



Hydraulic design and operation of variable-speed pumps as the water–energy saving strategies in pressurized irrigation systems

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Received: 26 June 2020 / Accepted: 1 February 2021 / Published online: 16 February 2021
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Abstract

Low efficiencies of irrigation pumping stations usually stem from their improper designing, operation, and maintenance of such systems. In the present study, the water and energy losses and the pressure variations of a pressurized irrigation system were investigated through analysing the characteristic curves of the pumps and assessing the discharge and pressure heads needed by the system during the irrigation season (i.e. the system demand curves). Variable-speed pumps can be adjusted to the system demand, making them more efficient than constant-speed pumps while bringing down water and energy consumption. Given this assumption, the suitability of variable-speed pumps to save water and energy in a 100 hectares apple and peach orchard, located in Isfahan Province, central Iran, was investigated. The pressure head, the pump efficiency, and the water and energy losses of the orchard's irrigation system designed based on variable-speed pumps were calculated and compared with those of common constant-speed systems. The results showed that using variable-speed technology in designing pumping stations not only increases the efficiency and reduces unnecessary pressures but also can result in optimal water use and, depending on operational condition, 44–54% reduction in energy consumption can be achieved, which is significant in national scale.

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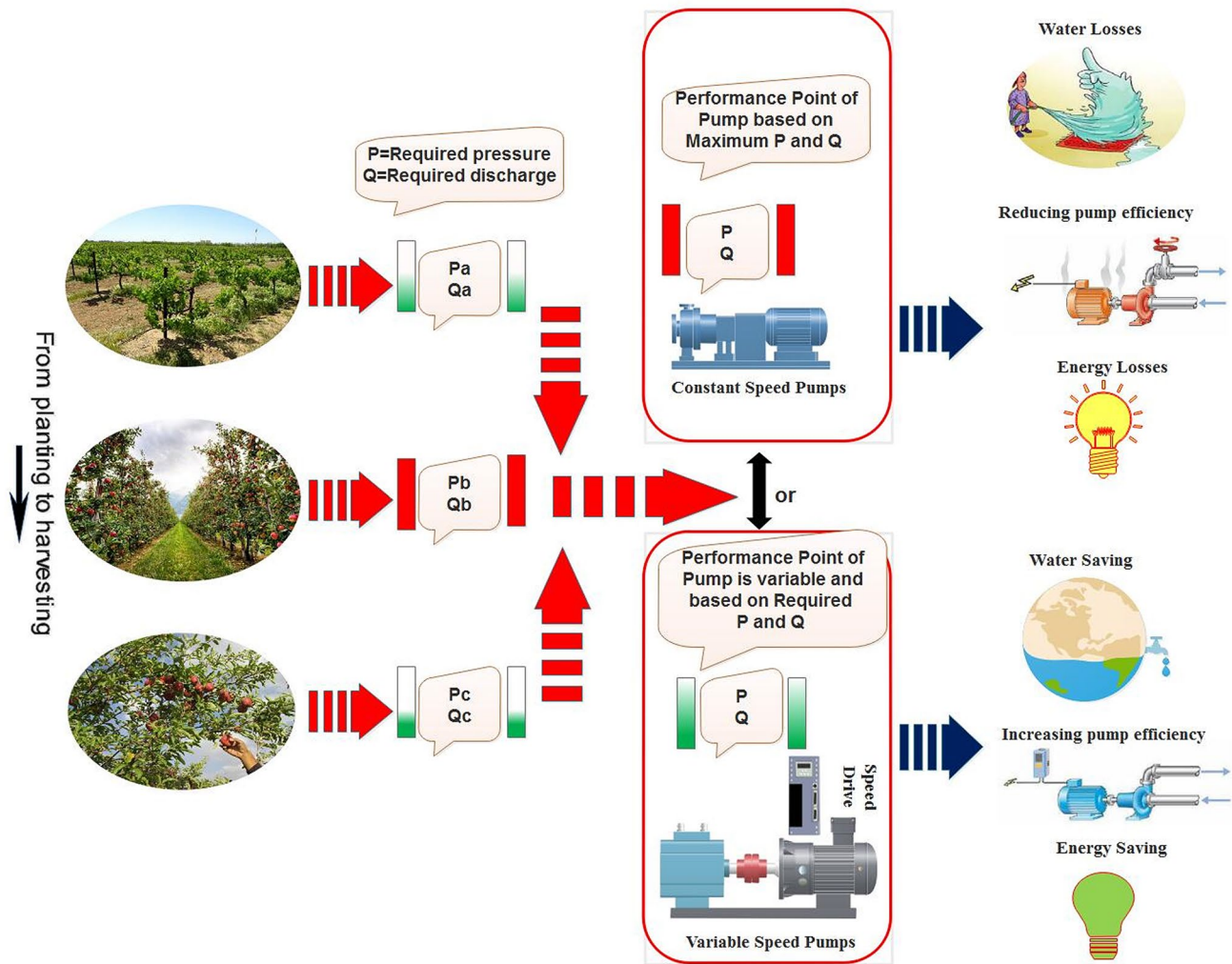
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Graphic abstract



Keywords Energy losses · Saving water · Irrigation projects · Variable-speed pumps

Introduction

Pump systems consume almost 22% of all electric energy generated throughout the world (Goman et al. 2019). Among various parameters, energy consumption is considered to be the most important factor affecting the life cycle costs of pumping stations. Regular irrigation pumping stations, in which constant-speed electric motors are used to drive pumps, are typically designed to cover the maximum water demand of the system. When the system works at lower water requirement periods and lower pressure head is needed, the constant-speed designing approach can result in considerable energy losses. In other words, during off-peak water demand periods, pumps operate at higher pressures than needed, indicating the low energy efficiency of

the pumps and consequently, the undesirable operation of the system. Factors such as inappropriate pump selection, changes in operating and hydraulic conditions, and changes in water demand can worsen the performance of the system and diminish its efficiency even more.

Dramatic development of pressurized irrigation projects, mainly in the last two decades, specifies the need to establish novel approaches in designing and operating these systems, in order to minimize the water and energy loss and to operate the systems in a sustainable and economic manner. While increasing water productivity is the main goal of implementing pressurized irrigation systems, energy consumption and the importance of operation methods are usually less appreciated, especially in countries such as Iran, where the government grants energy carriers subsidies.

