA, 2013) demonstrates the attention that EPA currently pays to the water-energy nexus. This is understandable. In the USA (United States of America), electricity use accounts for 25–40% of the operating budgets for wastewater (NYSERDA, 2008), while drinking water and wastewater systems account for 3–4% of the total consumption (Eisenberg, 2012). These figures are even higher in California (Wolff, 2010) where just the transport of pressurised water accounts for 6% of total energy consumption (Water in the West, 2013). As a matter of fact, in Europe the agriculture energy demand is on average 2% of the total energy consumption (MOE, 2011), a figure that in more agricultural Mediterranean, southern countries, such as Spain, rises up to 3% (Corominas, 2010).

This paper describes and shows, through a case study, the energy weaknesses of EPANET. Lastly, in order to to adapt the most worldwide used water network software to present needs, some improvements are suggested.

THE EPANET ROLE IN THE PRESSURIZED URBAN AND IRRIGATION SYSTEMS ANALYSIS

EPANET was conceived in a bid to track the evolution of the water quality from the source (injection point) to the customer’s tap (user point). This general interest allowed EPA to allocate public funds to develop a software package that, at the end, will compete with commercial software programs promoted by companies that supported the State with their taxes.

The hydraulic analysis, including the extended period simulation, is a necessary prerequisite in performing the water quality analysis. In all, the EPA developed a complete software package to control the water quality along the system and, at the same time, it models the hydraulic system behavior. A collateral resulting from the very first moment, attracted much more attention of the hundreds of thousands EPANET’s users, for example the water network sectorization study is one of the most widespread uses of the program (Renaud et al. 2014; Di Nardo et al. 2014), while for quality purposes, its reason being thet the program is rarely used. In the irrigation field, where all agricultural constituents (such as nitrogen) are non-reacting, their movement and fate within the distribution network does not change at all.

Even not being conceived to help them, agricultural designers of pressurized irrigation systems immediately became aware that EPANET should be a useful tool to facilitate their daily work. User-friendly, reliable, powerful and zero cost, are strong reasons to attract professionals of a field (with much less economic potential, than those of the water industry) that can easily pay for powerful and updated commercial packages. Even not being conceived to simulate irrigation network behaviours on demand schedules (to perform such analysis other software packages, (Calejo et al. 2008), are more appropriate) is the most used program in the world of agricultural engineering, specially in developing countries (Arora & Jaiswal, 2013; Abdulrazzaq & Jahad, 2014) owing to its accessibility, reliability and is completely free of cost.

However, as said before, from an energy standpoint, this referent software package has limited capability to the point where in certain circumstances it can even supply erroneous results. Being the energy issues of increasing importance in the urban and agricultural areas, users must be fully aware of the EPANET inconveniences, to this regard. In what follows, firstly, major and minor EPANET energy's drawbacks are listed, later some improvements were suggested and finally a case study of an irrigation network conceived to show the previously described handicaps, is presented.

MAJOR ISSUES

The errors which can mislead program users are firstly mentioned.

EPANET calculates incorrectly the efficiency of variable speed pumps and, thus, power.

This error has already been the focus of a technical note (Marchi & Simpson, 2013). Although, this issue is well documented, details of where the error lies and how it is transmitted to other results (power and energy expenditure) will be given in this paper to help engineers avoid it.

EPANET ignores the natural energy.

The transportation and distribution of pressurised water are carried out at the cost of the elastic (water and pipe) energy. This energy can proceed from two sources, natural (or gravitational) supplied by tanks and shaft energy supplied by pumps. EPANET only recognises the latter energy. There is no energy report on gravitational systems and it only accounts for the energy which the pumps supply in mixed systems (natural and pumped energy). Therefore, when the energy is supplied (partially or totally) by a tank, EPANET's results do not allow energy audits to be performed.

EPANET miscalculates pumping expenditure when the simulation is not carried out within 24 hours.

In practice, it is relatively common to find pressurised systems operating daily for less than 24 hours. This applies to intermittent water supplies, a frequent scenario in developing countries and habitual in pressurised irrigation networks. If the number of daily operational hours, n_t, is less than 24, EPANET increases energy expenditure to the factor of $24/nt$. The error is repeated for all simulation periods which are not multiples of 24 hours. In irrigation systems, water is typically supplied for less than 24 hours per day. This error once more is an evidence that shows the program was conceived for urban water networks where, except for the intermittent supplies of the developing countries, the network operates 24 hours per day and 365 days per year and therefore, this error has no impact.

