REDUCING ENERGY CONSUMPTION IN PRESSURIZED IRRIGATION NETWORKS USING NEURAL NETWORKS-SOMS CLUSTERING TECHNIQUE

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ABSTRACT

With continuously increasing cost of energy, conservation of energy in pressurized irrigation networks has become an important goal. Such networks are usually designed to irrigate sectors of approximately equal areas in turns. Pumps are often operated to guarantee maximum head required for all sectors. This design criterion, however, does not guarantee minimum energy consumption. In this study, Neural Networks, Self-Organizing Maps (SOMs) clustering technique is used for grouping (sectoring) hydrants with the same characteristics in order to minimize the energy consumption. To identify the hydrant characteristics, three dimensionless parameters are proposed; the relative elevation (z^*), the relative distance from pump station (l^*), and the relative head at hydrant (h^*). MATLAB - EPANET Toolkit is used to implement the suggested clustering technique and evaluate the impact of proposed management on energy consumption. The proposed methodology is applied to a drip irrigation network at Kostol area, Egypt. Results show that energy savings up to 16.42% can be achieved for the whole irrigation season.

Keywords: Neural Networks, Clustering, Energy saving, Irrigation Network

1. INTRODUCTION

Water Scarcity is an increasing problem for many countries nowadays. In Egypt, water share at year 2018 reached about 570 m^3/capita/year, which is less than the water poverty line (1000 m^3/capita/year). To improve irrigation efficiency, pressurized irrigation techniques are now widely used. However, the expansion in pressurized irrigation will cause significant increase in energy consumption. The balance between the two objectives; maximizing irrigation efficiency and minimizing energy consumption in such systems is highly required. Different alternatives to reduce energy consumed by irrigation systems, and increase economic benefits were evaluated (Gilley and Watts, 1977; Gilley and Supalla, 1983). Physical and management changes in center pivot irrigation networks were proposed by Buchleiter et al. (1986). The proposed improvements could reduce energy use up to approximately 37%.

Abadia et al. 2008, and 2012 presented and applied a methodology for total energy efficiency assessment considering the pump station and network system. Measures to improve global energy efficiency GEE for an irrigation system was proposed and an increase from 22% to 32.7% was estimated. Rodríguez Díaz et al. (2009) proposed an alternative management technique including sectoring based on elevation and dynamic head at the pump station. This technique resulted in an energy saving up to 22%. Moreno et al. 2010a, b. conducted an analysis of energy performance of pressurized irrigation systems, and compared between networks managed on-demand, and on rotations. Energy savings of 9.5% was achieved in the networks managed on-demand. Jiménez-Bello et al. 2010, and 2011, used a genetic algorithm to minimize energy consumption in irrigation networks by grouping intakes. Grouping either intakes or hydrants to ensure a minimum operating pressure resulted in 36.4% energy savings. The methodology was applied in a case study located in Spain. The results estimated from the model were then compared with field results. Another optimization tool, simulated annealing (SA), was proposed by Prats et al. (2011). Results showed that an energy saving of 11.8 % and 15.5 % was achieved for on-demand and sectorization scenarios, respectively.

Carrillo Cobo et al. (2011) presented a new methodology for sectoring considering both hydrant elevation and its distance from the pump station. All hydrants were identified by two dimensionless coordinates; the relative elevation (z^*), and the relative distance (l^*). The k-means clustering algorithm was used to identify the various sectors. A potential energy savings of about 8 % over the annual energy consumption was obtained. Rodríguez Díaz et al. (2011) used the performance indicators established by the International Program for Technology and Research in Irrigation and Drainage (IPTRID) to evaluate water and energy consumption in pressurized irrigation networks.