Variable-speed drives (VSDs), pieces of equipment designed to adjust the speed of machinery, can be effectively employed to control the speed of irrigation pumps and, as a result, to adjust the pressure head needed to provide a given discharge. When VSDs were first introduced, their applications in the industry were limited due to primary technical hurdles and high cost. However, given the fact that VSD technology has significant potential for improving industrial energy efficiency (Abdelaziz et al. 2011), and even for reducing the amount of greenhouse gases emissions (Saidur et al. 2012), implementing VSD in industrial fields such as mine cooling systems (Du Plessis et al. 2013), the textile industry (Habib et al. 2016), chiller systems (Yu and Chan 2009), and refrigeration systems (Qureshi and Tassou 1996; Watcharapongvinij and Therdyothin 2017) has been increased during the last decades. Successful practical applications of VSD in water distribution systems, as well as theoretical modelling studies in this field, have been also reported in the literature. Hanson et al. (1996) showed that using VSD in sprinkler irrigation systems can reduce pump power by up to 56%, which reduces the overall energy consumption of the system. Lingireddy and Wood (1998) investigated the potential economic and hydraulic benefits of using VSD to improve the performance of municipal water distribution systems. Lamaddalena and Khila (2012) showed that using VSD in trickle irrigation systems can result in up to 35% reduction in energy cost. Marchi and Simpson (2013) proposed a correction to the EPANET (Rossman 1994) water distribution system modelling software and used the model to predict the efficiency of variable-speed pumps in order to assess different energy consumption scenarios. Hashemi et al. (2014) proposed a methodology for optimizing the operation of pumping stations equipped with variable-speed pumps. Brar (2015) investigated the feasibility of VSD technology to save energy in centre pivot irrigation systems. Delfan Azari and Parvaresh Rizi (2015) concluded that VSDs have advantages over flow control valves in terms of energy saving in a trickle irrigation system. Menke et al. (2016) mathematically modelled the variable-speed pumps in a water distribution network to determine the optimal operational schedule of the system. They found that networks using variable-speed pumps have lower operating costs than that of networks operated with constant-speed pumps. Valer et al. (2016) assessed the performance of irrigation pumping stations equipped with photovoltaic variable-speed pumps and examined the technical and economic aspects of this novel approach. A benefit–cost analysis showed that variable-speed photovoltaic pumps offer economic advantages over the conventional constant-speed pumps. Using mathematical modelling, Uossef Gomrokchi and Parvaresh Rizi (2018) showed that employing variable-speed electric motors to drive irrigation pumps results in up to 18% reduction in energy consumption. The use of pumps in irrigation

can be accompanied by a variety of operational approaches, which naturally results in different energy consumption. Minimizing energy expenditure is one of the main goals of the managers of pressurized irrigation systems. From the energy consumption standpoint, they can keep energy demands by opening and closing valves while meeting pressure constraints (Pardo et al. 2020).

According to the report published in 2018 by the Iranian Ministry of Energy, the energy consumed by agriculture sector in Iran, which recorded 3.8% of the total energy consumption in the country in 2005, reached 4.3% in 2017 (IME 2018). Agricultural energy consumption per capita in Iran is estimated to be more than 3.3 times higher than the world average. This high energy consumption rate mainly stems from the fossil fuel and electricity subsidy policy implemented by the government, as well as issues related to the efficiency of pumps used in the agriculture sector. Nevertheless, the energy subsidy policy in Iran is gradually changing and the fossil and electric energy consumed to produce agricultural products is becoming more and more expensive. As a result, it is more attractive and even necessary to consider energy-saving strategies such as using variable-speed pumps in order to reduce energy consumption in agriculture. Despite this necessity, a few studies have attempted to evaluate different aspects of implementing the VSD technology in pumping stations linking with irrigation system plan in Iran (Delfan Azari and Parvaresh Rizi 2015; Uossef Gomrokchi and Parvaresh Rizi 2018) and the other regions (Valer et al. 2016; Lamaddalena and Khila 2012). Previous studies have not compared the use of constant and variable-speed pumps in irrigation projects in terms of both water and energy consumption. In present research, it has been shown that the use of VSPs creates a good potential for the on-demand operation method, and therefore, by reducing water consumption, it will lead to a reduction in energy consumption; related researches does not directly address this issue. Details of the relationship between irrigation planning and the use of different operation programmes with constant and variable-speed pumps in this study are not seen in other researches. In other word, the present study aims to evaluate the suitability of variable-speed pumps to save water and energy in a semiarid region in Iran, while the proposed methodology can be used for other case studies with different irrigation scheduling and pressure needs. Detailed analysis before every modernization process can be helpful for managers to provide a preliminary assessment of water and energy requirements (Rodríguez Díaz et al. 2011). It should be noted that in this study, comparing the performance of the constant-speed pumps and variable-speed pumps has been done in such a way that in designing the irrigation system, pump selection (sizing, combination, and impeller diameter of pumps), and the changes in the irrigation system curve, all potential of energy consumption are almost encountered.

This has not been mentioned in other research or at least has not been noticed in this outline. Therefore, the ability to save the water and energy simultaneously at variable-speed pumps is weighed against the constant-speed pumps with ideal design.

Methodology

The points that should be considered in selecting and designing pumps in irrigation systems, in addition to the mechanical characteristics of the pump and the electrical features of the pumping system, are: hydraulic behaviour of the pumping system, method of operation of the pumping station in relation to the irrigation system, irrigation water requirement in different growth periods, and hydraulic features of the irrigation system. These features change over time. Therefore, for proper performance of the pumping system, the capability to change its mode of operation should be predicted.

Given the pipes and extensions (like valves) of the system at the downstream of the pumping station, a system curve is drawn that represents the relation between discharge and the pressure in the distribution point(s) of the system. These curves have been drawn in different zones. Changes in the operation methods, like valve closure, change the system curve as well (as seen in scenario1). It is worth mentioning that in conventional design of the irrigation networks, peak discharge is usually considered as the base of design (only one point of a curve) and virtually the system curve is ignored. Similarly, the flexibility of the irrigation system for water and energy consumption decreases proportionally to the actual need. In this research, system characteristics are considered as the basis of system design (as a capability in the design method to reduce water and energy consumption), and moreover, the pump operation methods are investigated and proposed to adapt with the water and energy demands (as a capability in the operation method to reduce water and energy consumption).

Different number of irrigation zones may be defined in each project with hydraulic connection between them (named Irrigation District in this paper). Zoning and the use of different combinations of pumps refer to the irrigation system design and operation plan, but this type of the system helps to compare the application of different scenarios and the potential to reduce water and water consumption in one pressurized irrigation network.

