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Irrigation distribution network analysis

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Abstract: *The main purpose of this paper was to explore the possibility and limits of two basic approaches to water distribution system analysis. First approach represents demand-driven analysis, where on the first place lies nodal demand regardless from actual pressure. The second type is pressure driven analysis. This method is particularly suitable for the reason that most of the irrigators, mainly field crops is directly dependent on the pressure at the inlet to the machine and the demand is a function of pressure. Pressure driven analysis provides a better picture of the pressures as well as demands and thus the overall operation of the network. It is also preferable when assessing various unusual operating situations, such as very small load at once operated irrigation details, as well as assessing leaks and failures on the network, etc..*

Keywords: *demand-driven analysis, Epanet, irrigation networks, pressure-driven analysis, simulation model*

I. Introduction

Hydraulic assessment of irrigation network is particularly important while optimizing its operation, as well as in context of the proposal of the modernization and reconstruction. Pressure fluctuations in the system have in the case of the pressurized water distribution system a negative impact on the proper functionality of irrigation details, such as traveling gun sprinklers, pivot sprinklers or micro - sprinklers. Therefore, it is necessary to apply hydraulic analysis of the irrigation system that assess its behavior at different demand situation. Such hydraulic analysis is particularly important for verification of the optimal pressure conditions during operation of the system, which is in the case of the irrigation systems significantly variable in time.

The hydraulic analysis of the irrigation system can be accessed in two ways. The first approach represents so called Demand Driven Analysis (DDA), where fixed demands at nodes are given as input data, regardless of the actual pressure in the node. A different approach represents a Pressure-Driven Analysis (PDA), which takes into account the relationship between the pressure and the demand in the node. This relationship is usually known, because it is based on a specific irrigation detail (and is usually defined by the manufacturer in irrigator manual). These functional relationship is in this type of analysis basic input defining demands in the network. Additional data about demand from network is only the location of demands on the network. This approach is particularly important in cases where the demand is significantly dependent on the pressure (could have very different values) in the demand node, as is the case of irrigation sprinklers.

There are many computer models which can simulate water distribution pressurized systems, by help of which it is possible to analyse the hydraulic behavior of the network. However, in most cases available models serves for the DDA only. However, if we consider the change in flow regimes and demands at hydrants, such analysis is more difficult. Lamaddalena and Pereira [1],[2] have proofed that even in cases where the flows in network comply with the original dimensioning flows, there may occur states during operation with very low pressures in the system, for example due to inappropriate irrigation detail placement during operation. Therefore, it is evident that it is necessary to address the performance analysis of the irrigation system, because of the significant spatial variability of flow situations [3]. This variability is particularly important in the case of irrigation systems, because the node demands are relatively large (for example, in comparison with demands in drinking water distribution systems). Demands, which occurs in the drinking systems due to their large number and relatively small size are “statistically balanced in time”, and summary approximately constant (for some hour of the day), but the change of the location of a large demand in the case of the irrigation uptake from network significantly affect and change whole hydraulic state of the system.

In view of these facts, several models have been developed to help improve the methodology of the analysis of the functionality of irrigation systems while one is accomplishing their design or for purposes of operation and management [4], [1], [5]. Shortages of these simulation models is that they cannot be easily adapted to situations where the behavior of the network is significantly affected by pressure conditions. This condition can occur when the system does not have the appropriate flow restrictor eventually the pressure regulator to the hydrants. Different models have been developed for water distribution systems in urban areas that utilize different types of non-stationary flow [6], [7], [8], [9]. However, applications of this type of models in irrigation systems is rather rare. In order to perform an analysis of the irrigation networks different models and strategies were developed [10], [11], [12]. Model FLUCS [11] simulates the flow in the network, by using a simplified system of the characteristic equations of flow. Performance analysis is accomplished on the basis of the calculations of relative pressure deficits at any hydrant within a given number of configurations of hydrants that work in parallel. These configurations were randomly generated and there is much more of them than is the number of the hydrants. The authors tested the model with data collected in irrigation system Capitan in southern Italy. The results demonstrated the capability of the model to reproduce the pressure conditions that were observed at selected hydrants.

As is apparent from the preceding text issue of evaluation of the effectiveness of irrigation systems is not sufficiently investigated. Therefore, the authors of the paper has focused on a comparison of mentioned two modelling approaches, which are crucial for such analysis. The aim was to provide a complex overview of the water distribution systems hydraulic evaluation in irrigation, from the point of view of its variable operation.