MINOR ISSUES

Energy aspects that should be considered in order to adapt EPANET to present day needs are mentioned below.

Concerning the energy consumption

The kWh which are really consumed in pumping stations (the real power demanded and the energy effectively consumed) are not solely dependent on pumping efficiency. The efficiency of electric motors and of variable speed drivers, which in certain circumstances can cause significant energy loss should it be considered; this is an important and well known issue (Burt et al. 2008).

Concerning tariffs

EPANET only contemplates a single value for power contract costs while, actually time of day rates and seasonal variations applies, as it occurs with the price of energy.

Concerning energy intensity

EPANET calculates the energy intensity (kWh/m^3) as referred to the volume supplied to the system. As it is more representative if referred to the registered volume (consumed by the users), especially in highly leaky systems, it is convenient to provide simultaneously both energy intensities.

Concerning the energy expenditure in systems with several pumping stations

EPANET, without any limitation in the number of nodes and lines in the system, has formidable powers of calculation. Networks of a significant size can be fed by different pumping stations which are subject to different tariff regimes, given that they currently depend on the maximum contracted power. The programme, in its present state, contemplates a single tariff for the whole system.

POTENTIAL IMPROVEMENTS

The first required improvement should be the correction of the preceding drawbacks, which included the adequate head - flow pump modeling, irrespective of its characteristics. Besides some new capabilities could be incorporated. The description of two of the most relevant ones are as follows:

Energy assessment. Using the EPANET input data and their results, very valuable information can be obtained from an energy point of view, for example, the ideal and real network performance. By comparing these values, the system's margin of energy efficiency improvement can be estimated. Furthermore, assessing the relevance of topographical energy permits us to identify the pipes in which this energy can be recovered by installing Pumps as Turbines (PATs) or, if that is not an option, dissipating it by pressure reducing valves (Cabrera et al. 2014).

Energy audit can also be performed to discover where the system is more inefficient. The audit, which matches the energy entering and leaving the system, can identify and quantify the losses. These can be caused by friction (in pipes and valves), pumping station inefficiencies and leaks which are a sum of the energy embedded in the water losses and the additional friction in the pipes, a consequence of the greater flow required (Cabrera et al. 2010).

Currently, the Programmer's Toolkit API (Rossman, 1999) allows these calculations to be performed but, not directly. As energy efficiency becomes more and more important, it would be desirable to automate all of these calculations.

CASE STUDY

Figure 1 and Table 1, correspond to a system designed to show the weak points of EPANET as mentioned above. It is an irrigation network divided into three sectors, each of them being active for six hours. The third sector irrigates in two three-hour periods. The system operates for a total of 18 hours a day. Both pumps are fed by a tank at a constant level (30 m).

