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PUMPING PRESSURE AND FLOW RATE RELATIONSHIP TO REDUCE ENERGY CONSUMPTION IN IRRIGATION SYSTEMS

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ABSTRACT. In the context of the current energy crisis, electricity consumption, especially by large consumers, must be reduced, rationally, without affecting the quality of services provided. Pressure pumping stations (PPS) in irrigation systems are usually equipped with 4 to 8 electric pumping sets with an installed power that can even exceed 1 MW. Since the PPS serving the irrigation plots must work mainly on demand, the required flow rate in the network can vary widely even during each day of the irrigation period. Also, due to the dependence of the pressure loss on the flow carried in the pipe network, this dependence is usually represented by an increasing quadratic function, and the variation of the required flow also leads to a variation, generally significant, of the pressure required from the PPS. To ensure the necessary flow, the PPS are automated with Supervisory control and data acquisition (SCADA) systems, which optimally control the configuration of the electric pumps in operation and their speed. This article presents a mathematical model and algorithm that facilitate the determination of the correlation between the pressure and flow required from the PPS ($(p\text{-}Q)_C$), rendered by an increasing function. The implementation of $(p\text{-}Q)_C$ in the SCADA system software at PPS 2 in the Trifești-Sculeni irrigation system, in the eastern part of Romania, determined a reduction of energy consumption by up to 16%.

Keywords: Irrigation systems; pressure pumping stations; pressure and flow in pipeline; energy savings.

INTRODUCTION

In order to avoid any ambiguities, we would expressly like to mention that large irrigation systems, with an area of the order of several thousand hectares and structured on several plots, besides PPSs, are also served by other types of pumping stations such as basic pumping stations, repumping stations, etc.

The specificity of PPSs, the only type of pumping station which is actually the subject of this study, consists in the high variability of the required flow, caused by the variation in the number and position of the hydrants simultaneously in operation. Thus the increase in flow leads, because the pressure losses in the pipe network of the plot are directly proportional to the flow squared, to a generally significant increase in the pressure required from the PPS.

To reduce the electricity consumption of the PPS, the following three problems must be considered:

1 - the correct determination of the flow and pressure requirements of the pipeline network of the plot;

2 - determining the formation of pumps from the PPS equipment and the functional parameters of the pumps that optimally satisfy (with high precision and with minimal active electrical power consumed) these network requirements;

3 - assessment of the relative electricity savings of PPS for flow requirements and representative (time) periods.

In determining the flow and pressure requirements, the main particularities of the pipeline network of the plot must be considered: a - the configuration and constructive characteristics of the transport-distribution network are complex; b - the number and plan position of the flow distribution nodes are variable; c - the distributed flow is dependent on the pressure in the node. Regarding the plan configuration, the network of the plot is of a branched type, made up of pipes of different orders (Cazacu *et al.*, 1982; Popescu, 1983); the pipes of the lower order – inferior, are called the main lateral/antennas and they are equipped with hydrants to which only one mobile sprinkling watering equipment (MSWE) can be connected. When designing each antenna *k*, $k=1,2,..,n_{M.L}$ (where $n_{M.L}$ - the number of antennas in the plot network), the type and maximum number of mobile sprinkling watering equipments admitted into operation must be known (equal to the maximum number of hydrants in operation on the respective antenna, $\left(n_{Hyd.F}^{\max}\right)_k$); for technical and economic reasons, each antenna *k* is divided into $\left(n_{Hyd.F}^{\max}\right)_k$ sections, thus generally presenting a telescopic configuration (the diameter of the antenna decreases from upstream to downstream), and each section is served by a single mobile sprinkling watering equipment. Each of those $\left(n_{Hyd.F}^{\max}\right)_k$ sections is delimited, in the direction of water flow, by two hydrants - the first called the "upstream end", and the second – the "downstream end" (*Eq. 1*).

$$0 \le \left(n_{Hyd.F}^{\min}\right)_k \le \left(n_{Hyd.F}\right)_k \le \left(n_{Hyd.F}^{\max}\right)_k,\ k=1,2,..,n_{M.L}, \tag{1}$$

Depending on the number of hydrants in operation on each antenna *k*, $\left(n_{Hyd.F}\right)_k$, and from the imposed/random position of these hydrants on the sections in relation to the "upstream end" and "downstream end" hydrants, many network operation scenarios can be generated (Popescu, 1983), every scenario s leading to specific flow–pressure requirements, (Q_s, p_s).

When designing the plot network and PPS, the following imposed scenario are considered to be the least favourable (*Eq. 2*) and on each antenna it is considered that only the "downstream end" hydrant operates.

$$\left(n_{Hyd.F}\right)_k = \left(n_{Hyd.F}^{\max}\right)_k,\ k = 1,2,..,n_{M.L}, \tag{2}$$

In the operation of the irrigation plot, theoretically, any random/imposed scenario could be implemented in the SCADA (SCADA International, 2021) system, either automatically (only if all hydrants related to the plot network are equipped with appropriate sensors) or by a human operator (from the SCADA system console). However, in the absence of these facilities, only the following two "extreme" scenarios are considered representative: 1 - the "extreme downstream scenario" (**EDwS**), when only "downstream end" hydrants operate on each antenna, and 2 - the "extreme upstream scenario" (**EUpS**), when only "upstream end" hydrants operate on each antenna.

In these two "extreme" scenarios, the total number of hydrants in operation in the plot network, N_{Hyd}^{f}, varies between, a lower limit, $N_{Hyd}^{\mathrm{f}.Inf}$, and an upper limit, $N_{Hyd}^{\mathrm{f}.Sup}$ (*Eq. 3*)

$$N_{Hyd}^{\mathrm{f}.Inf} \le N_{Hyd}^{\mathrm{f}} \le N_{Hyd}^{\mathrm{f}.Sup} \tag{3}$$

where: $N_{Hyd}^{\mathrm{f}} = \sum_{k=1}^{n_{M.L}} \left(n_{Hyd.F}\right)_k$,

$N_{Hyd}^{\mathrm{f}.Sup} = \sum_{k=1}^{n_{M.L}} \left(n_{Hyd.F}^{\max}\right)_k$

The maximum number of variants for requirements $(Q_s,\ p_s)$ in each of the two "extreme" scenarios", $N_V^{\max}$, is given by *Eq. 4* and the total number of hydrants in operation in the variant ν, $N_{Hyd}^{f.\nu}$, is given by *Eq. 5*.