II. Methods

As mentioned in the previous section, the authors of the paper has focuses on the analysis of the irrigation systems in terms of the reliability providing the required pressure at the hydrants and reliability of achieving the requested node demands. The dependence on the pressure in the node is an important from the point of view of a uniformity of water distribution over the irrigated area.

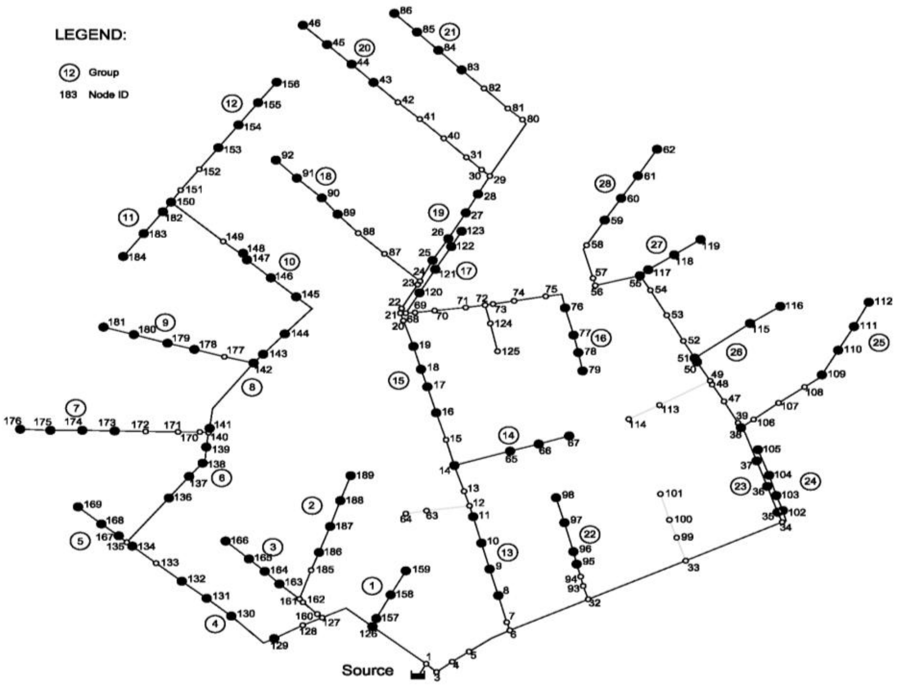

Fig. 1 Situation of the "Trhove Myto II" irrigation network, 4 hydrants in group

A computer model EPANET [13] was used for the hydraulic analysis. Its GUI version served for the development of the hydraulic model of studied network itself. Its Toolkit version (basically DLL file) allowed the calculation of pressures, respectively demands in individual hydrants in a large number of demand situations (because of the variability in sprinklers deployment). As the case study an older irrigation system "Trhove myto II." was used. This system is located in the southern part of Slovakia (Fig. 1). It is an older system, which is approaching the end of its useful life and is suitable for demonstrating procedures of reconstruction design. Authors would like to demonstrate an analysis by which the following calculations could serve as tool in designing reconstruction which could improve its functionality. It was originally designed as a branched network with two main branches. Hydraulic model was created for purpose of the system analysis. This model contains 188 pipes and 189 nodes. Pipe material as in most systems proposed in the former Czechoslovakia is combination of asbestos cement and cast iron pipes.

For the purpose of this work, generator of the demand situations was created, because as was already emphasized, the irrigation systems are characterized by significantly variable pressure- flow situation which could be modelled by help of such tool. It is not possible to assess and properly evaluate the system taking to the consideration only a single demand situation. The authors created a computer model for generating realistic demand situations, whose mission is positioning of the selected irrigation detail (number of sprinklers defined by user) in various places of the irrigation area. This is done alternatively, as placement of sprinkler is changing, which is true also in real operation of the irrigation system. Such alternative placement of irrigators lead to the high amount of demand and hydraulic situations (e.g., many thousands of situations), which has to be assessed and evaluated by the simulation model. For such purpose hydraulic model should be run programmatically in batch mode. Relevant programs for this task have been developed by the authors of paper using the aforementioned EPANET Toolkit.