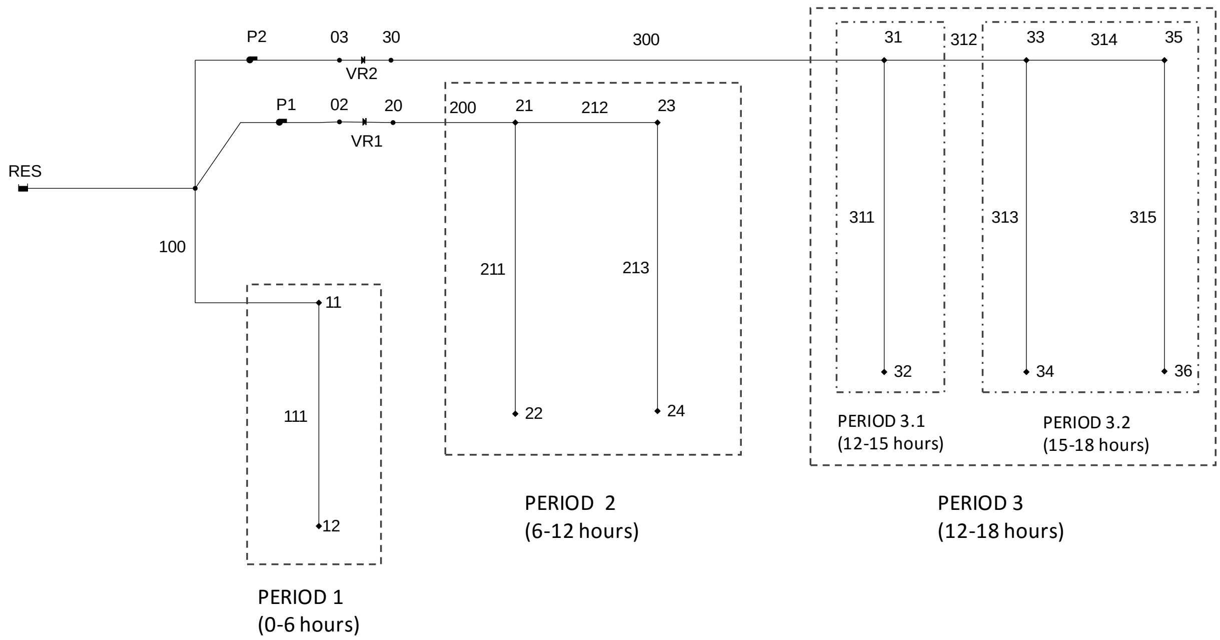

Figure 1. Network layout

Level zero is assigned to the node with the lowest elevation (node 12). Service pressure is 10 m, the elevation of the tank 30 m, and the roughness of the pipes 0.1 mm. Table 1 depicts the network characteristics and Table 2 shows those of the pumps which guarantee minimum pressure at high elevations. Leaks are modelled through node's emitters.

Table 1. Pipe and node data

Pipe	Length (km)	Diameter (mm)	Node	Elevation (m)	Base Demand (l/s)	Emitter Coefficient ($m^{3-\alpha}$ /s)	Period of Demand (hours)
100	0.5	250	11	10	10	0.121221	0-6
111	0.5	200	12	0	20	0.026605	0-6
200	1.0	300	21	45	10	0.212212	6-12
211	0.5	175	22	50	15	0.058170	6-12
212	0.5	250	23	50	10	0.108260	6-12
213	0.5	175	24	55	15	0.083563	6-12
300	3.0	300	31	75	20	0.390568	12-15
311	0.6	200	32	80	20	0.056493	12-15
312	0.5	300	33	80	20	0.098951	15-18
313	0.6	200	34	85	20	0.053649	15-18
314	0.5	250	35	85	20	0.098423	15-18
315	0.6	200	36	90	20	0.091827	15-18
			RES	30	-	-	-

Each pumping station is on for six hours (the irrigation period). The highest elevated sector (sector 3) is fed by pumping station P2 equipped with a variable speed driver to adjust the system's pressure requirements. For the first three hours, it rotates at 75% of its nominal speed, subsequently rotating at 100% (Table 2). The pumps are timed to switch on and off.

Table 2. Pump's characteristics

PUMP	Head (H) – flow (Q) curve	Efficiency curve	Operating Schedule	Operating characteristics	Rotation speed (N/N_o)
P1	$H_1=53.33 - 0.003704\ Q^2$	$\eta_1=-0.0164\ Q^2+1.8708Q+19.929$	6-12 h	61.13 l/s; 39.49 m.w.c.	1
P2	$H_2=136 - 0.00369\ Q^2$	$\eta_2=-0.0096\ Q^2+1.6707Q+11.126$	12-15 h	52.09 l/s; 66.49 m.w.c.	0.75
			15-18 h	106.13 l/s; 94.43 m.w.c.	1

The daily water balance in each sector (with the apparent losses included in the amount of water consumed) is provided in Table 3. Leakages are held to be pressure-dependent, and modelled by nodal emitters (exponent α=1.1) with coefficients which are proportional to the length of the pipes converging on it (see Table 1).

Table 3. Water audit

	SECTOR 1 (0-6 hours)	SECTOR 2 (6-12 hours)	SECTOR 3 (12-15 hours)	TOTAL (0-18 hours)
$V_{injected}$ (m^3/day)	737.42	1320.41	1708.77	3766.61
$V_{consumed}$ (m^3/day)	648	1080	1296	3024
$V_{leakage}$ (m^3/day)	89.42	240.41	412.77	742.61
$\eta_{volumetric}$	87.9%	81.8%	75.8%	80.2%

By simulating the day-to-day operation of the system (18 hours), with a hydraulic interval of 1 hour, the global balance between the power supplied and consumed (energy audit) is calculated by means of the results provided by EPANET and following the methodology previously described (Pardo et al. 2010). The calculation of the energies involved in the system are based on the equations shown in Table 4.