$$N_V^{\max} = N_{Hyd}^{\mathrm{f}.Sup} - N_{Hyd}^{\mathrm{f}.Inf} + 1 \tag{4}$$

The flow and pressure/piezometric head requirements in the variant ν are given by *Eq. 6* for **EUpS** and, respectively, by *Eq. 7* for **EDwS**. In order to reduce the amount of calculation, but without significantly influencing the accuracy of the results, in practice it is accepted to determine the flow and pressure requirements of the network for a number of variants N_V, $2 \le N_V < N_V^{\max}$, but, in this case, the actual number of hydrants in operation must be specified for each variant $\overline{N}_{Hyd}^{f.\mu}$, increasing relative to the index μ (*Eq. 8*): In this case, the flow and pressure/piezometric head requirements are given by *Eq. 9* for **EUpS** and, respectively, by *Eq. 10* for **EDwS**.

$$N_{Hyd}^{f.\nu} = N_{Hyd}^{\mathrm{f}.Inf} + \nu - 1, \text{ with } \nu = 1,2,...,N_V^{\max} \text{ and } \mathbf{N}_{Hyd}^{f} = \left\{N_{Hyd}^{f.\nu}\right\}_{\nu=1:N_V^{\max}} \tag{5}$$

$$\left(Q_{am}^{\nu}, p_{am}^{\nu}\right) \text{ or } \left(Q_{am}^{\nu}, H_{am}^{\nu}\right), \text{ with } \nu = 1,2,...,N_V^{\max} \text{ and } \left(\mathbf{Q}_{am}, \mathbf{H}_{am}\right) = \left(Q_{am}^{\nu}, H_{am}^{\nu}\right)_{\nu=1:N_V^{\max}} \tag{6}$$

$$\left(Q_{av}^{\nu}, p_{av}^{\nu}\right) \text{ or } \left(Q_{av}^{\nu}, H_{av}^{\nu}\right), \text{ with } \nu = 1,2,...,N_V^{\max} \text{ and } \left(\mathbf{Q}_{av}, \mathbf{H}_{av}\right) = \left(Q_{av}^{\nu}, H_{av}^{\nu}\right)_{\nu=1:N_V^{\max}} \tag{7}$$

$$\bar{N}_{Hyd}^{\mathrm{f}.Inf} = N_{Hyd}^{\mathrm{f}.Inf} \le \bar{N}_{Hyd}^{f.\mu} \le \bar{N}_{Hyd}^{\mathrm{f}.N_V} = N_{Hyd}^{\mathrm{f}.Sup}, \text{ with } \mu = 1,2,...,N_V \text{ and } \bar{\mathbf{N}}_{Hyd}^{f} = \left\{\bar{N}_{Hyd}^{f.\mu}\right\}_{\mu=1:N_{\mathrm{V}}} \tag{8}$$

$$\left(\bar{Q}_{am}^{\mu}, \bar{p}_{am}^{\mu}\right) \text{ or } \left(\bar{Q}_{am}^{\mu}, \bar{H}_{am}^{\mu}\right), \text{ with } \mu = 1,2,...,N_V \text{ and } \left(\bar{\mathbf{Q}}_{am}, \bar{\mathbf{H}}_{am}\right) = \left(\bar{Q}_{am}^{\mu}, \bar{H}_{am}^{\mu}\right)_{\mu=1:N_V} \tag{9}$$

$$\left(\bar{Q}_{av}^{\mu}, \bar{p}_{av}^{\mu}\right) \text{ or } \left(\bar{Q}_{av}^{\mu}, \bar{H}_{av}^{\mu}\right), \text{ with } \mu = 1,2,...,N_V \text{ and } \left(\bar{\mathbf{Q}}_{av}, \bar{\mathbf{H}}_{av}\right) = \left(\bar{Q}_{av}^{\mu}, \bar{H}_{av}^{\mu}\right)_{\mu=1:N_V} \tag{10}$$

Plotting points with coordinates (7)/(10) and (8)/(11), the lower and upper enveloping curves are obtained, respectively, for the requirements (Q_s, p_s) or (Q_s, H_s) of the plot network, curves bounding the plane domain Ω_s .

Buono da Silva Baptista *et al.* (2019) analyse the energy efficiency for the centre pivot in plots with variable topography when using variable speed drives; for the presented case study it resulted in a 12% reduction in energy consumption. Córcoles *et al.* (2019) deal with the problem of reducing the energy consumption of water abstraction from wells with a variable water table level. This reduction in energy consumption is based on the installation of variable speed drives and the results show potential energy savings of up to 23% due to the increase in water pumping efficiency compared to fixed speed drives.

In order to reduce energy consumption, Cruz *et al.* (2019) review the feasibility of using low-pressure sprinkling watering devices (with pressure requirements lower than 103 kPa).

In several other works (Sanchez-Ferrer *et al.*, 2021; Shi *et al.*, 2018; Candelieri *et al.*, 2018; Castro Gama *et al.*, 2015; Bagirov *et al.*, 2013; Todini and Rossman, 2012; Rossman, 2000; Giustolisi *et al.*, 2012; Li *et al.*, 2012; Alexandrescu *et al.*, 2008; Toma, 2005, 2012), mathematical models are presented to facilitate the energy optimization of PPS serving the supply pipelines and/or water distribution networks of an urban drinking water supply system. Ben-Galim *et al.* (2016) and Groepper *et al.* (2005) determine pressure–flow correlations, in a fully developed turbulent flow, for hydraulic industrial facilities and/or for the primary element of any flow sensor, respectively.

Other works (Córcoles *et al.*, 2015; Jiménez-Bello *et al.*, 2015; Lamaddalena *et al.*, 2015; Tarjuelo *et al.*, 2015; Fernandez Garcıa *et al.*, 2014; Gonzalez Perea *et al.*, 2014) present methodologies to determine the optimum pumping station regulation of on-demand irrigation networks. The studied water distribution networks are equipped as follows:

a) with one or more pressure sensors;

b) an automation system controls the opening and closing events of the valves at the hydrant;

c) each hydrant has a flow limiter and a flowmeter.

The analysis methodology consists in generating random scenarios with respect to the number and position of hydrants in operation (open hydrants); then, under the assumptions that the demand flow discharge for each open hydrant is considered constant and fully developed turbulent flow, the following elements are determined for each scenario:

a) the pressure head at the pumping station, to supply the exact pressure necessary to ensure the minimum pressure in the most restrictive of the nodes of the network with open hydrants;

b) the best combination of variable speed pumps and fixed pumps and calculation of the energy consumption.