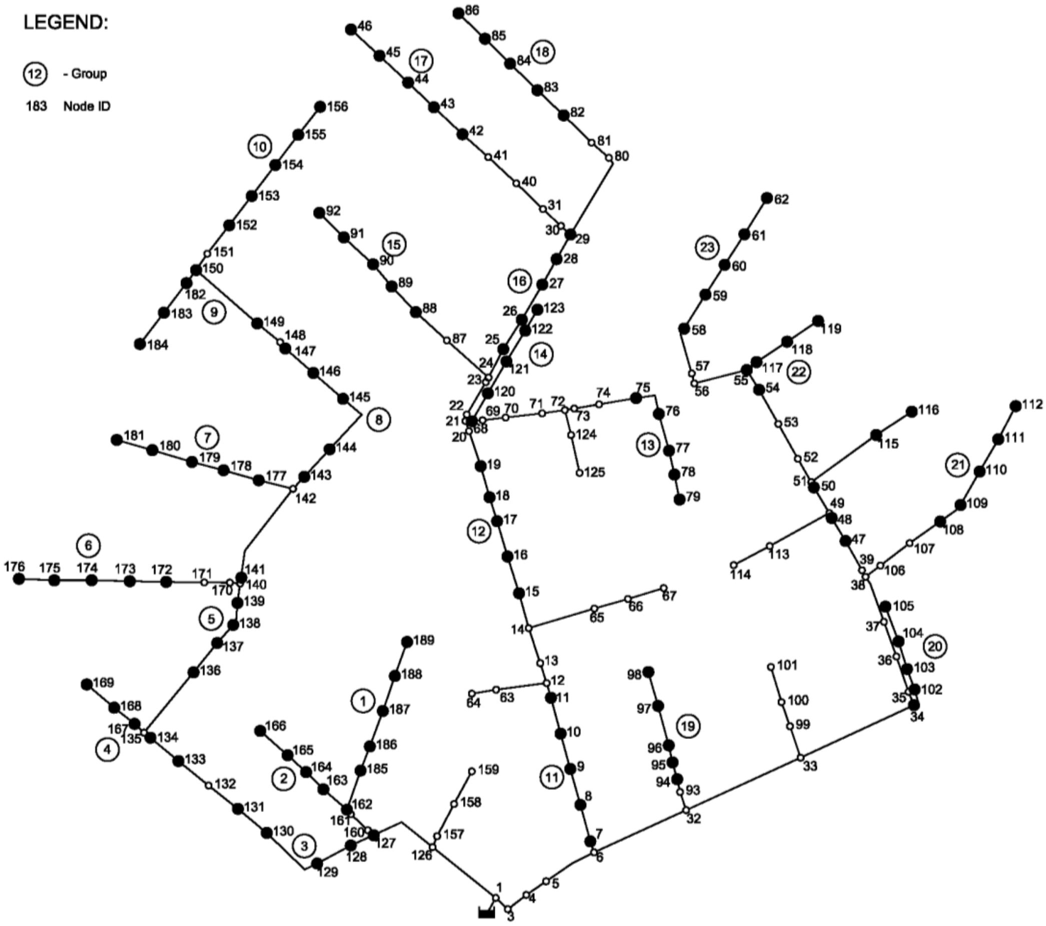

Fig. 2 Situation of the "Trhove Myto II" irrigation network, 5 hydrants in group

In general, can be said that during the operation, hydraulic situations in which is demand concentrated in some parts of the network (irrigators are in some parts close to each other) are usually more problematic with regard to ensure necessary pressure on hydrants. For this reason, i.e., to investigate primarily critical placement of the irrigators in the network, it was considered to use so called group placement of sprinklers, which is, with regard to the operational benefits popular in practice. This means that, e.g. five or six sprinklers forms a group, and are located on neighbouring hydrants. After applying necessary amount of water, the machinist moves such group to other place, again as group to some other neighboring hydrants. Number of irrigators in a group together with the minimal number of free hydrants between the groups (hydrants without a demand) are the main input parameters in mentioned model to generate demand situations.

Because of this strategy, prior to the analysis of the irrigation system realistic deployment of group of sprinklers were established. Two alternatives was considered, with four and five sprinklers in the group. Considering the arrangement of the proposed system, a total of 28 groups with four sprinklers (Fig. 1) and 23 groups with five sprinklers were proposed (Fig. 2). These represent potential placing of irrigators, where irrigation is needed.