Rodríguez Díaz et al. (2012b) analyzed the location of critical hydrants. Management strategies considering the critical hydrants and network sectoring were compared. Results showed that a potential energy savings of around 10.5% and 31.4% were possible when theoretical irrigation requirements are satisfied. Fernández García et al. (2017) combined critical hydrants control and sectoring into a new model. Average energy savings of about 16.7% was achieved by disabling the optimal number of critical hydrants and operating these hydrants at off-peak hours.

Lima et al. 2018, and 2019 developed a model to simulate on-demand network behavior, considering crop patterns in the irrigated area. It was concluded that integral management of both water and energy is required. In the current study, the objective is to develop a model using the Neural Networks-Self-Organizing Maps (SOMs) clustering technique, which has advantages over many of the traditional clustering techniques, to sector irrigation networks in order to minimize energy consumption. The suggested model is applied to a drip irrigation network at Kostol area, on the right bank of Lake Nasser, south of Aswan High Dam, Egypt.

2. STUDY AREA

The general layout of the drip irrigation network at Kostol area is shown at Figure 1. The network irrigates 173 farms each with an area of 20 Feddans (about 8.4 hectars), with dimensions of 192 × 440 m. The study area is located in an arid region. The average reference evapo-transpiration rate, ET_o, is 7.40 mm/d, with a maximum rate of 10.40 mm/d in June, Figure 2. The main crops in the area are citrus trees and vegetables. The network includes 72 hydrants, each hydrant's base demand is 0.8 ℓ/s/fed (1.905 ℓ/s/hec). The maximum difference between hydrants' elevations is 44m, the lowest elevation is 187 m, and the highest elevation is 231 m. The main pipeline has a length of around 10.9 km with diameters between 1650 to 600 mm, and the total length of the pipelines is 40.417 km, with diameters between 1650 and 150 mm.

The minimum head required at the pump station is estimated to guarantee an operation head of 30 m at each hydrant. However, for critical hydrants, booster pumps are used to satisfy this head. For such hydrants, a minimum head of 5 m at the sump of each booster pump is provided by the main pump station.

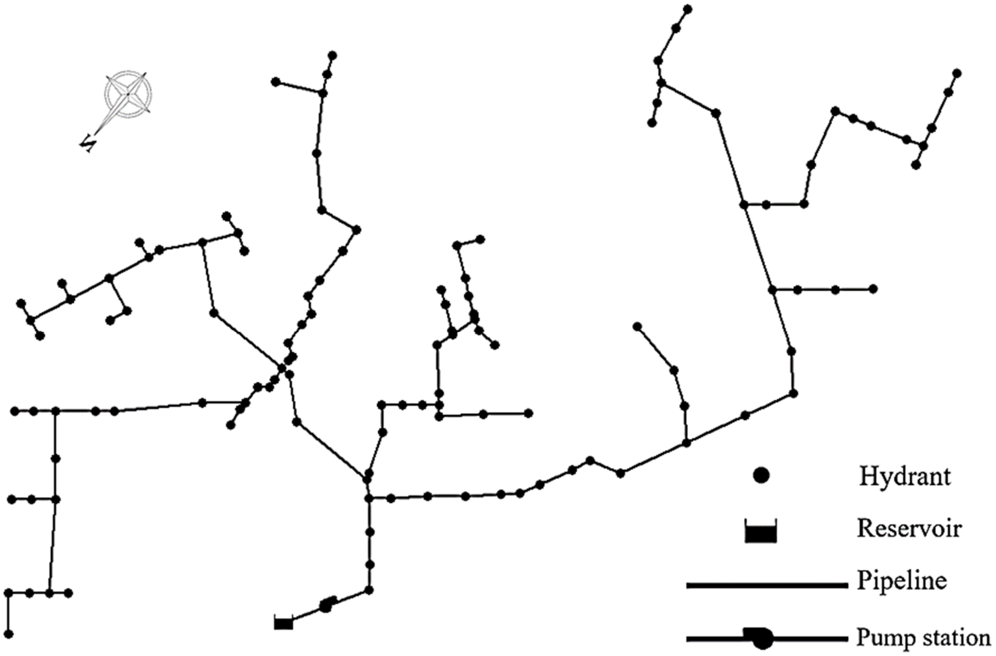


Figure 1. Kostol irrigation network.