In the case study with sprinkler irrigation (Córcoles *et al.*, 2015), the energy saving with respect to manometric regulation with fixed pressure was up to 7.6 %.

In the works by Popescu (1983), the flow and piezometric head requirements (*Eq. 9*) and (*Eq. 10*) were determined under the following hypothesis: a) for each open hydrant, the flow is pressure-dependent; b) the flow and/or pressure associated with these hydrants verify the uniformity conditions imposed by the Christiansen criteria (Cazacu *et al.*, 1982); c) the irrigation plot is equipped with a certain type of mobile sprinkling watering equipment; d) the variation of pipe resistance as a function of flow rate is neglected; e) the lower and upper wrapping curves are approximated, by the method of least squares, by analytical expressions in the form of power functions.

In the paper by Popescu (1983), in addition, the pump formation of the PPS equipment (pumps driven at constant or quasi-constant speed – when the variation of the asynchronous motor slip as a function of the motor load is taken into account) that satisfies, with the optimal energy efficiency, the requirements (Q_s, H_s) of the network is also determined. Considering the three study issues listed at the beginning of this section, it can be stated that no publication addresses all these issues in a unified manner for PPSs, and possibly, only for other technical systems.

This situation can be justified by the following: I - worldwide, mainly smaller areas belonging to private farms are irrigated; II - due to the labour shortage, highly productive sprinkler irrigation equipment with its own pumping equipment or pressure regulators, such as fixed central pivot and linear displacement systems, is used.

However, the present study is important for irrigation systems in Romania for the following reasons: a - rehabilitating and modernizing old irrigation plots, mainly with European funds (limited in amount and allocated in several annual stages); b - the plot network configuration was kept, but the old PREMO and asbestos pipes have been partially/totally replaced with PEHD pipes; c - the hydrants are not equipped with a pressure regulator; d - concerning MSWE, due to insufficient funds, in most cases, new IATFs were purchased, but a large part of the old sprinkler wings (SW) were kept in operation; e - the pumping sets were totally/partially replaced, and at least part of the new motors are equipped with a frequency converter – for variable speed drive; f - PPS were automated with the SCADA system.

In the *Materials and Methods* section, we aim to solve problems 1 and 3 stated at the beginning of this section for PPSs in a unified manner by developing appropriate mathematical models and algorithms.

Concerning problem 1 - knowing the flow rate and pressure/piezometric load requirements (*Eq. 9*) and (*Eq. 10*), the correlation $(p\text{-}Q)_C$ between the pressure (indicated by the pressure sensor) and flow rate (indicated by the flowmeter) will be determined through an original methodology; the correlation $(p\text{-}Q)_C$ is rendered by the set of numerical values (*Eq. 11*):

$$\left(\mathbf{Q}_{pQc},\mathbf{p}_{pQc}\right)=\left(Q^{\nu}_{pQc},p^{\nu}_{pQc}\right)_{\nu=1:N_V^{\max}} \quad (11)$$

Regarding problem 3, the relative $\left(Q^{\nu}_{pQc},p^{\nu}_{pQc}\right)$, with $\nu=1,2,...,N_V^{\max}$ e energy savings, ΔE_r, achieved in the whole irrigation season for the year, with moisture deficit with the calculation assurance of 80%, will be evaluated; for this purpose, we have developed an expeditious and original calculation algorithm, which is based on the correlation $(p\text{-}Q)_C$, but which does not involve the energy characteristics of the electric pumping sets.

Concerning problem 2, determination of the pump formation in the PPS equipment and the functional parameters of the pumps that optimally meet the requirements (Q_s, p_s) of the network - we mention (SCADA International, 2021) that currently this problem is effectively solved by equipping the PPS with pressure and flow sensors and a SCADA automation system.

The hypotheses adopted in this study are as follows:
1 - the flow and pressure/piezometric head values (*Eq. 9*) and (*Eq. 10*) were determined by applying the mathematical model from the works by Popescu (1983);
2 - the coordinate points (*Eq. 11*) belong to the median curve of the domain Ω_s bounded by the lower and upper wrapping curves;
3 - the reference plane for piezometric loads passes through the axis of the pressure sensor;
4 - PPS partially/fully equipped with variable-speed pumping sets ensure the satisfaction of any regime (*Eq. 11*) with optimal and constant energy efficiency (but variable speed operation and optimization of this operation mode are not actually the subject of this study);
5 - in the absence of correlation $(p\text{-}Q)_C$ (*Eq. 11*), the SCADA system is programmed to impose the operation of the PPS at a constant pressure, higher than the pressure p_s related to any requirement (Q_s, p_s) of the irrigation plot.

In the *Results and Discussion* section, the mathematical models and algorithms elaborated in the paper are applied to a representative case study, the basic data, taken from Popescu (1983), being those related to the irrigation plot served by PPS 2, from the Trifești-Sculeni Irrigation System, Iași County, and result in an electricity saving of up to 16%.

MATERIALS AND METHODS

In this section the mathematical models and/or algorithms for solving the two proposed problems, 1 and 3 from the *Introduction*, will be developed.

Algorithm for determining the correlation between flow and pressure requirements

In order to determine the correlation $(p\text{-}Q)_C$ between the flow and pressure requirements, as shown by coordinates (*Eq. 11*), the following steps were carried out (*Figure 1*), where g – gravitational acceleration, where $g = 9.80665\ \text{ms}^{-2}$.

Notes: considering approximate functions of power form, the functions F_{INF} and F_{SUP} represent the following expressions (*Eqs. 12-13*).

Assessment of the relative electricity savings of PPS

In the operation of the irrigation plot, the flow and pressure requirements associated with any random and feasible scenario s, (Q_s, p_s), are the coordinates of a point S, $\mathrm{S} \in \Omega_s$.

$$F_{INF}\left(\mathbf{X}_{INF},\bar{\mathbf{Q}}_{am},\bar{\mathbf{H}}_{am}\right)=\sum_{\mu=1}^{N_V}\left|a_{INF}+b_{INF}\left(\bar{Q}_{am}^{\mu}\right)^{C_{INF}}-\bar{H}_{am}^{\mu}\right| \tag{12}$$

$$F_{SUP}\left(\mathbf{X}_{SUP},\bar{\mathbf{Q}}_{av},\bar{\mathbf{H}}_{av}\right)=\sum_{\mu=1}^{N_V}\left|a_{SUP}+b_{SUP}\left(\bar{Q}_{av}^{\mu}\right)^{C_{SUP}}-\bar{H}_{av}^{\mu}\right| \tag{13}$$