Based on the explanations provided above, the following steps can be enumerated for conducting research:

1. Considering the appropriate zoning and determining the hydrants that should irrigate at the same time.
2. Calculations of irrigation water requirement and development of irrigation scheduling.
3. Calculations and drawing of system characteristic curves in different zones based on irrigation network data and results of step 2.
4. Definition of operation scenarios including scenarios of using constant and variable-speed pumps, with or without using valves' manoeuvre.
5. Selecting pumps (or a combination of suitable pumps) that have the necessary compatibility with the system curves (in terms of flow and pressure range, acceptable engine speed range, suitable efficiency, the ability to be parallel to the similar pumps).
6. Application of different scenarios of operation of pumps in each zone, performing calculations to obtain the generated pressure, efficiency of pumps at the point of operation, the amount of distributed water for irrigation and energy consumption for pumps during the irrigation season (details of this item is described in the case study section and the necessary diagrams are provided).

Indeed, these steps are not completely separable and may be revised due to the possibility of multiple choices in the type of pump, the number of zones, and the ways of irrigation scheduling in other items. Finally, a final pattern will be achieved for the implementation of the sixth item.

Adjusting the speed of a pump

The similarity equation can be used to adjust the speed of a variable-speed pump. This equation is written as follows:

$$\frac{N_1}{N_2} = \left(\frac{Q_1}{Q_2}\right), \frac{N_1}{N_2} = \left(\frac{H_1}{H_2}\right)^{\frac{1}{2}}, \frac{N_1}{N_2} = \left(\frac{P_1}{P_2}\right)^{\frac{1}{3}} \quad (1)$$

where N , Q , H , and P are, respectively, the pump speed, the pump flow rate, the pressure head, and the pump power. A variation in frequency causes a corresponding variation in pump speed. According to Eq. 1, changing the pump speed results in a variation in pump discharge and pressure, and, consequently, a variation in the power consumed by pump. Pump speed can be adjusted using a power inverter controlled by a programmed computer to output power according to the difference between irrigation system water demand and the measured discharge in the system. The system demand curves over the growing season, which are functions of the irrigation water requirement, determine the required pressures to be produced by pumps. To estimate the pump energy consumption, the following equation can be used:

$$E = \left(\frac{\gamma QH}{\eta}\right)t \quad (2)$$

where E is the energy consumed (kWh), Q is the discharge supplied by pump (m^3/s), H is the pressure head (m), γ is the

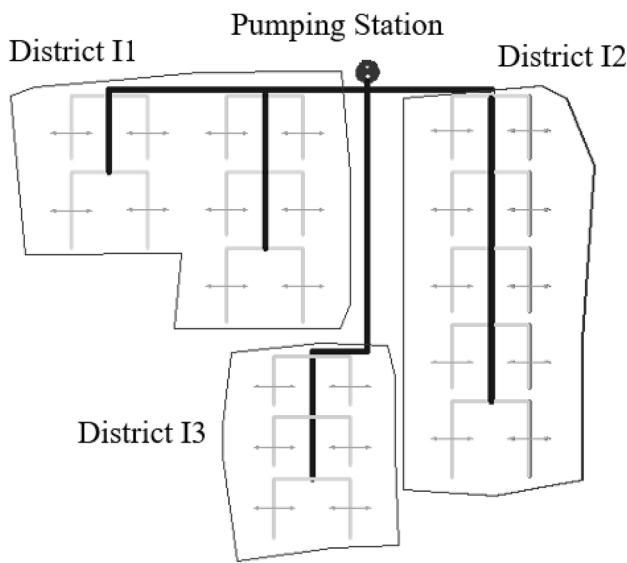


Fig. 1 The plan of the orchard under study, the layout of the irrigation system, and the location of the pumping station

Table 1 The area and the maximum water demand of each irrigation district

District name	Product type	A ^a (ha)	Q _{max} ^a (l/s)
District I1	Apple	40	94
District I2	Apple	40	71
District I3	Peach	20	34

^aObtained from the technical report of the irrigation system

water specific weight (N/m³), η is the pump efficiency, and t is the pump operating time (h).

Table 2 The water demands for each irrigation decade

	Q _R ^a (m ³ /hr)					
	April	May	Jun	July	August	September
First decade						
District I1	22 ^c	95	146	212	226	168
District I2	22 ^c	95	146	212	226	168
District I3	15 ^c	47	69	99	108	82
Second decade						
District I1	33	110	164	226	337 ^b	146
District I2	33	110	164	226	237	146
District I3	18	53	78	106	111	69
Third decade						
District I1	55	142	208	256	226	120
District I2	55	142	208	256 ^b	226	120
District I3	40	68	99	120 ^b	110	58

^aCalculated based on the irrigation water requirement in each decade

^bMaximum of the pressure requirement in the district

^cMinimum of the pressure requirement in the district

Case study

A 100 hectares apple and peach orchard located in Isfahan Province, central Iran, was considered for the present study. A trickle irrigation system, designed as three separate irrigation districts which are operated singly, is used to irrigate the orchard. A schematic plan of the orchard and the irrigation system is presented in Fig. 1. Overall characteristics of each district and their maximum water demand (Q_{max}) are also shown in Table 1 (based on the technical report of the irrigation system design).

The increase of the irrigation efficiency at the farm level would conduct to reductions of energy consumption because less water would have to be pumped. Therefore, appropriate irrigation scheduling may lead to both water and energy savings (Rodríguez Díaz et al. 2011). When there is no possibility of real-time irrigation in many irrigation projects, irrigation scheduling for specified timeframe closes irrigation management to on-demand irrigation and thus reduces water and energy consumption. This approach is considered for all scenarios in this research to analyse just the effects of pump type on water and energy consumption, as many as possible. The orchard is irrigated during six months from late-March to late-September. Each month in the six-month irrigation period is divided into three parts called the 1st, 2d, and 3d decade. The water demands of these decades (Q_R) are listed in Table 2. The pressure needed for each decade (P_R) was calculated given the decade’s water demand, the layout of the irrigation system, and the location of pumping station (Table 3). P_R represents the pressure requirement of the system at various time. In other words, according to the

Table 3 The pressure needed in each irrigation decade

P_R^a (m)		April	May	Jun	July	August	September
First decade	District I1	14	16	19	25	27	21
	District I2	11	14	18	27	29	21
	District I3	9	13	18	29	32	22
Second decade	District I1	15	17	21	27	28	19
	District I2	11	15	20	29	31	18
	District I3	9	14	21	32	34	18
Third decade	District I1	15	19	25	30	27	18
	District I2	12	18	26	34	29	16
	District I3	12	18	29	38	33	16

^aDepended on irrigation district location, system characteristics, and required irrigation water

zoning and scheduling of the irrigation, a certain amount of pressure is required at any period of operation. Indeed, it is not easy to match the required pressure variation at the constant-speed pumps, which are selected based on the maximum pressure required.