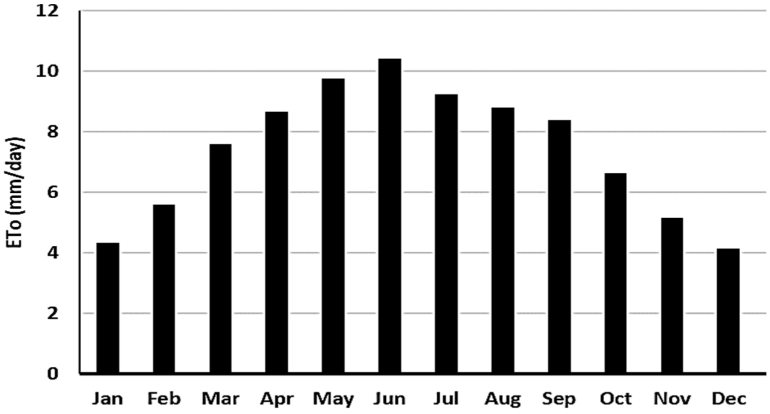


Figure 2. Average monthly reference evapo-transpiration rates at Kostol (Agricultural RC, and Desert RC, 2013)

2.1 Dimensionless Parameters

Three dimensionless parameters; $z*$, $l*$, and $h*$ are used in the proposed methodology to identify the hydrant characteristics for the study area.

Relative head h^* at hydrant

The minimum head, H_p, required at the pumping station to operate the hydrants' sub-units properly is

$$H_p = max(z_i + h_{fi} + h_i) \tag{1}$$

where z_i = the elevation of hydrant i measured from pump station elevation; h_{fi} = the friction losses from pump station to hydrant i ; and h_i = head at hydrant i to operate the sub-units. The relative head at hydrant i,

$$h_i^* = {h_i}/{H_p} \tag{2}$$

Relative elevation z^* of hydrant

$$z_i^* = {z_i}/{z_p} \tag{3}$$

where z_p = the elevation of pump station.

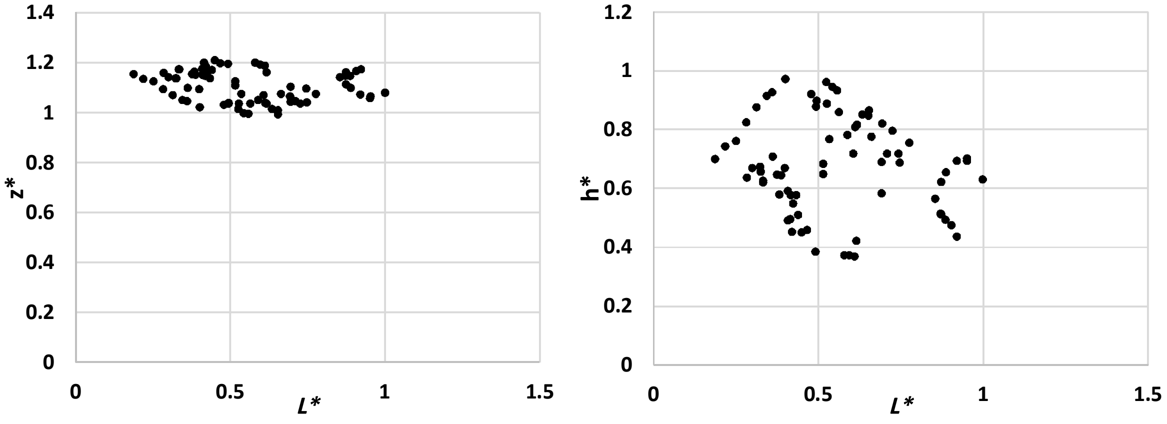
Relative distance l^* of hydrant

$$l_i^* = {l_i}/{l_{max}} \tag{4}$$

where l_i= the distance of hydrant i from pump station, and l_{max} is the distance from the pump station to the furthest hydrant.