Not all these groups works simultaneously. This number of groups depends on the maximum delivery rate of the pump station. It was determined that in the case of 4-sprinklers is the number 23 groups and 18 for the 5-sprinklers group. To obtain the number of all possible combinations following equation is used (permutations, combinatorics):

$$\text{Total number of demand situation} = \left(\frac{\text{number of posible groups}}{\text{number of simultaneousy operating groups}}\right)$$

In this paper authors investigated the operation of the system when system is fully loaded, e.g, the total number of irrigators is considered for situation when the maximum possible flow is taken from the pumping station. Combination (without repetition) of these values represent amount of possible hydraulic situation (possible irrigators' placement). 98 280 possible situation was enumerated by above mentioned combinatorics formula for setting of group to 4 irrigators and in case of 5 irrigators in group was estimated total number of 33 649 situations. This values represents the total number of hydraulic situations which should be evaluated. Due to the large amount of such situations it is not possible to evaluate them in the EPANET user interface. So therefore for purpose of this analysis another generator of operational situations was developed. Generator, at first produces demand situations and automatically changes on the basis of the placement of the irrigators data about the network (basically data about demands from network nodes). Subsequently this software tool developed by authors of this paper evaluates hydraulics of the network in each generated demand condition and writes results (pressures and flows) into a file. These files are then subjected to the statistical analysis.

For purpose of this analysis two alternatives of generators of the demand deployment were developed. In the first case, demand from node is constant and do not depends on pressure (7.5 ls-1). In the second case, when PDA was accomplished, at first it was necessary to determine the parameters of the irrigator used according to its pressure/flow curve, which is usually provided by the manufacturer. The parameters "emitter coefficient" and "emitter exponent" serves in EPANET for definition of this function. It is defined as dependence between the pressure and the pressure in the node using the following form:

$$Q = C \cdot P^{y} \tag{1}$$

Where Q is flow through sprinkler (demand), C is emitter coefficient, P is pressure in sprinkler and y is emitter exponent. In addition, as stated above, it is necessary to determine the locations of irrigators.

Using this alternative of generator, similarly as in the first case (generator with constant demands) pressures in the nodes in all generated demand situations were evaluated. In addition to this also nodal outputs from network have been recorded, as these were pressure-dependent and therefore variable (as it is in reality). The program described hereinbefore was created with regard to the possible application in the context of assessing the proposals of the irrigation systems or for its reconstruction and also for evaluating the functionality of existing irrigation systems.

III. Results

Testing of the irrigation network hydraulics was performed under two variants of demands placement conditions (4 and 5 sprinklers in the group) and two alternatives of hydraulic analysis (DDA and PDA). The results are interpreted in Figure 3.

In the first step mean pressures were evaluated. The mean pressure value in the group for all operating situations, which has been analyzed is in Fig. 3 interpreted in the form of box plot. Due to the significant amount of output data about pressure were these data aggregated for each group to the mean pressure in a group for the demand situation. Box plots were chosen in view of the fact that they offer a simple possibility of evaluation and also provide a better overview of large amounts of given data. Thanks to this, they can provide a better understanding of the pressure behavior in each group as well as the performance of the whole network within the demand situation. The structure of the graph is the same for all the alternatives within Fig. 3. The horizontal axis represents the individual demand group. On the vertical axis is the mean pressure head in the demand group.

In Fig. 3a, and 3b are presented pressures for five sprinklers in the group. As we can see, the minimum pressures in PDA (Fig. 3, b) are at least 10 -15 [m] higher than it is the case for the DDA (Fig. 3, a). Another fact that one can note is that the dispersion of the values in the PDA is smaller than is in the case of DDA. This fact can be logically inferred from fact of using the fixed demand, which is greater - this demand do not exist in real situation, because of the insufficient pressure in the network, which limit this value. Unrealistically greater demands leads to greater flows and greater hydraulic losses – and smaller pressures in hydrants. In the case of PDA with a lower pressure also demand in nodes is reduced, which is of course physically correct.

For both cases, the groups with the lowest pressure are group's number 1 and 15 and the largest variance of values occur in groups 9 and 10. This illustrates degree at which these groups are affected by changes in demand situations in other parts of the network. This information can in both cases helps us to identify potentially problematic group and this was subsequently addressed in more detailed further analysis. Eventually it is possible to propose in this part of irrigation system another way how to operate irrigation, sprinklers or chose other irrigators which needs different pressure at the inlet to the machine.