The flow rate Q_s can be estimated from the flowmeter indication, but although the nominal hydraulic characteristics of the MSWEs are known, in the absence of concrete information on the number and position of open hydrants on each antenna, the pressure p_s is not known; thus, according to hypothesis 4 of the *Introduction*, it is accepted that the PPS operate at a constant pressure $\bar{p}_{\mathrm{s}}^{\mathrm{const}}$, covering any flow and pressure requirement of the irrigation plot. The design scenario for the plot network and associated PPS, which satisfies *Eq. (2)*, presents the maximum flow and pressure requirements, $\left(\bar{Q}_s^{\max},\bar{p}_s^{\max}\right)$, which are given in both *Eq.(10)* for $\mu = N_V$ and *Eq. (7)* for $\nu = N_V^{\max}$.

$$\bar{Q}_s^{\max}=\bar{Q}_{av}^{N_V}=Q_{av}^{N_V^{\max}} \text{ and } \bar{p}_s^{\max}=\bar{p}_{av}^{N_V}=p_{av}^{N_V^{\max}} \tag{14}$$

Therefore, according to hypothesis 4, the constant pressure $\bar{p}_{\mathrm{s}}^{\mathrm{const}}$, currently set by the SCADA system, must verify the inequality (*Eq. 15*):

$$\bar{p}_{\mathrm{s}}^{\mathrm{const}} \geq \bar{p}_{av}^{N_V} \tag{15}$$

Compared to the constant pressure $\bar{p}_{\mathrm{s}}^{\mathrm{const}}$, when satisfying the flow requirement at the pressure imposed by the correlation $(p\text{-}Q)_C$ and the attached median curve, one could reduce the PPS pressure by a value $\Delta\bar{p}_{pQc}^{const}$ (*Eq. 16*),

$$\Delta\bar{p}_{pQc}^{const} \in \left[\left(\Delta\bar{p}_{pQc}^{const}\right)_{\min},\left(\Delta\bar{p}_{pQc}^{const}\right)_{\max}\right] \tag{16}$$

with the interval limits given by the following inequalities (*Eq. 17*):

$$\left(\Delta\bar{p}_{pQc}^{const}\right)_{\min} \geq \bar{p}_{am}^{N_V}-\bar{p}_{pQc}^{N_V};\left(\Delta\bar{p}_{pQc}^{const}\right)_{\max} \geq \bar{p}_{am}^{N_V}-\bar{p}_{pQc}^{1} \tag{17}$$

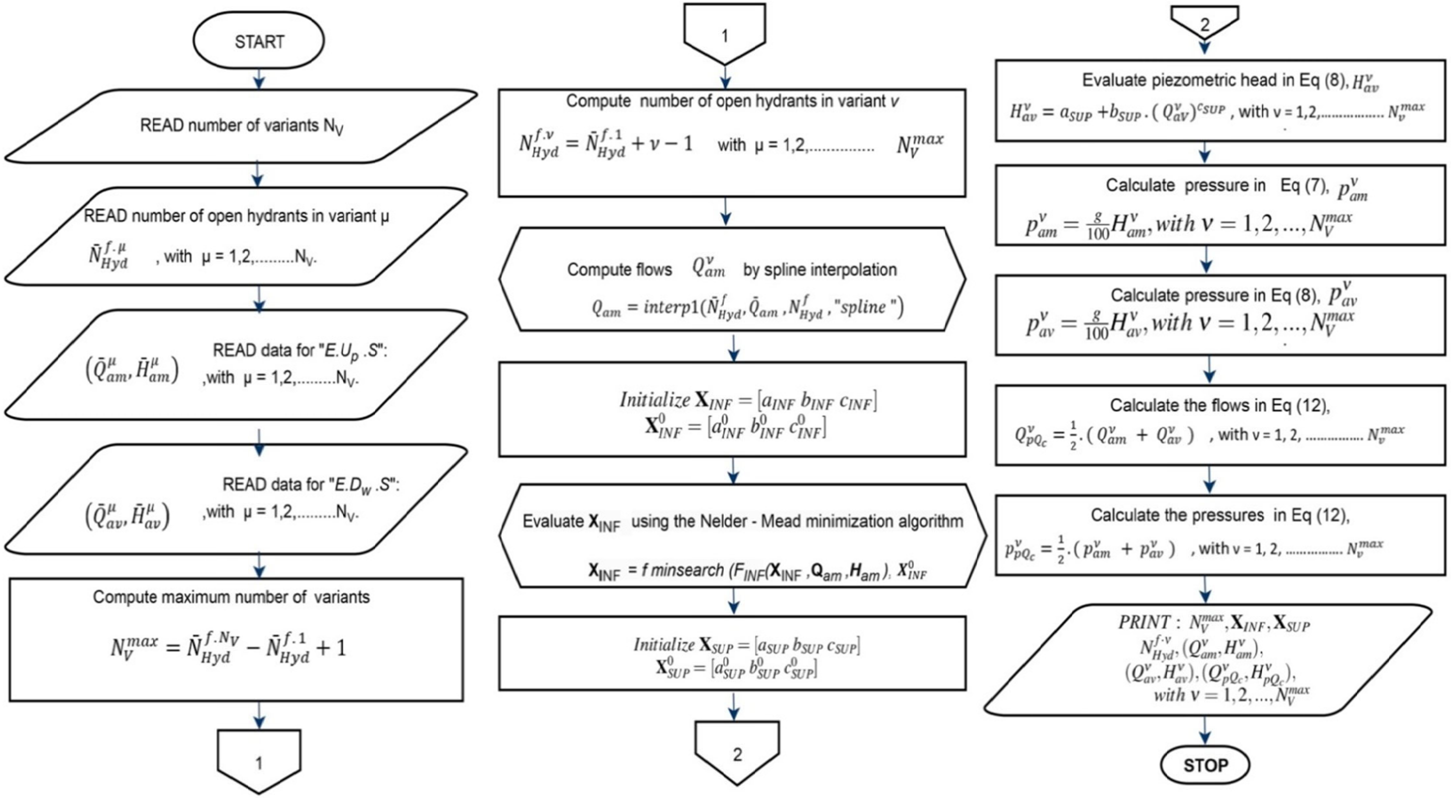

Figure 1 – Flow chart of algorithm for correlation (p-Q)$_C$

For the purpose of assessing the relative electricity savings of PPSs for representative flow requirements and (time) periods, we used the following basic data related to the irrigation plot: 1 - the area of the plot actually irrigated, S_{plot}^{nett}, (hectare, ha); 2 - the crop plan of the plot; 3 - the irrigation regime; 4 - the volumetric efficiency to the network of the plot, η_{plot}^{vol} (%); 5 - the maximum flow and pressure requirements of the plot network, $\left(\bar{Q}_s^{\max}, \bar{p}_s^{\max}\right)$, (dm^{3}s^{-1},bar), given by ***Eq.*** ***14***; 6 - the constant pressure $\bar{p}_s^{\text{const}}$, set by the SCADA system, (bar); 7 - correlation (p-$Q)_C$, given by ***Eq.*** ***11***, (bar, dm^{3}s^{-1}).