2.2 Networks' parameters

Figures 3(a) and 3(b) show the inter-relationship between the three parameters; $z*$, $l*$, and $h*$ of the networks' hydrants.



(a) $z*$ versus $l*$ (b) $h*$ versus $l*$

Figure 3. Dimensionless parameters for all hydrants

The maximum distance from the pump station is 12.186 km and the minimum distance is 0.465 km and the values of l^* range from 0.04 to 1.0. Pump station elevation (z_p) is 188.26 m and the elevations of hydrants vary from 187 m to 231 m. Hence, values of z^* vary between 0.991 and 1.229. Values of h^* vary between 0.367 and 0.97. As shown in the figures variation of h^* throughout the network is much more significant compared to z^*.

In this study, z^*, l^* and h^* are firstly used to cluster hydrants then the best combination of these parameters to reduce energy consumption is selected. Values of h^* are estimated at the beginning of the simulation to guarantee the required head at all the hydrants.

3. METHODOLOGY

3.1 Neural networks-self-organizing maps clustering algorithm

Artificial Neural Networks (ANNs) are models for simulation, recognition of patterns, time series prediction, or optimization problems. Figure 4 shows a simple form of neural network. These models are based on concepts from the nature of the human brain, Müller.et al. (1995). Neural networks are basically divided into supervised and unsupervised networks. Self-organized maps (SOMs) are one of the unsupervised neural networks types, Kohonen (1982). The essential idea of SOMs is to map the data patterns into an n-dimensional grid net of neurons or units. This technique organizes an unlimited number of input data in a grid, where neighbor nodes have mutual similarity, Vesanto et al. (1999).

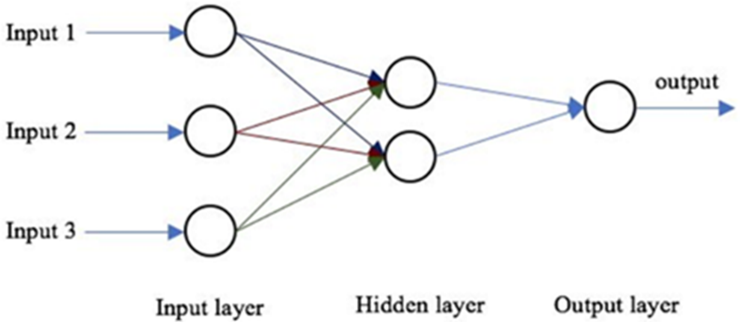


Figure 4. Simple neural network layout.

3.2 Crop water requirements and irrigation time

CROPWAT 8.0, Clarke et al. (1998), is used to estimate the reference evapo-transpiration rate (ET_o) for the studied area. The crop coefficient (k_c) is determined for the crop growth stages. For known values of roots depth (d_r), and irrigation system efficiency, gross water depth to be applied (D_g) is calculated. The maximum allowable interval between two successive irrigations (*Irrigation Interval, II*) and required time for irrigation (t_{req}) are estimated. For each month, maximum number of sectors (N_{sec}) the network can be clustered into is estimated as follows;

$$N_{sec} = \frac{II \times t_a}{t_{req}} \tag{5}$$

where t_a = available time for irrigation (hr/d). Table (1) shows the required time for irrigation, the number of days between two successive irrigations, and the number of sectors to guarantee the required irrigation depth for each sector.