The pumping station, located upstream of all three irrigation districts, is equipped with five centrifugal pumps: a pair of similar pumps operated in parallel (B1 and B2), one smaller third pump (A), and two standby pumps. The

characteristic curves of the A and B (B1 and B2) pumps are presented in Figs. 2 and 3, respectively.

The pump curve changes according to the rotational speed of the pump (N) of the pump or its impeller diameter, so the baseline of speed change is the constant-speed pump curve with the impeller diameter and the rotational speed chosen in the early design of the pumping system.

In any pumping project, the system curve represents the dynamic head of the system. At any time of operation a point with the coordinates (Q_R, P_R) exists where the need for the

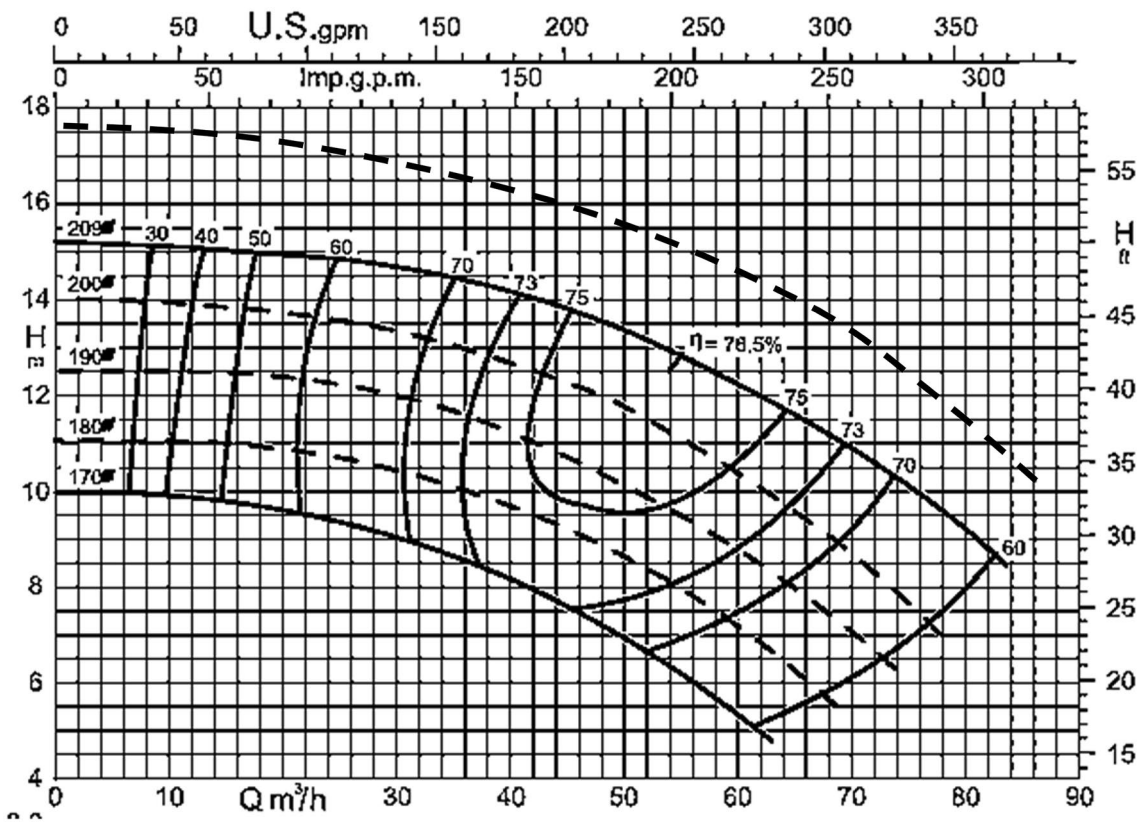


Fig. 2 The characteristic curves of the A pump

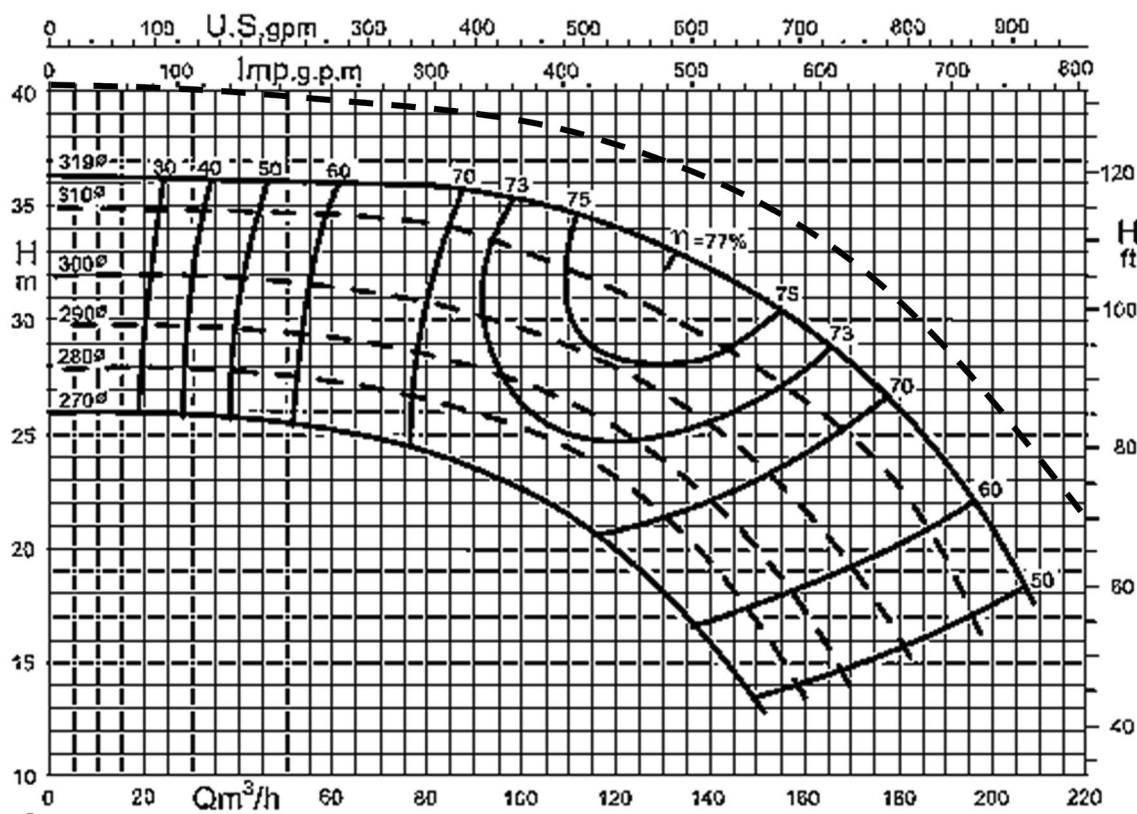


Fig. 3 The characteristic curves of the B pump (B1 or B2)

system downstream the pump(s) is shown (in this research: pressurized irrigation system). The set of these points is the system curve of the irrigation system. However, using system hydraulic resistance equations, the mathematical form of this curve is obtained.