Further evaluation has aimed on analysis of demands at the hydrants during the PDA. The aim was to analyze at what level are influenced the demand in demand nodes by the pressure, which could be evaluated in this type of analysis. Logically, the DDA don't offer this type of assessment. Mean deficits of demand in nodes were calculated according to the following formula:

$$\overline{Q}_c = \frac{\sum_{i=1}^{n}(Q_{ci} - Q_p)}{Q_p} \tag{2}$$

Where $\overline{Q}_c$ is average deviation from required demand at node, Q_{ci} is nodal demand calculated by the simulation model, Q_p is required (design) flow through the sprinkler.

The first paragraph under each heading or subheading should be flush left, and subsequent paragraphs should have a five-space indentation. A colon is inserted before an equation is presented, but there is no punctuation following the equation. All equations are numbered and referred to in the text solely by a number enclosed in a round bracket (i.e., (3) reads as "equation 3"). Ensure that any miscellaneous numbering system you use in your paper cannot be confused with a reference [4] or an equation (3) designation

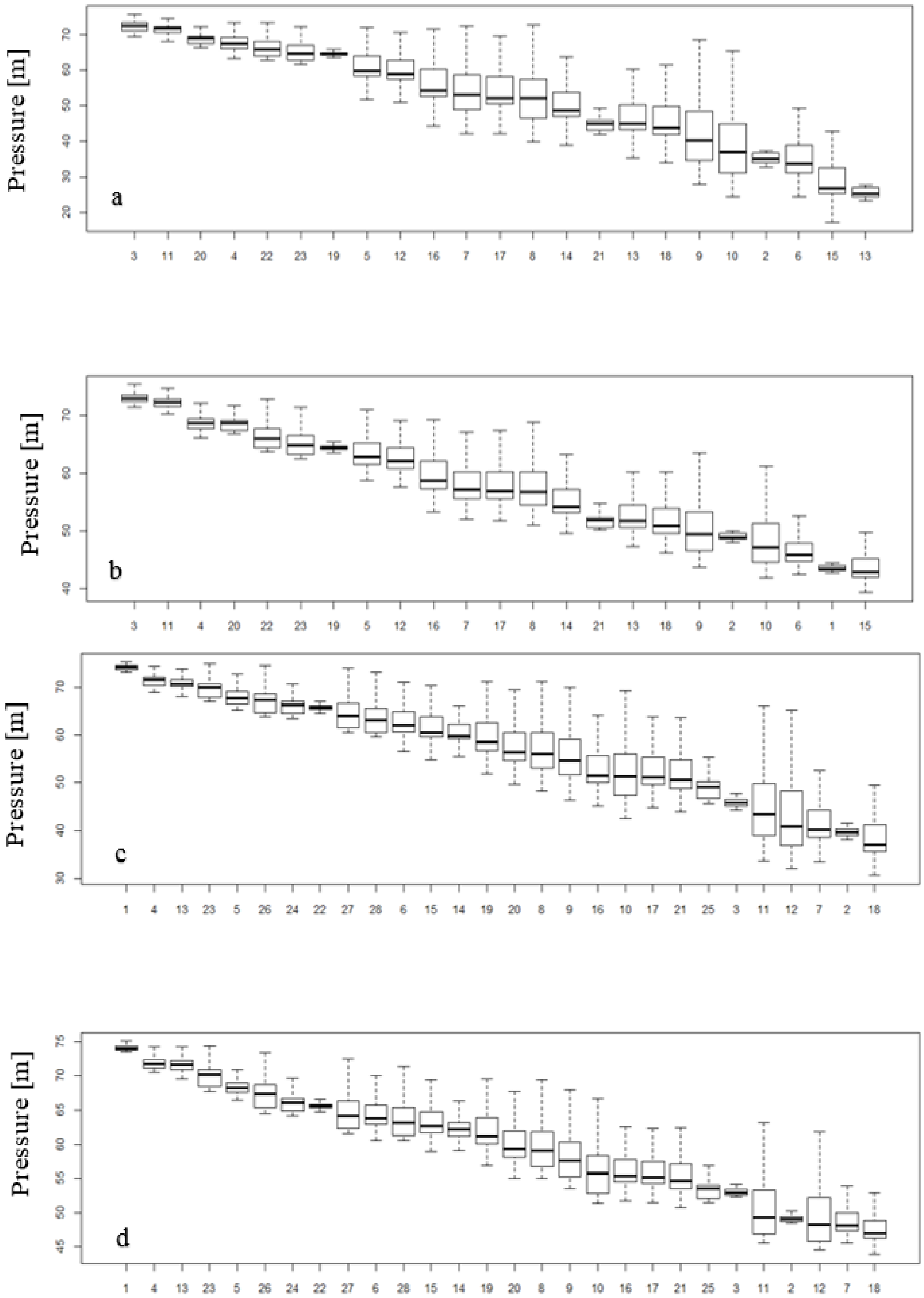

Fig. 3 Boxplot of mean pressures in group, a) DDA 5 hydrants in group, b) PDA 5 hydrants in group, c) DDA 4 hydrants in group, d) PDA 4 hydrants in group