3.3 Energy and power requirements

The minimum pump head (Hp) to guarantee minimum required head at the most critical hydrant is estimated. For the flow rate and the head at the pump station, the power (P_j, *kw*) required for sector j , is calculated using the following equation;

$$P_j = \frac{\gamma \times Q_{p,j} \times H_{p,j}}{\eta} \tag{6}$$

where γ = water specific weight (9.81 kN/m^3); $Q_{p,j}$ = flow rate at the pump station for sector j (m^3/s); $H_{p,j}$ = pressure head at the pump station (m); and η = pump station efficiency, considered constant and equals to 0.75.

The energy consumed for month k ($E_{c,k}$, *kWh*) is estimated as follows;

$$E_{c,k} = \sum_{i=1}^{n} P_j \times t_{req,k} \times N_k \tag{7}$$

where n = the maximum number of sectors, and N_k= Number of irrigation days in month k.

Table (1). Values of II, t_a, t_{req}, and N_{sec}

Months	***II* (days)**	***t_a* (hr)**	***t_{req}* (hr)**			**N_{sec}**
			(Trees)	**(Veg.)**	***(Total)***	
Jan	2	20	9	3	12	3
Feb	2	20	11	4	15	2
Mar	1	18	8	3	11	1
Apr	1	18	9	4	13	1
May	1	16	9	3	12	1
Jun	1	16	10	0	10	1
Jul	1	16	9	0	9	1
Aug	1	16	8	0	8	2
Sep	1	18	8	0	8	2
Oct	2	18	13	4	17	2
Nov	1	20	5	2	7	2
Dec	2	20	8	4	12	3

The hydrants are grouped into sectors with homogeneous dimensionless parameters. For this purpose, neural networks clustering technique is used. The number of the clusters is identified and fixed at the start of the simulation for each month of the irrigation season. For any specific month, the network can be sectored into no more than three sectors, otherwise, the available time to irrigate each sector will not be enough to apply the required irrigation depth for that month.

After simulating the sectorized network with the new operating conditions, the head at the most critical opened hydrant is estimated, if the head is higher than the required operation head, then the pump head can be successively reduced by steps of 0.10 m until the head at that hydrant reaches the required head. A 5 % tolerance in hydrant pressure head is assumed. No deficit irrigation is considered in the current study.