Given that the minimum values of irrigation demands occur at the first month of the irrigation period (see Table 1), the A pump is the only operating pump in this month. At the other five months, the B1 and B2 pumps are operated in parallel. Furthermore, since the third district (I3) has the minimum irrigation demand in all months compared to the other two districts (I1 and I2), the A and B1 pumps is the only operating pump used to irrigate this district.

Pumps A and Bs (B1 and B2 are similar) have been selected based on Figs. 2 and 3. However, in different irrigation districts, based on the maximum requirements, different impeller diameters of pumps were employed (to use the maximum potential of constant-speed pumps to match with the real requirements). For example, we could have 2 or 3 of pump A, with different impeller diameters in their cases (according to Fig. 2), and based on operation plan, each of them may start to work or be standby.

Four different operating scenarios, P1 to P4, were analysed to determine the effectiveness of using variable-speed pumps as a water and energy saving strategy. The

conventional method of using constant-speed pumps was considered in the first three scenarios, while the last scenario was dedicated to using variable-speed pumps.

The P1 scenario: constant-speed pumps with a flow control valve (demand-based adjusting)

In this scenario, the pumps are operated at fixed speeds and a flow control valve regulates the amount of discharge (Q) required to meet the demand of each decade. As a result, the characteristic curves of the pumps remain the same, while the system demand curve changes according to the valve opening. These characteristics curves are shown for tow irrigation district for instance (Figs. 4 and 5). This scenario reduces the water loss but increases the required pressure.

In fact, the primary curve of the irrigation system is the "points of system demand" in the figures, but only meets the B pumps and A pump at two points (labelled 1 and 2 in the figures). For example, several system curves that regulate flow in other points of system demand are seen in Figs. 4 and 5. According to the vertical lines drawn in the mentioned figures, discharge reaches the desired amount, but the required pressure increases as the height of the vertical lines at each point. (The results of the pressure required for the scenarios are presented in Figs. 14, 15, and 16.)

Fig. 4 The characteristic curves of the constant-speed pumps in the P1 scenario (district I1)

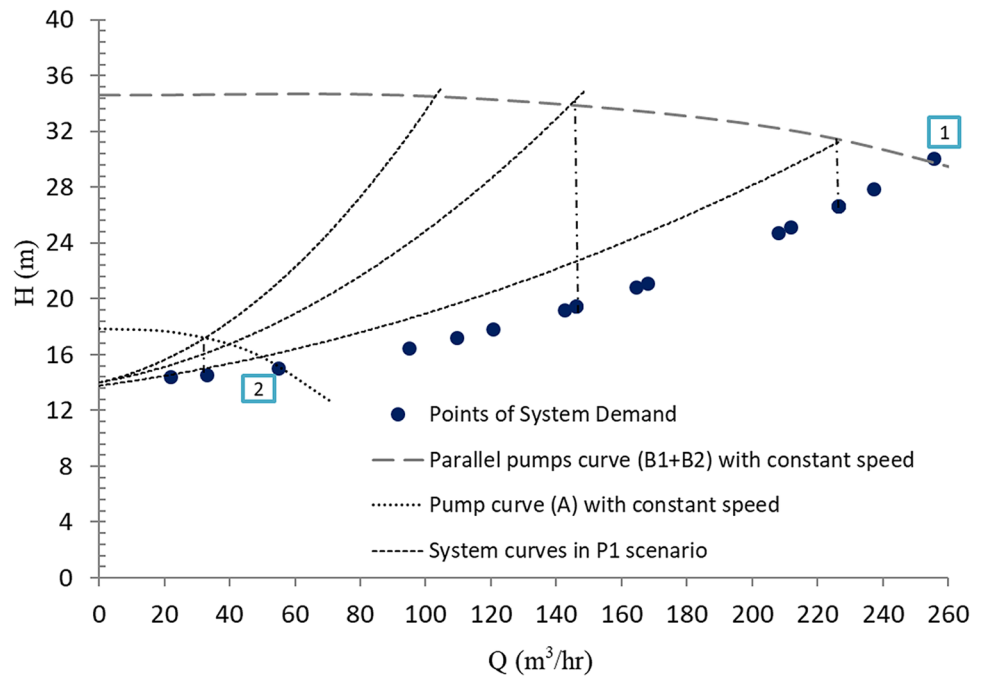
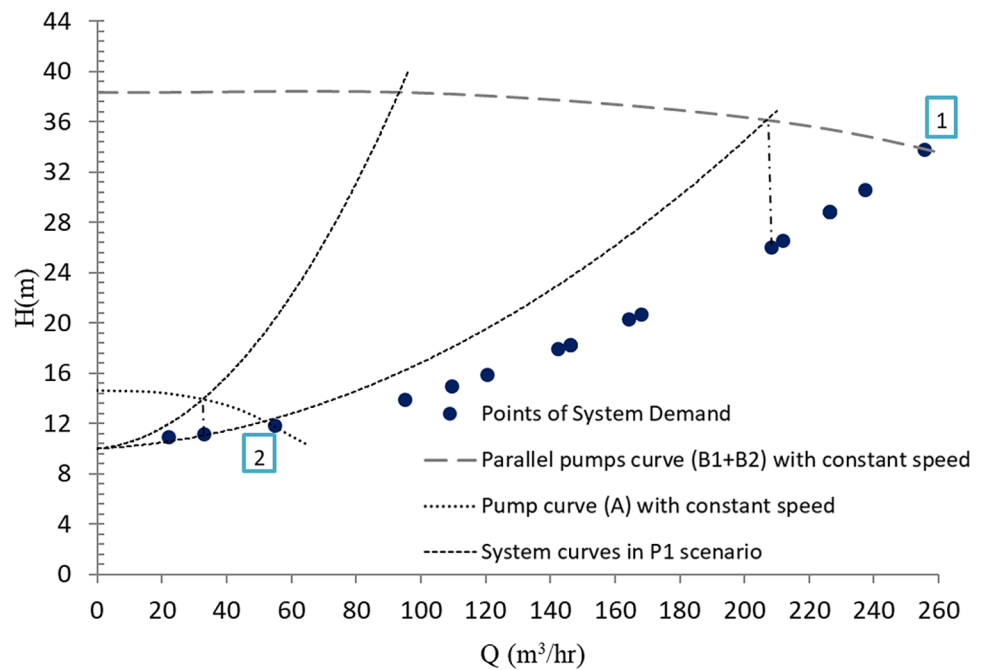