Table 4. Energies involved in the energy audit

ENERGY CONSUMED kWh	Useful energy	Useful energy delivered to users	$E_u(t_p) = \gamma \cdot \sum_{t_k=0}^{t_k=t_p} \left(\sum_{i=1}^{n} q_{ui}(t_k) \cdot h_i(t_k) \right) \cdot \Delta t_k$
	Energy losses	Leakage energy losses	$E_l(t_p) = \gamma \cdot \sum_{t_k=0}^{t_k=t_p} \left(\sum_{i=1}^{n} q_{li}(t_k) \cdot h_i(t_k) \right) \cdot \Delta t_k$
		Friction energy losses	$E_f(t_p) = \gamma \cdot \sum_{t_k=0}^{t_k=t_p} \left(\sum_{j=1}^{n_l} q_j(t_k) \cdot \Delta h_j(t_k) \right) \cdot \Delta t_k$ $being\ q_j(t_k) = \left(q_{uj}(t_k) + q_{lj}(t_k) \right)$
		Wasted energy in pumping stations	$E_{wp}(t_p) = \gamma \cdot \sum_{t_k=0}^{t_k=t_p} \left(\sum_{i=1}^{n_p} \left(q_{Pi}(t_k) \cdot h_{Pi}(t_k) \cdot \left(1 - \frac{1}{\eta_{pi}(t_k)} \right) \right) \right) \cdot \Delta t_k$
ENERGY SUPPLIED kWh		Shaft energy (supplied by pumps)	$E_P(t_p) = \gamma \cdot \sum_{t_k=0}^{t_k=t_p} \left(\sum_{i=1}^{n_p} \left(\frac{q_{Pi}(t_k) \cdot h_{Pi}(t_k)}{\eta_{pi}(t_k)} \right) \right) \cdot \Delta t_k$
		Natural energy (supplied by external sources)	$E_n(t_p) = \gamma \cdot \sum_{t_k=0}^{t_k=t_p} \left(\sum_{i=1}^{n_n} q_{ni}(t_k) \cdot h_{ni}(t_k) \right) \cdot \Delta t_k$

From equations shown in Table 4, being t_p the period of calculating the expressions, the equation 1 concerning the final balance results in:

$$E_{supplied}(t_p) = E_n(t_p) + E_p(t_p) = E_u(t_p) + E_l(t_p) + E_f(t_p) + E_{wp}(t_p) = E_{consumed}(t_p) \quad (1)$$

The previous equation (1) states that the energy supplied by reservoirs and pumps must be equal to energy delivered to the users plus the losses, because this system does not include compensation tanks (Cabrera et al., 2010). Results are shown in Table 5.

Table 5. Power Balance

	POWER CONSUMED (kW)					**POWER SUPPLIED (kW)**		
Period	Useful Power	Power lost (leaks)	Power lost (friction)	Power lost (pumping station)	**TOTAL CONSUMED**	Natural power	Average pump power	**TOTAL SUPPLIED**
1(0-6 h)	8.34	1.17	0.54	0	**10.05**	10.05	0	**10.05**
2 (6-12 h)	32.44	7.28	1.95	8.76	**50.43**	17.99	32.44	**50.43**
3 (12-18 h)	57.67	18.78	12.97	16.08	**105.51**	23.28	82.23	**105.51**
3.1(12-15 h)	35.66	10.85	2.79	8.05	57.35	15.33	42.02	57.35
3.2(15-18 h)	79.69	26.71	23.15	24.11	153.67	31.23	122.44	153.67

In every scenario, the power supplied (sum of the natural and shaft power) is equal to that consumed, and sum of the useful power plus losses (friction in the pipes, dissipated in leakages and lost at the pumping station).

Table 6 compares the results provided by the EPANET energy analysis with the results of Table 5. For the sake of simplicity, the cost of the energy is taken to be time-constant, with an average value of 0.1 €/kWh. The differences correspond to the underlined errors:

1. In period 1 (the lowest elevation area is irrigated), all the supplied energy is natural. EPANET does not consider this power. The natural energy is omitted in all three scenarios. Additionally, when the pumps are not working, energy consumption is always nil.
2. In period 2, in which sector 2 is irrigated, the error in the estimation of cost of the energy must be added to the omission of natural energy. It can be seen how EPANET over estimates the expenditure to the expected factor (24/18).
3. Lastly, all three errors are present in scenario 3. Natural energy is not considered and, during period 3.1 when the pump is rotating at 75% of its nominal speed, the pump's efficiency is not correctly calculated, translating an error to power and costs. However the ratio is no longer 4/3. It is higher (1.37) because, as EPANET's efficiency is inferior to the real value, it overestimates the power of the pump.