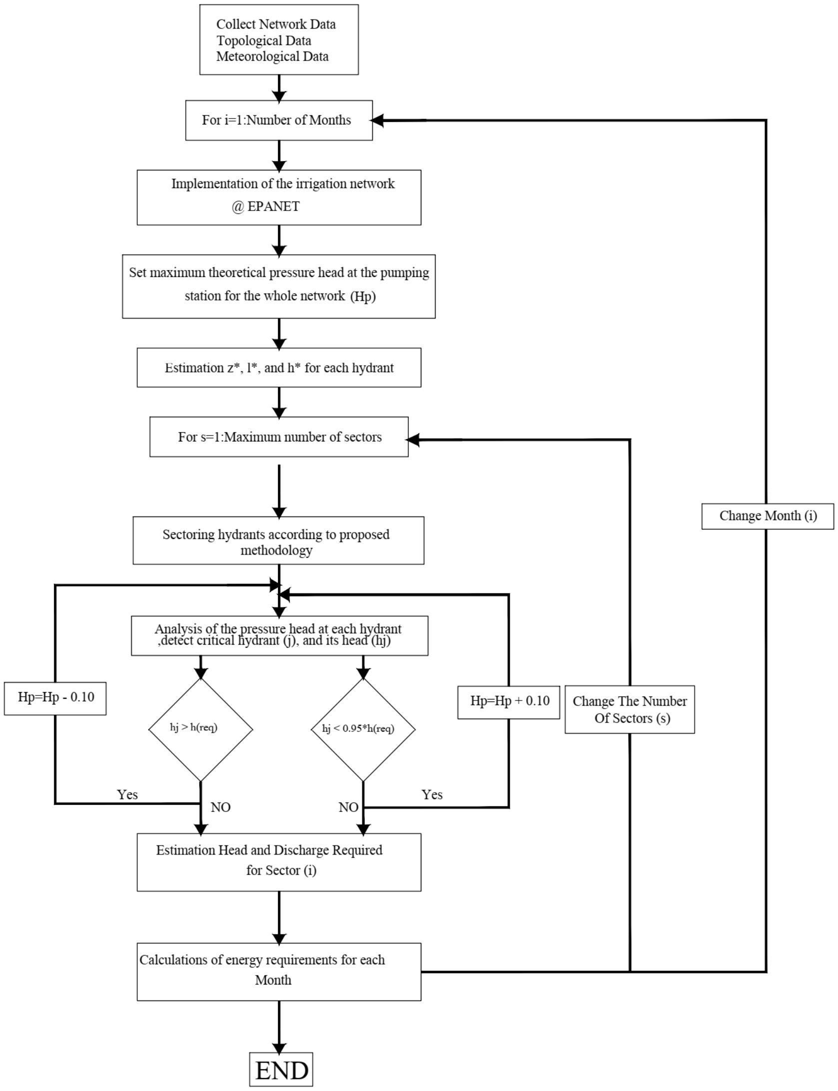


Figure 5. Algorithm flowchart.

The flowchart shown in Figure 5 summarizes the algorithm used to obtain energy consumption for the proposed sectors for the whole irrigation season. Matlab - Epanet Toolkit, Rossman (2000) is used to evaluate the impact of proposed management on the network hydraulic behavior and energy consumption.

4. RESULTS AND DISCUSSION

Energy consumption for all months of the irrigation season is calculated for both existing operating conditions (one sector) and according to the suggested operating conditions (sectoring using self-organized maps (SOMs)).Different combinations of the dimensionless parameters are tested to determine which combination achieves the greatest energy savings. These combinations included: (*l*,z*,h**), (*l*,z*),* (*l*,h**), (*z*,h**), and (*h** only). The network is divided into a number of sectors according to irrigation water requirements for each month. Figure 6 shows energy savings percentage for the different combinations.

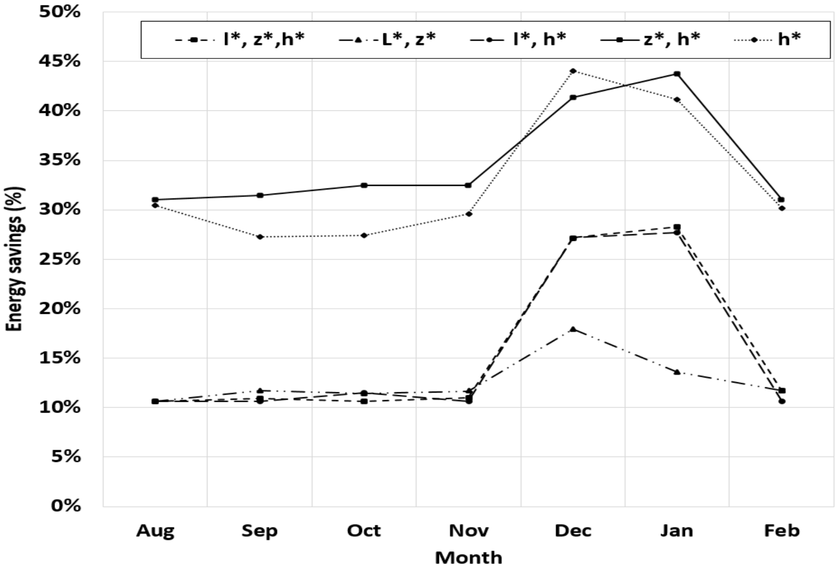


Figure 6. (%) Energy savings in sectored months for the different combinations of l^*, z^*, and h

Table 2, Number of Sectors, Energy Consumption (kWh), Energy Savings (%) for each month, total Energy consumption during the whole season (kWh), total energy savings (%)