Fig. 5 The characteristic curves of the constant-speed pumps in the P1 scenario (district I2)



The P2 scenario: constant-speed pumps without a flow control valve

In this scenario, the characteristic curves of the pumps and the system demand curve remain the same during the irrigation period. The operating point of the system does not change with time, and the corresponding head and flow rate are supplied by the operating pumps (the points labelled 1 and 2, in Figs. 4 and 5).

The P3 scenario: constant-speed pumps with a flow control valve (monthly adjusting)

This scenario is basically the same as the P1 scenario except that the valve opening is changed every month. The maximum demand of each month determines the valve opening for that month, and as a result, each month has a unique system demand curve.

The P4 scenario: variable-speed pumps operated in parallel

In this scenario, the pumping station is designed and operated using VSDs. The intersection of pump characteristic curve and system demand curve determines the operating point of pumps. Using VSDs, pump characteristic curves and irrigation system curve can be effectively matched in such a way that the desired flow rate and pressure are supplied to the system. The curve of the irrigation system is identical for all scenarios when the discharge control valve is fully open (“Points of system demand “in Figs. 4 and 5). However, by closing the control valve at each stage, the pump curve has more gradient. (In the P1 scenario and in Figs. 4 and 5, some of these curves are plotted for the sample.) In Figs. 8 and 9, this system curve that the operation of the VSD is based on is named as the points of the irrigation system demand.

Adjusting the speed of the pumps is accomplished by following the algorithm presented in Fig. 6. For example,

when the irrigation system needs less water and pressure, the rotational speed is reduced to lower energy consumption.

The three irrigation districts in the orchard under study are successively irrigated during a period of 21 h (seven hours for each district). First, the I1 district is irrigated using the B1 and B2 pumps operated in parallel. Then, the speed of the pumps is gradually adjusted to meet the flow rate and pressure required to irrigate the I2 district. For the I3 district, which has the minimum command area, one of the parallel pumps is stopped and the speed of the other pump is adjusted according to the water demand of the district (Figs. 7, 8, 9).

Results and discussion

Water consumption

For each scenario, the variation of water consumption as a function of time is shown in Fig. 10.

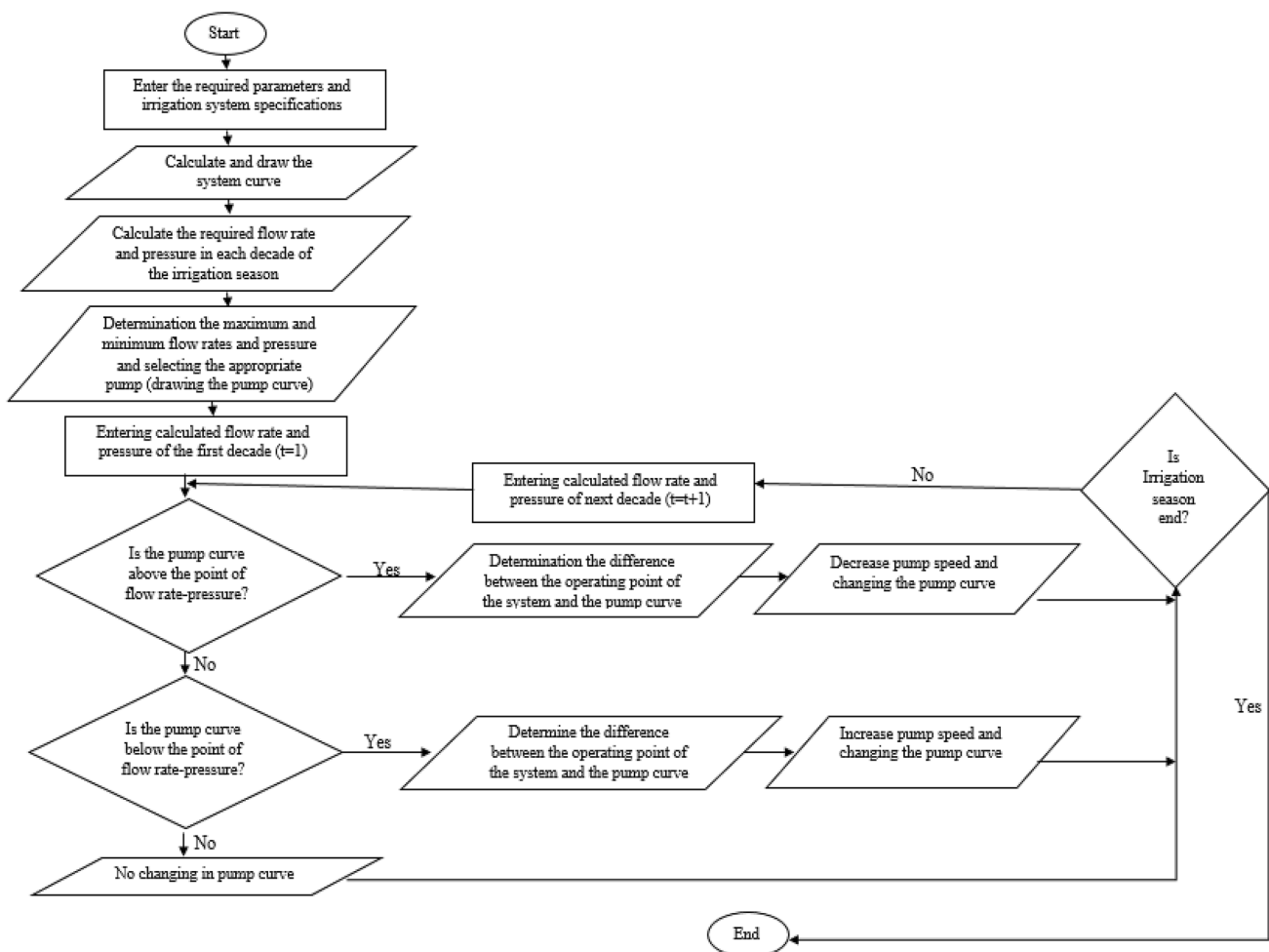


Fig. 6 The algorithm used to adjust pump rotational speed matching to water demand