Table 6. Comparison of the energy analysis and EPANET' results

	CALCULATED ANALYSIS					**EPANET ANALYSIS**		
Period	**Average power (kW)**	Natural power (kW)	Shaft power (kW)	Pump efficiency (%)	Cost /day (€)	**Average power (kW)**	Average efficiency (%)	Cost /day (€)
1	**10.05**	10.05	0	-	-	**-**	-	-
2	**50.73**	17.99	32.44	73.00	19.44	**32.72**	72.33	26.17
3	**105.51**	23.28	82.23	80.58	49.34	**84.78**	76.21	67.82
3.1	57.35	15.33	42.02	80.85		47.02	72.26	
3.2	153.67	31.23	122.44	80.30		122.57	80.18	

According to EPANET, the average efficiency of pump P2 is 76.21, while the average efficiency for the operating conditions of the example is 80.58. EPANET does not correctly calculate the efficiency when rotational pump's speed is different from the nominal one, simply because it does not consider the affinity laws. More details can be seen in Marchi & Simpson (2013) The inaccuracy is shown in Figure 2. For the working point P3.1 EPANET's efficiency is 72.26 %, the value obtained from a direct lecture on the efficiency curve. But, taking into account the laws of similarity that apply to a pump working at different rotational speeds, the right result is 80.85%. And the same applies to the second working point P3.2.