The crop plan of the plot specifies the following elements: a - number of agricultural crops, N_{ac}; b - the agricultural crops, $\mathbf{ID}_{ac} = \left\{ ID_i^{ac} \right\}_{i=1:N_{ac}}$; c - the share of the area S_{plot}^{nett} allocated to each crop, $\mathbf{PD}_{ac} = \left\{ PD_i^{ac} \right\}_{i=1:N_{ac}}$, (%).

The irrigation regime specifies: a - the number of months of the irrigation period, N_{mth}; b - the months of the irrigation period, $\mathbf{ID}_{mth} = \left\{ ID_j^{mth} \right\}_{j=1:N_{mth}}$; c - the monthly watering norms, with 80% assurance (20% probability of overshoot), for each crop $\mathbf{m}_{ac}^{mth} = \left\{ m_i^j \right\}_{i=1:N_{ac};j=1:N_{mth}}$, (m^{3}ha^{-1}); d - the duration of monthly watering, T, (days); e - the duration of diurnal watering, t, (hours).

Using the basic data for the irrigation plot, mentioned above, in order to determine the relative electricity savings of the PPS, the following steps were carried out (***Figure*** *2*). Notes: The equations for $\left(\Delta P_r^{mth}\right)_j$ and ΔE_r are original; their deduction is presented below (***Eqs.*** ***18-19***).

It is found that the relative energy savings ΔE_r are given by the weighted (arithmetic) average of the relative monthly power/energy savings $\left(\Delta P_r^{mth}\right)_j$, the weights being the flow rates $\bar{Q}_j^{mth}$, with $j = 1, 2, ..., N_{mth}$.

In the above equations (17) and (18), the following notations were used: $\tilde{P}_j^{mth}$, $\bar{P}_j^{mth}$ - the electrical power required monthly by the PPS to satisfy the requirements $\left(\bar{Q}_j^{mth}, \bar{p}_s^{\text{const}}\right)$ and $\left(\bar{Q}_j^{mth}, \bar{p}_j^{mth}\right)$, respectively; ΔP_j^{mth} - the monthly power saving to ensure the flow requirement $\bar{Q}_j^{mth}$; $\bar{\eta}_{ps}$ - the average efficiency of the pumping sets in the PPS, considered constant according to hypothesis 4 of the *Introduction.*

$$\left(\Delta P_r^{mth}\right)_j = \frac{\Delta P_j^{mth}}{\tilde{P}_j^{mth}} = \frac{\tilde{P}_j^{mth} - \bar{P}_j^{mth}}{\tilde{P}_j^{mth}} = \frac{\dfrac{\bar{Q}_j^{mth}}{10\bar{\eta}_{ps}}\left(\bar{p}_s^{\text{const}} - \bar{p}_j^{mth}\right)}{\dfrac{1}{10}\dfrac{\bar{p}_s^{\text{const}}\bar{Q}_j^{mth}}{\bar{\eta}_{ps}}} = 1 - \frac{\bar{p}_j^{mth}}{\bar{p}_s^{\text{const}}} \tag{18}$$

$$\Delta E_r = \frac{\sum\limits_{j=1}^{N_{mth}} \Delta P_j^{mth}}{\sum\limits_{j=1}^{N_{mth}} \tilde{P}_j^{mth}} = \frac{\sum\limits_{j=1}^{N_{mth}} \dfrac{\bar{Q}_j^{mth}}{10\bar{\eta}_{ps}}\left(\bar{p}_s^{\text{const}} - \bar{p}_j^{mth}\right)}{\sum\limits_{j=1}^{N_{mth}} \dfrac{1}{10}\dfrac{\bar{p}_s^{\text{const}}\bar{Q}_j^{mth}}{\bar{\eta}_{ps}}} = \frac{\dfrac{\bar{p}_s^{\text{const}}}{10\bar{\eta}_{ps}}\sum\limits_{j=1}^{N_{mth}} \bar{Q}_j^{mth}\left(1 - \dfrac{\bar{p}_j^{mth}}{\bar{p}_s^{\text{const}}}\right)}{\dfrac{\bar{p}_s^{\text{const}}}{10\bar{\eta}_{ps}}\sum\limits_{j=1}^{N_{mth}} \bar{Q}_j^{mth}} = \frac{\sum\limits_{j=1}^{N_{mth}} \bar{Q}_j^{mth}\left(1 - \dfrac{\bar{p}_j^{mth}}{\bar{p}_s^{\text{const}}}\right)}{\sum\limits_{j=1}^{N_{mth}} \bar{Q}_j^{mth}} = \frac{\tilde{S}_{\Delta \text{Pr}}}{\bar{S}_Q} \tag{19}$$