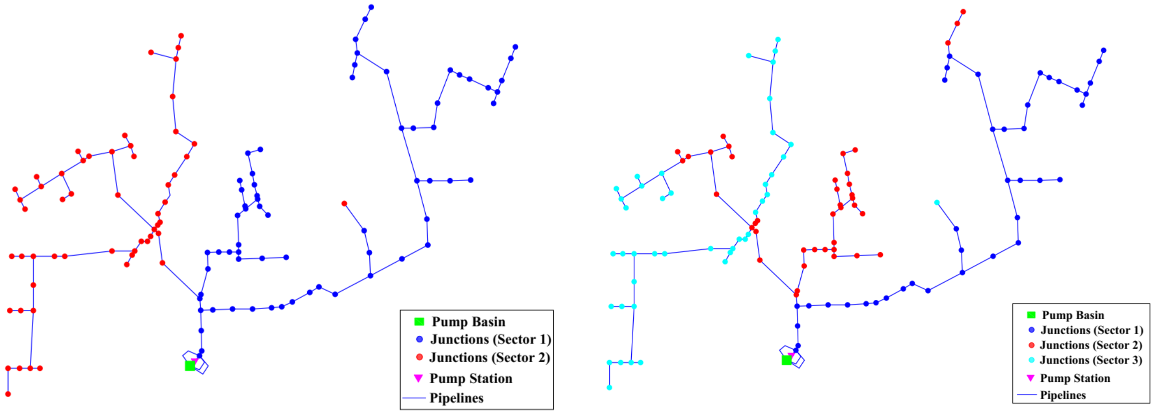
Months	Jan			Feb			Mar			Apr		
	No. Of Sectors	Energy Cons.	Energy Savings %	No. Of Sectors	Energy Cons.	Energy Savings %	No. Of Sectors	Energy Cons.	Energy Savings %	No. Of Sectors	Energy Cons.	Energy Savings %
Network as One Sector	1	319703	-	1	360955	-	1	586122	-	1	670345	-
z*, h*	3	179886	44%	2	248918	31%	1	586122	0%	1	670345	0%
h*	3	188042	41%	2	252078	30%	1	586122	0%	1	670345	0%
z*, l*,h*	3	229223	28%	2	318847	12%	1	586122	0%	1	670345	0%
l*, h*	3	231167	28%	2	322538	11%	1	586122	0%	1	670345	0%
z*, l*	3	276227	14%	2	318624	12%	1	586122	0%	1	670345	0%

Months	May			Jun			Jul			Aug		
	No. Of Sectors	Energy Cons.	Energy Savings %	No. Of Sectors	Energy Cons.	Energy Savings %	No. Of Sectors	Energy Cons.	Energy Savings %	No. Of Sectors	Energy Cons.	Energy Savings %
Network as One Sector	1	639406	-	1	515650	-	1	479555	-	1	426271	-
z*, h*	1	639406	0%	1	515650	0%	1	479555	0%	2	293960	31%
h*	1	639406	0%	1	515650	0%	1	479555	0%	2	296472	30%
z*, l*, h*	1	639406	0%	1	515650	0%	1	479555	0%	2	380902	11%
l*, h*	1	639406	0%	1	515650	0%	1	479555	0%	2	380902	11%
z*, l*	1	639406	0%	1	515650	0%	1	479555	0%	2	380902	11%

Months	Sep			Oct			Nov			Dec			Total Energy Consumption (MWh)	Average Energy Savings %
	No. Of Sectors	Energy Cons.	Energy Savings %	No. Of Sectors	Energy Cons.	Energy Savings %	No. Of Sectors	Energy Cons.	Energy Savings %	No. Of Sectors	Energy Cons.	Energy Savings %		
Network as One Sector	1	412520	-	1	452913	-	1	360955	-	1	319703		5544	-
z*, h*	2	282835	31%	2	305997	32%	2	243869	32%	3	187451	41%	4634	16.42%
h*	2	300093	27%	2	328865	27%	2	254085	30%	3	178894	44%	4690	15.41%
z*, l*, h*	2	367476	11%	2	404709	11%	2	321298	11%	3	232866	27%	5146	7.17%
l*, h*	2	368615	11%	2	400966	11%	2	322538	11%	3	232866	27%	5151	7.10%
z*, l*	2	364142	12%	2	401231	11%	2	318847	12%	3	262241	18%	5213	5.97%