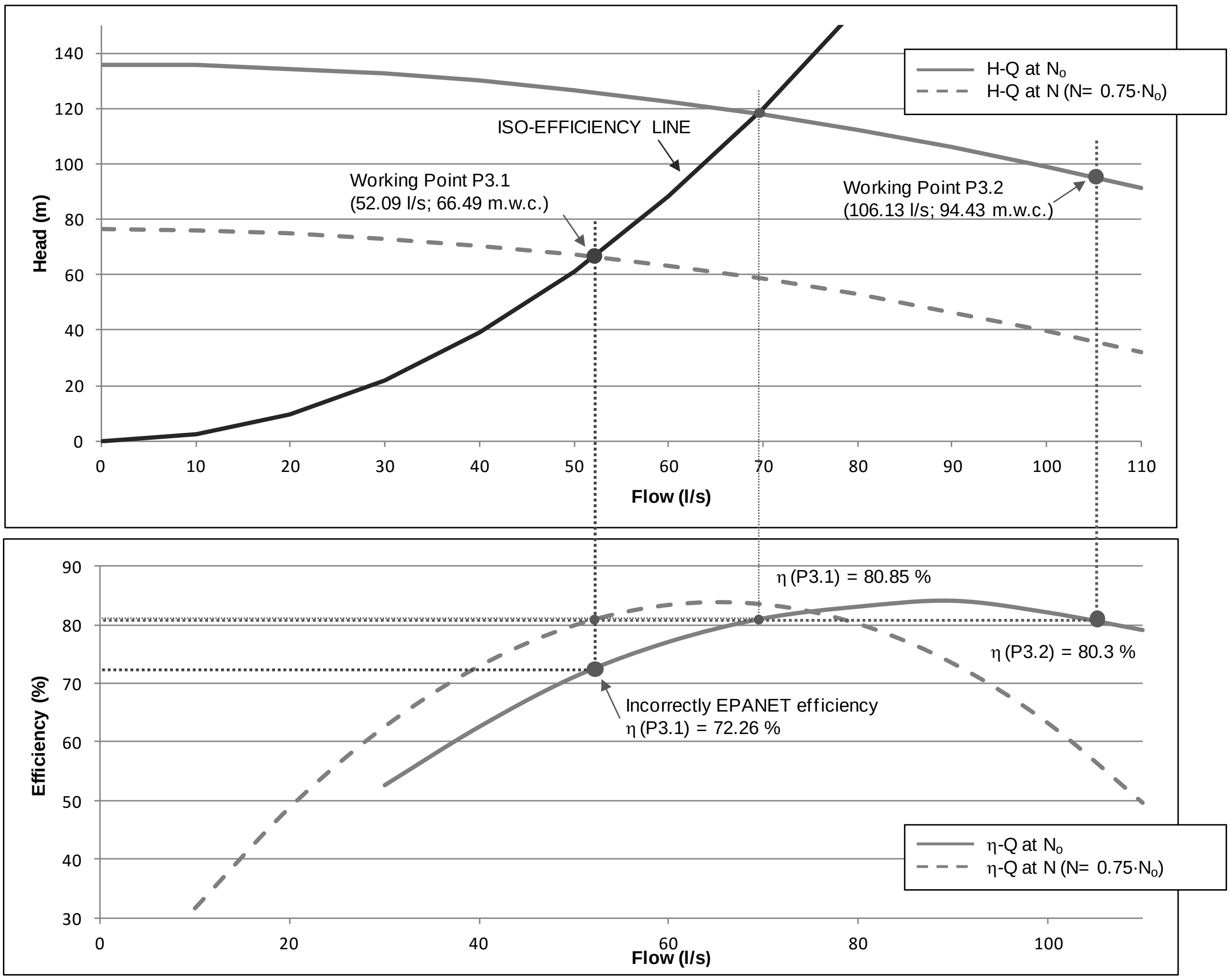

Figure 2. Pump operating point at two different speeds.

Lastly, it should be highlighted that, for the water tariffs contracted at the several pumping stations, it is impossible for EPANET to apply differing energy (and power term) prices.

CONCLUSION

From the point of view of energy, the calculation module of EPANET (the worldwide reference programme in both urban and agricultural fields) presents notable deficiencies and shortcomings. They have been classified into two main groups, major and minor issues (see the corresponding sections) and practically demonstrated in the case study. That happens at a time when energy efficiency and its consequences (GHG emissions) is of utmost priority, EPANET's energy component should be updated and completed. So far, its contribution to the energy efficiency improvements of these systems can be substantially enhanced if the issues previously discussed are taken into account. EPANET (the program, the source and the toolkit) have played invaluable roles in practice and research and, with some minor rearrangements, will follow increasing its brilliant service record.

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NOMENCLATURE

$h_i(t_k)$	Piezometric head at node i at time t_k (m.w.c.)
$h_{ni}(t_k)$	Piezometric head at the reservoir i at time t_k (m.w.c.)
$h_{pi}(t_k)$	Piezometric head of the pump i at time t_k (m.w.c.)
$E_f(t)$	Friction energy in pipes for the simulation period (kWh)
$E_l(t)$	Energy trough leaks for the simulation period (kWh)
$E_n(t)$	Energy supplied by the reservoirs for the simulation period (kWh)
$E_u(t_p)$	Energy supplied for the simulation period (kWh)
$E_{wp}(t)$	Energy wasted in pumping station for the simulation period (kWh)
n	Number of demand nodes of the network (dimensionless)
n_l	Number of pipes of the network (dimensionless)
n_n	Number of reservoirs (dimensionless)
n_p	Number of pumps (dimensionless)
N	Rotation speed of the pumping unit using one variable frequency drive (r.p.m.)
N_o	Nominal rotation speed of the pumping unit (r.p.m.)
$q_{li}(t_k)$	Leakage flow rate at node i at time t_k (l/s)
$q_{lj}(t_k)$	Flow rate at line j at time t_k (l/s) that finally is lost through leaks
$q_{ni}(t_k)$	Flow rate supplied by reservoirs i at time t_k (l/s)
$q_{pi}(t_k)$	Flow rate supplied by pumping station i at time t_k (l/s)
$q_{ui}(t_k)$	Consumed flow rate at node i at time t_k (l/s)
$q_{uj}(t_k)$	Flow rate necessary to satisfy the users demand that circulates at line j at time t_k (l/s)
t_k	Time in the steady state simulation (hour)
t_p	Total time of simulation (hour)
α	Emitter exponent (dimensionless)
γ	Specific weight of water (N/m^3)
Δt_k	Time interval of integration ($\Delta t = t_{k+1} - t_k$)
$\Delta h_j(t_k)$	Friction losses in line j at time t_k (m.w.c.)
$\eta_{pi}(t_k)$	Efficiency in pumping station i at time t_k (dimensionless)