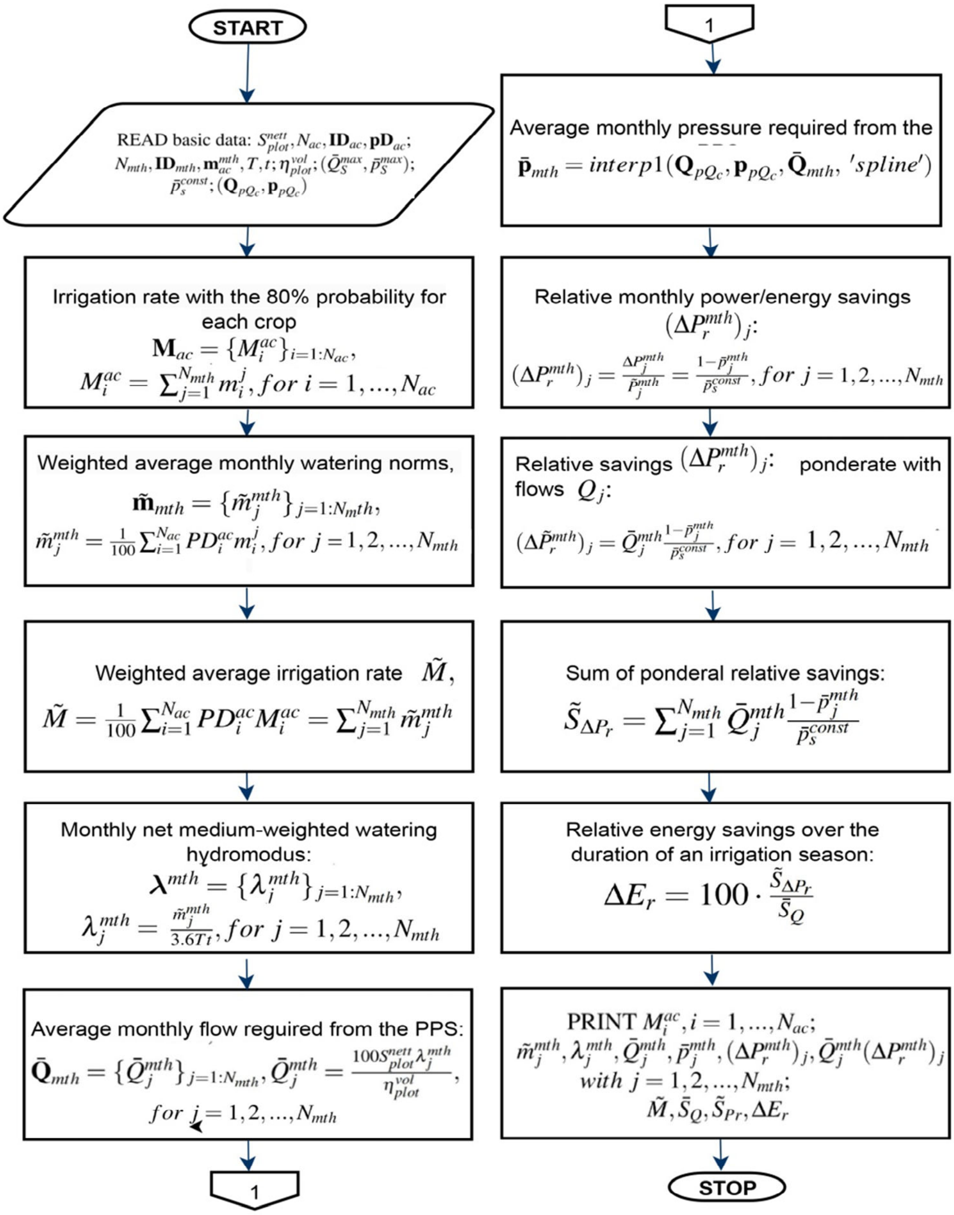

Figure 2 - Flow chart of algorithm for assessment of the relative electricity savings of PPS

RESULTS AND DISCUSSION

In this section a case study, taken from (Popescu, 1983), is presented on the irrigation plot of the Trifești-Sculeni irrigation system, in the eastern part of Romania, served by PPS 2. This plot, which will be called Plot 2 in the following, with a net irrigated area of S_{plot}^{nett}= 890 ha, shows the network of pressurized pipelines for transport and distribution, consisting of two main pipelines, CP1 and CP2, telescopic pipes with 3 sections and 4 antennas each, equipped with 175 hydrants that can simultaneously supply a maximum number of $N_{Hyd}^{f.Sup}$=34 MSWEs, of the sprinkler wing (SW) type, equipped with 22 sprinklers of the ASJ-1M type, with a nozzle diameter of 6 mm, located at a distance of 18 m.

The case study follows in sequence the calculation steps presented in sections 2.1 and 2.2, respectively.

Algorithm for determining the correlation between flow and pressure requirements

The case study follows the calculation steps presented in the flow chart of the algorithm for correlation $(p\text{-}Q)_C$ from *Figure 1* in sequence. The basic data for N_V = 4 is presented in *Table 1*. The numerical results for $N_V^{\max}$, $\mathbf{X}_{INF}^{0}$, $\mathbf{X}_{INF}$, $\mathbf{X}_{SUP}^{0}$ and $\mathbf{X}_{SUP}$ are as follows: $N_V^{\max}$=25, $\mathbf{X}_{INF}^{0}$={30.0, 40.0, 2.0}; $\mathbf{X}_{INF}$ ={43.140, 43.314, 2.0298}; $\mathbf{X}_{SUP}^{0}$={40.0, 20.0, 1.50}; $\mathbf{X}_{SUP}$ ={52.179, 27.508, 1.3208}.

The numerical results for $N_{Hyd}^{f.v}$ and the coordinates of the two wrapping curves and of the median curve are presented in *Table 2*. The data presented in *Table 2*, columns 3 to 8, were used for the graphs in *Figure 3*.

Assessment of the relative electricity savings of PPS 2

For the purpose of assessing the relative electricity savings of PPS 2 for representative flow requirements in the whole irrigation season for the year with moisture deficit with the calculation assurance of 80%, we used the following basic data related to Plot 2 from the Trifești-Sculeni Irrigation System (Popescu, 1983). The case study follows the calculation steps presented in the flow chart of the algorithm for assessment of the relative electricity savings of PPS from *Figure 2* in sequence.

The basic data (crop plan and values for watering norms $\mathbf{m}_{ac}^{mth}$), for $N_{a\,c}$= 5 and N_{mth} = 6, are presented in *Table 3*, rows 1 to 5 and columns 2 to 9.

Using these data, for T=28 days and t=20 hours, the remaining elements of the irrigation regime were calculated and are presented in *Table 3*, rows 6 and 7 and column 10; in addition, the irrigation rate $\tilde{M}$ is written in bold italic characters in row 6 and column 10.