Obtained values of the deficit in amount of the water supplied, which is based on the previous equation are interpreted in Fig. 4, 5. Figures shows the relative average deficit in the demand nodes when running all demand situations as in the case of the PDA. By these means we obtain a tool for identification of the hydrants, in which most commonly insufficient demand appears, respectively it is also possible to identify possible critical group for which the required nodal demand is not achieved, which is important information with regard to irrigation requirements.

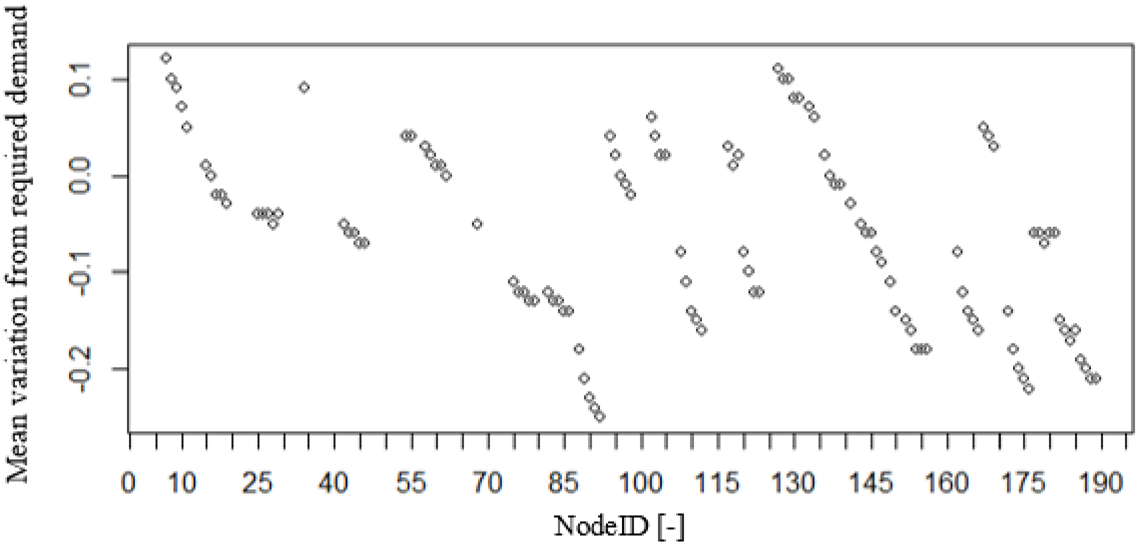

Fig. 4 Mean relative deficiency of the demand in PDA, 5 nodes in the group

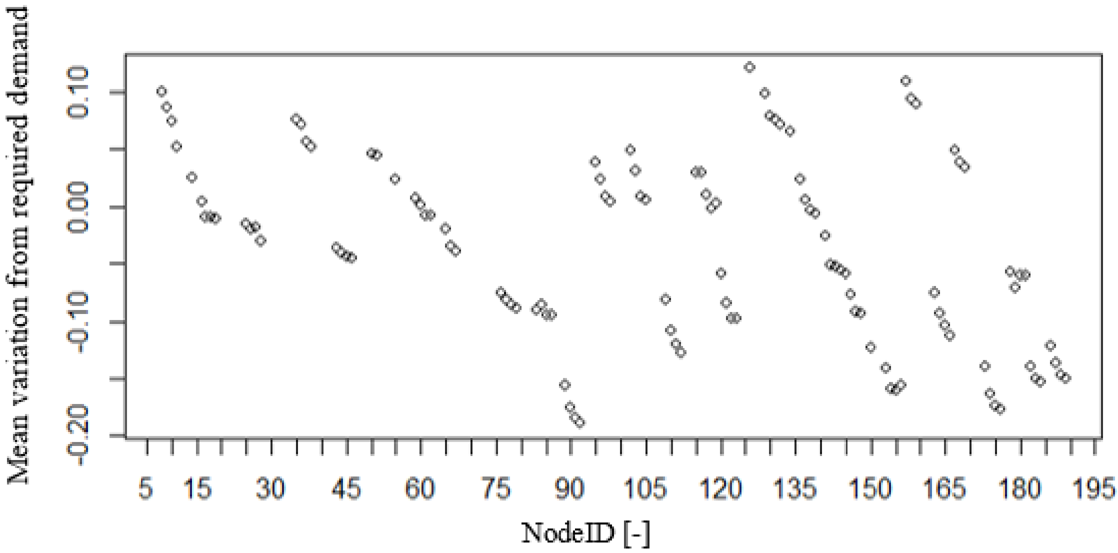

Fig. 5 Mean relative deficiency of the demand in PDA, 4 nodes in the group

To better illustrate the obtained results these values were ordered from largest to smallest and compared with one another in the Fig. 6. In the chart we can see, that the achievement of the required demand was higher in group with 4 sprinklers. This, together with the development of pressure points confirms that better pressure and demand conditions would by achieved with the deployment of 4 sprinklers in the group, so the operator of the irrigation system had rather to choose this pattern of irrigation and recommend it for operation.

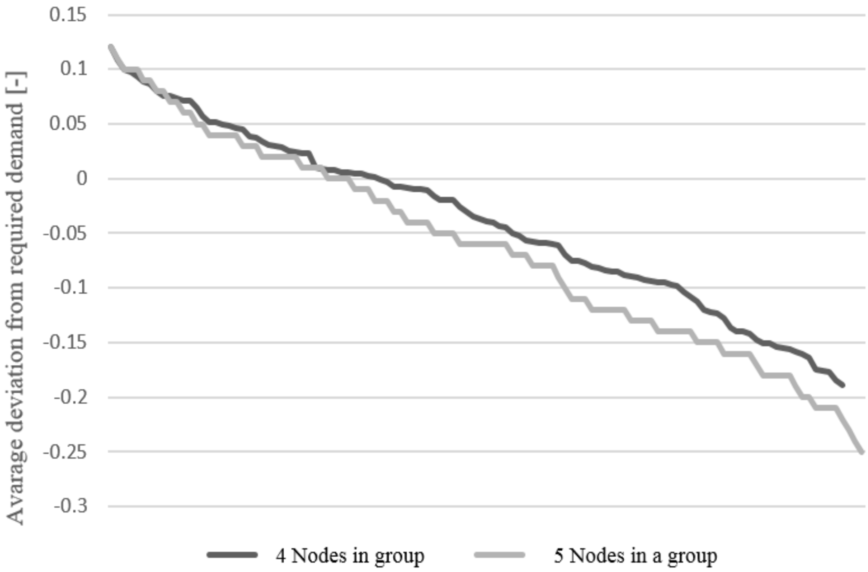

Fig. 6 Mean relative deficiency of the demand in PDA, 4 and 5nodes in the group