Fig. 7 The characteristic curves of the variable-speed pumps (P4 scenario- district I1)

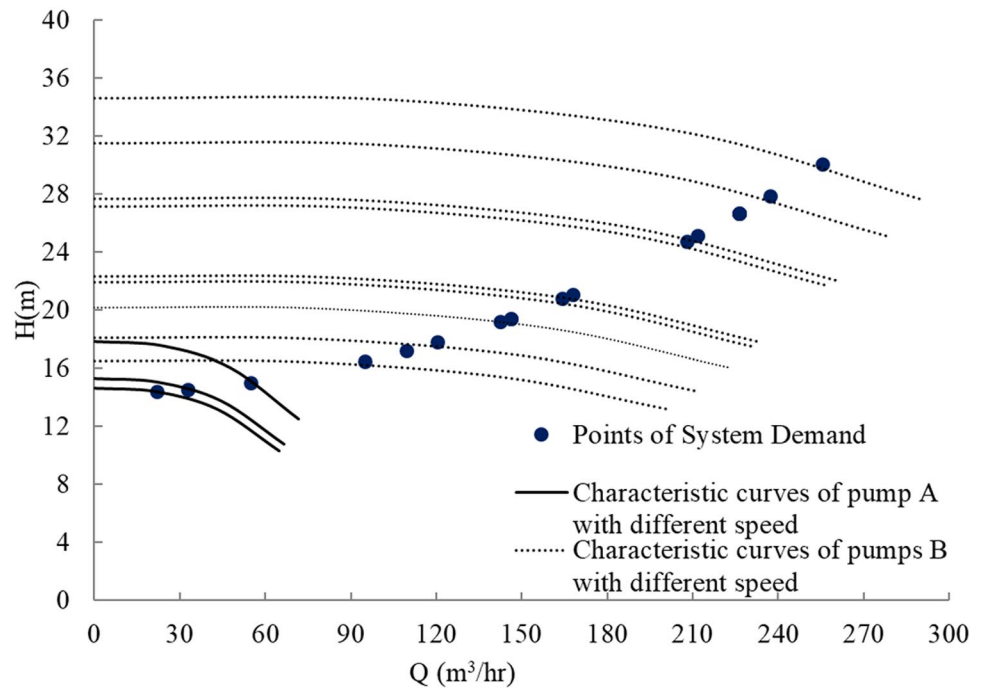
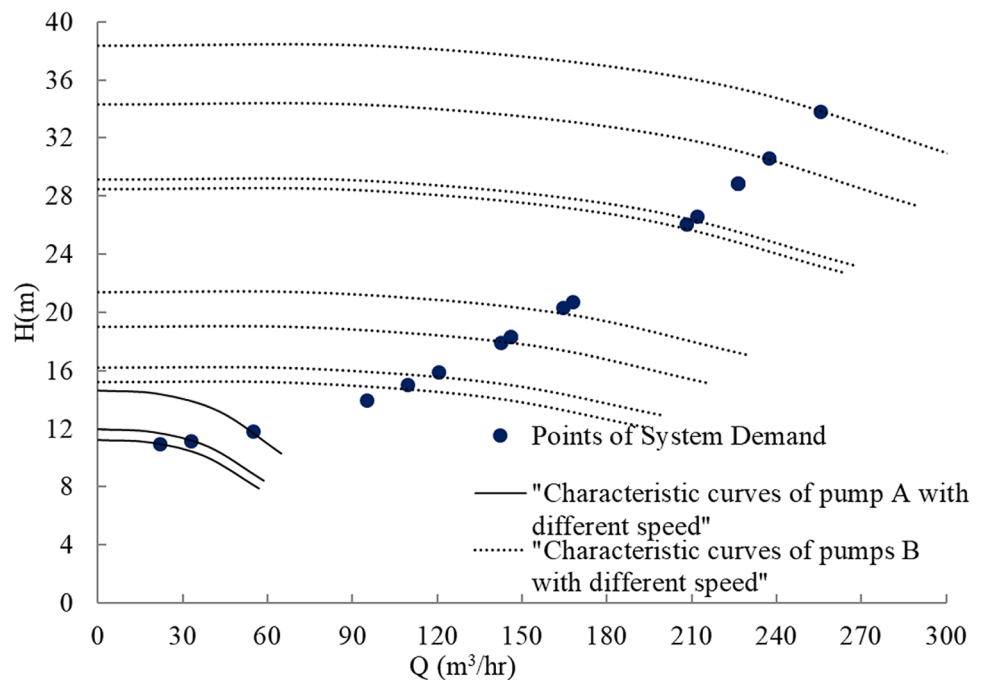


Fig. 8 The characteristic curves of the variable-speed pumps (P4 scenario- district I2)



Since in the scenario P1, flow regulation is based on the irrigation requirement of each decade, the amount of water consumed is equal to the amount of water required, and this is also the case for the P4 scenario where the VSDs are used. Thus, in Fig. 10, the curves of both P1 and P4 scenarios are matched. Furthermore, the P2 scenario results in the maximum water consumption rates.

Pump efficiency

Hydraulic pump efficiency is one of the most important factors in assessing a pumping station system and could be a representative of the overall performance of the pump-network system. The energy consumed by a pump is a function of its hydraulic efficiency. Two basic points should be

Fig. 9 The characteristic curves of the variable-speed pumps (P4 scenario -district I3)