Table 1 - Number of hydrants in operation and calculated hydraulic parameters effectively in the two "extreme" scenarios

μ	$\overline{N}_{Hyd}^{f.\mu}$	EUpS		EDwS	
		$\overline{Q}_{am}^{\mu}$ m^{3}s^{-1}	$\overline{H}_{am}^{\mu}$ mH$_2$0	$\overline{Q}_{av}^{\mu}$ m^{3}s^{-1}	$\overline{H}_{av}^{\mu}$ mH$_2$0
1	**2**	**3**	**4**	**5**	**6**
1	10	0.153	44.354	0.161	54.644
2	18	0.275	45.311	0.289	56.580
3	26	0.418	51. 711	0.428	61.183
4	34	0.546	55.350	0.572	65.332

Table 2 - Lower and upper wrapping curves and median curve coordinates

ν	$N_{Hyd}^{f.\nu}$	Lower Wrap		Upper Wrap		Median Curve	
		Q_{am}^{ν} dm^{3}s^{-1}	p_{am}^{ν} bar	Q_{av}^{ν} dm^{3}s^{-1}	p_{av}^{ν} bar	Q_{pQc}^{ν} dm^{3}s^{-1}	p_{pQc}^{ν} bar
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
1	10	153.00	4.325	161.00	5.359	157.00	4.842
2	11	165.87	4.341	176.19	5.389	171.03	4.865
3	12	179.56	4.361	191.64	5.421	185.60	4.891
4	13	194.00	4.383	207.33	5.455	200.67	4.919
5	14	209.13	4.408	223.25	5.489	216.19	4.949
6	15	224.86	4.436	239.39	5.525	232.12	4.981
7	16	241.13	4.467	255.73	5.562	248.43	5.015
8	17	257.86	4.502	272.28	5.601	265.07	5.051
9	18	275.00	4.540	289.00	5.641	282.00	5.090
10	19	292.46	4.581	305.90	5.681	299.18	5.131
11	20	310.19	4.625	322.95	5.723	316.57	5.174
12	21	328.10	4.673	340.16	5.766	334.13	5.220
13	22	346.13	4.724	357.50	5.810	351.81	5.267
14	23	364.20	4.777	374.97	5.855	369.58	5.316
15	24	382.25	4.834	392.55	5.902	387.40	5.368
16	25	400.21	4.893	410.23	5.949	405.22	5.421
17	26	418.00	4.954	428.00	5.996	423.00	5.475
18	27	435.56	5.017	445.85	6.045	440.70	5.531
19	28	452.81	5.081	463.77	6.095	458.29	5.588
20	29	469.69	5.147	481.74	6.145	475.71	5.646
21	30	486.13	5.213	499.75	6.196	492.94	5.705
22	31	502.04	5.279	517.79	6.248	509.92	5.764
23	32	517.38	5.346	535.86	6.300	526.62	5.823
24	33	532.05	5.411	553.93	6.353	542.99	5.882
25	34	546.00	5.474	572.00	6.407	559.00	5.941

Table 3 - Crop plan and the values for the elements of the irrigation regime with 80% assurance (20% probability of exceeding), in (m^{3}ha^{-1}) or (dm^{3}s^{-1}ha^{-1})

Nr. crt. line	**Crop,** ID_i^{ac}	**Weight,** PD_i^{ac} **[%]**	**Month,** ID_j^{mth}						M_i^{ac} **[m^{3}ha^{-1}]**
			IV	**V**	**VI**	**VII**	**VIII**	**IX**	
1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
1.	Wheat and barley	35	1260	1260	1260	900	0	0	4680
2.	Maize	20	0	270	990	1260	1260	630	4410
3.	Sunflower	20	0	450	1080	1170	630	450	3780
4.	Sugar beet	7	0	720	1080	1260	1170	900	5130
5.	Lucerne	18	0	450	1170	1080	720	450	3870
6.	Weighted average norms, $\tilde{m}_j^{mth}$		441	716.4	1141.2	1083.6	589.5	360	***4331.7***
7.	Net hydromodus, λ_j^{mth} (dm^{3}s^{-1}ha^{-1})		0.219	0.355	0.566	0.538	0.292	0.179	-

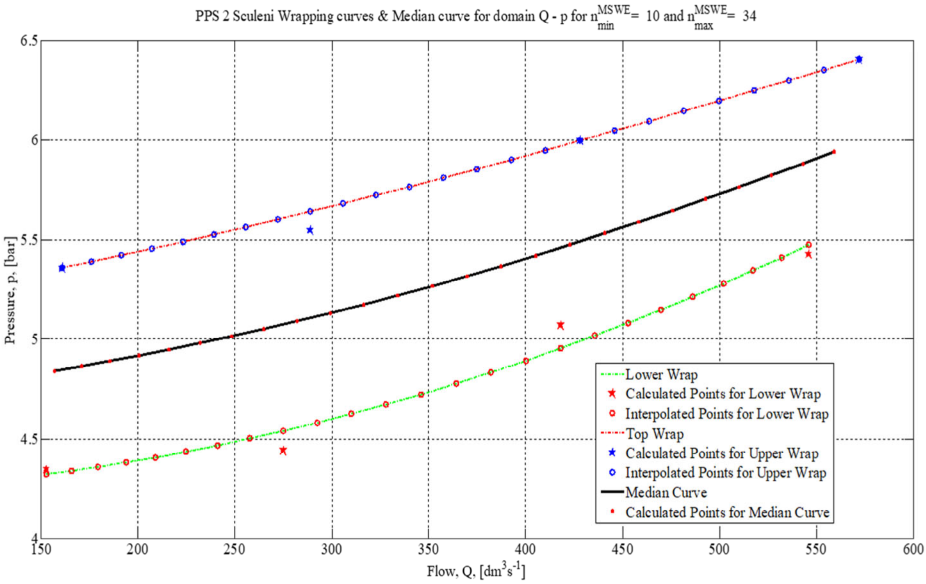

Figure 3 - Lower and upper wrapping curves and the median curve for flow and pressure requirements (*Q*$_s$, *p*$_s$) from PPS 2

For the basic data S_{plot}^{nett}=892 ha, $\eta_{plot}^{vol}=91.23\,\%$ (Chiorescu *et al.*, 2016) and median curve coordinates $\left(\mathbf{Q}_{pQc},\mathbf{p}_{pQc}\right)$ (*Table* 2, columns 7 and 8), the monthly flow and pressure required from the PPS, $\left(\overline{\mathbf{Q}}_{mth},\overline{\mathbf{p}}_{mth}\right)$, were calculated and are presented in *Table 4*, rows 1 and 2; in addition, the sum $\overline{S}_Q$ is written in bold italic characters in row 1 and column 8. Considering the maximum flow and pressure requirements of Plot 2, $\left(\overline{Q}_s^{\max},\overline{p}_s^{\max}\right)$=(572.00 dm^{3}s^{-1}, 6.407 bar), taken from *Table 2*, row 25, columns 5 and 6, the following three values were established for pressure $\overline{p}_{\mathrm{s}}^{\mathrm{const}},\overline{p}_{\mathrm{s}}^{\mathrm{const}}\in\left\{6.45,\ 6.55,\ 6.70\right\}$ bar (*Table 4*, column 1 and rows 3 to 8).