Based on the results of a comparison of PDA and DDA, we can say that the DDA overestimated hydraulic requirements on the network, in fact there would be first lower demand at the planned number of sprinklers and depending on it will be (for the same pump with the same characteristics QH) higher pressures on the pump station. If these pressures are redundant, they can be reduced by providing appropriate operation or technology at the pump station, thus saving energy costs (or they can be evaluated more realistically).

IV. Conclusion

The paper is focused on comparison of two approaches used in the analysis of water distribution systems in irrigation. The aim was to assess the shortage of DDA and also make an effort to highlight the appropriateness of applying PDA methodology in the case of irrigation systems. This is particularly suitable because the majority of irrigators, particular field crops is directly dependent on the pressure at the inlet to the machine and then the demand is a function of the pressure. From this point of view this type of analysis provides a better overall picture of the system as well as the quantity of water supplied, and it unrolling water irrigation rates which affects the proper development of crops.

Low pressure in the case of DDA as consequence of the fixed demand in the nodes, which influences calculated output pressure, could lead to oversizing the network in the design stage (with the impact on the investment costs). PDA therefore provides a better picture of the pressures as well as demands at nodes and thus on the overall performance of the network. It is also preferable when assessing various unusual demand situations, such as in terms of a very small intake of the system (one time operation of irrigation detail), as well as assessing leaks and failures on the network, etc.

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