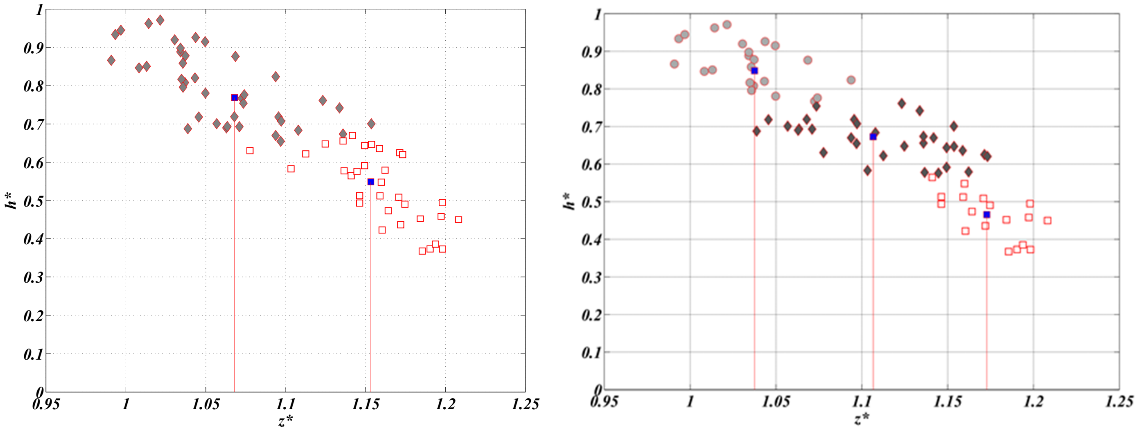
Monthly energy consumption (kWh), energy saving (%) and total saving for the irrigation season are shown in Table 2, for these combinations. For most of the months, greatest energy savings are achieved by using z^*,h^* for clustering of the hydrants. For the whole season, average energy saving reached 16.42%., with maximum savings of 43.73% in January. However, no savings are achieved in the months from March to July, due to the inability to operate the network in sectors. The use of h^* parameter only has achieved the second-best results with average energy saving of 15.41% i.e. about 1% less than the (z^*, h^*) combination. Hence, h^* parameter only may be used for sectoring the network to simplify the sectoring procedure. However, further studies for different networks should be made.

Figure 7(a) and (b) show the spatial distribution of the hydrants for each sector at Kostol area, based on z^*, and h^* parameters, using two, and three sectors, respectively. Resulting clusters are shown in Figure 8(a) and (b) for the network divided into two and three sectors, respectively.



(a) two sectors (b) three sectors

Figure 7. Spatial distribution of the hydrants for each sector at Kostol area, based on z^*, and h^*



(a) two sectors (b) three sectors

Figure. (8). Resulting clusters based on z^*, and h^*

5. CONCLUSIONS

In this study, a methodology for sectoring the network hydrants into hydraulically homogenous groups using the SOM clustering technique is presented. An algorithm based on MATLAB - EPANET Toolkit has been developed for this purpose. The developed algorithm has been applied to a drip irrigation network at Kostol in southern Egypt. The study of the combinations of hydrants' characteristic parameters z^*, h^*, and l^* showed that the highest energy saving may be realized using z^*, h^*, or h^* only. Significant energy savings could be achieved using this methodology, up to 16.42% in the studied area. Sectoring could not be applied to the whole irrigation season, particularly in months of maximum irrigation requirements.

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