Next, the results of the calculations, for each of the three values $\left\{6.45,\ 6.55,\ 6.70\right\}$ assigned to the pressure $\overline{p}_{\mathrm{s}}^{\mathrm{const}}$, are entered in columns 2 to 9, corresponding respectively to lines 3 & 4 , 5 & 6 and 7 & 8; in addition, the sums $\tilde{S}_{\Delta\mathrm{Pr}}$ are written in bold italic characters in column 8, and the relative energy savings ΔE_r are written in bold characters in column 9.

Notes: The following is found: 1 - the relative monthly power and energy savings, $\left(\Delta P_r^{mth}\right)_j=\left(1-\overline{p}_j^{mth}/\overline{p}_{\mathrm{s}}^{\mathrm{const}}\right)$, are dependent only on the pressure ratio $\overline{p}_j^{mth}/\overline{p}_{\mathrm{s}}^{\mathrm{const}}$ and show maximum values up to 0.27=27% in the months with low average flow $\overline{Q}_j^{mth}$, findings consistent with those reported in (Corcoles *et al.*, 2016); 2 - the relative electricity savings related to PPS 2 throughout the irrigation season, ΔE_r depend, in addition, on the flow rates $\overline{Q}_j^{mth}$ and can have values of up to 15.66~16%.

Table 4 – Assessment of monthly relative power savings, and relative energy savings over the duration of an irrigation season, ΔE_r

Month, ID_j^{mth}		IV	V	VI	VII	VIII	IX	Sums	ΔE_r (%)
1		2	3	4	5	6	7	8	9
1. Required flow, $\bar{Q}_j^{mth}$, dm^{3}s^{-1}		239.8	389.5	620.5	589.2	320.5	195.7	***2355.2***	-
2. Pressure from $\left(\bar{p}-\bar{Q}\right)_C$, $\bar{p}_j^{mth}$, bar		4.9965	5.3738	6.1716	6.0529	5.1843	4.9095	-	
$\bar{p}_s^{\text{const}}$ = 6.45 bar	3. $\left(1-\bar{p}_j^{mth}/6.45\right)$ (-)	0.23	0.17	0.04	0.06	0.20	0.24	-	**12.39**
	4. $\bar{Q}_j^{mth}\left(1-\bar{p}_j^{mth}/6.45\right)$	54.03	64.99	26.78	36.27	62.90	46.75	***291.73***	
$\bar{p}_s^{\text{const}}$ = 6.55 bar	5. $\left(1-\bar{p}_j^{mth}/6.55\right)$ (-)	0.24	0.18	0.06	0.08	0.21	0.25	-	**13.72**
	6. $\bar{Q}_j^{mth}\left(1-\bar{p}_j^{mth}/6.55\right)$	56.87	69.95	35.85	44.71	66.83	49.02	***323.23***	
$\bar{p}_s^{\text{const}}$ = 6.70 bar	7. $\left(1-\bar{p}_j^{mth}/6.70\right)$ (-)	0.25	0.20	0.08	0.10	0.23	0.27	-	**15.66**
	8. $\bar{Q}_j^{mth}\left(1-\bar{p}_j^{mth}/6.70\right)$	60.96	77.10	48.94	56.90	72.51	52.31	***368.72***	

CONCLUSIONS

In the operation of pumping stations equipped, at least in part, with variable speed pumping sets and a SCADA system, by determining the configuration of the pumps in operation and/or their speed, the operating points of the pumps may be imposed. But from the usual hydraulic design data, the only known operating point is the one in the design hypotheses, $\left(\bar{Q}_s^{\max}, \bar{p}_s^{\max}\right)$, with the hydraulic parameters evaluated with *Eq. (14)*. Thus, to fully satisfy any flow requirement, the constant current pressure set by the SCADA system, $\bar{p}_s^{\text{const}}$, is at least equal to the pressure $\bar{p}_s^{\max}$. Thus, for any scenario concerning the number and position of hydrants with MSWEs in operation, with the flow rate Q_s indicated by the flow meter, with $Q_s < \bar{Q}_s^{\max}$, the SCADA system imposes the operating point $\left(Q_s, \bar{p}_s^{\max}\right)$. For energy-saving purposes, according to *Eqs. (18)* and (*19*), the pressure p_s must be imposed, with $p_s < \bar{p}_s^{\max}$, and two procedures can be applied: I - based on the lower and upper wrapping curves; II - based on the median curve represented by the correlation (p - Q)$_C$. In procedure I, the operating point $\left(Q_s, p_s\right)$ must be included in the domain Ω_s (Popescu, 1983); therefore, the double inequality, $p_{am}^s \le p_s \le p_{av}^s$, must be satisfied, where, using the flow chart in *Figure 1*, it follows that $p_{am}^s = \dfrac{g}{100}\left[a_{INF} + b_{INF}\left(Q_s\right)^{c_{INF}}\right]$ and $p_{av}^s = \dfrac{g}{100}\left[a_{SUP} + b_{SUP}\left(Q_s\right)^{c_{SUP}}\right]$.

The disadvantage of the procedure I is that the SCADA system cannot control both pressures simultaneously, p_{am}^{s} and p_{av}^{s}.

In method II, the pressure p_s corresponding to the flow rate Q_s is obtained by spline interpolation using the flow chart in *Figure* 2, so that the operating point $\left(Q_s, p_s\right)$, placed on the median curve, according to hypothesis 4 of the *Introduction,* can be imposed by the SCADA system.

As shown in the case study, the correlation *(p-Q)_C*, implemented in the SCADA system software at PPS 2 of the Trifești-Sculeni irrigation system, during one irrigation season with 80% assurance, lead to a relative energy saving of up to 16%.

This methodology is intended to be useful in irrigable areas to improve the management of PPSs where the use of fixed pressure regulation is extensive.

The study developed in this paper is entirely original, so there was no external funding for this.

In the future, the flow and pressure requirements (*Eq.* 6) and (*Eq.* 7) are to be determined by calculation on the basis of a mathematical model presented in (Pricop et al., 2000, 2005); then the probability of feasible satisfaction of all possible requirements will be determined when they are approximated with the correlation (*Eq. 11*); the future mathematical model will also check the following hypotheses: 1 - the irrigation plot is equipped with $N_{T}^{MSWE} \geq 1$ types of MSWE, with different hydraulic characteristics; 2 - the flow and pressure requirements of the irrigation plot are also given by the position of the MSWE at the hydrants; 3 - the variation of the resistance of the pipes as a function of the flow is considered; 4 - the water losses due to the leakiness of the network are considered uniformly distributed along the length of the pipes; 5 - all possible flow requirements will be generated by using the random daily demand curve and/or WINGENERA simulation model (Lamaddalena *et al.*, 2015).

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