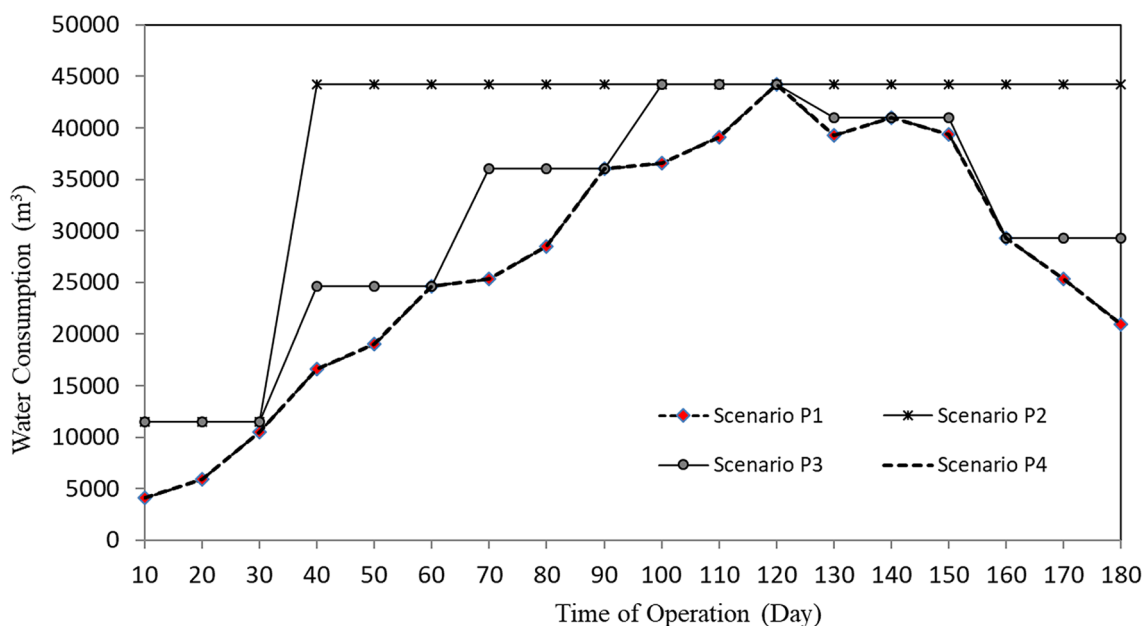
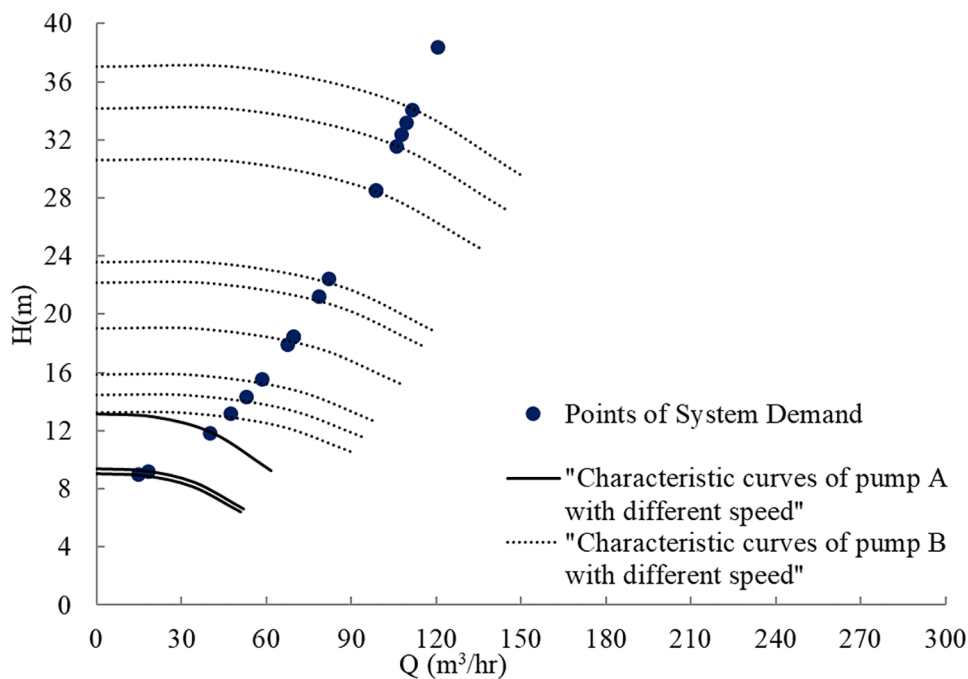


Fig. 10 The amount of water consumed in each operation scenario

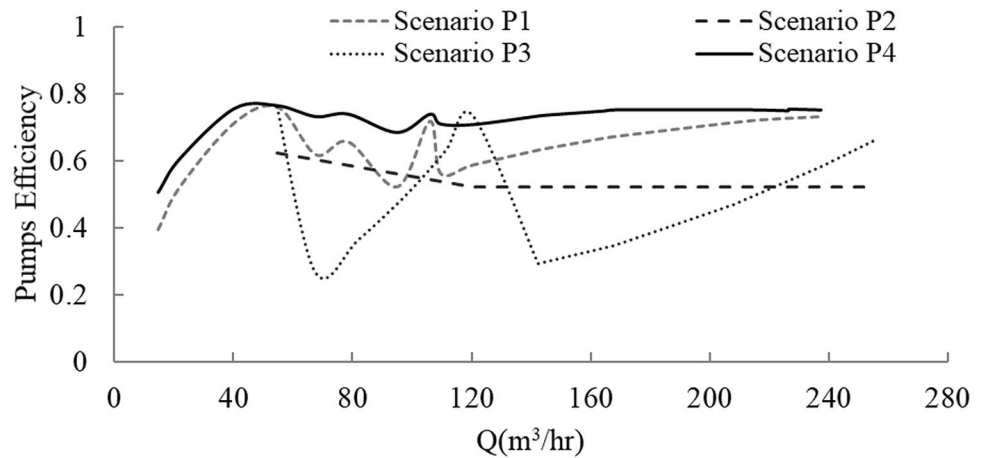
considered while analysing the hydraulic pump efficiency: the efficiency should be greater than a reasonable threshold (i.e. as close as possible to its optimum value), and, most importantly, the energy needed to achieve this efficiency should be as minimum as possible.

In different working conditions for each pump, the “operating point” of the pump will also change, and its efficiency will naturally change. In this research, pumps experience different operating points based on different operational

scenarios in different districts. As a result, different efficiencies are obtained for each pump in the operation period. Each curve in Fig. 11 represents the average of efficiency of pumps, which employed to cover one irrigation districts (here, district I1) during the operation period, against the different supplied discharges.

According to Fig. 11, in comparison with the P1, P2, and P3 scenarios, the P4 scenario provides the greatest efficiencies, as well as the lowest variations in the calculated

Fig. 11 Pumps efficiencies in each scenario (district I1)



efficiencies. It should be noted that higher efficiency during pump operation means less depreciation of pump and blades and reduction of maintenance cost. In all cases, this score belongs to VSDs. This trend is seen in districts I2 and I3 with different command areas and water requirements as well.

Although the command area and hydraulic conditions of different irrigation districts are different, the pattern of efficiency changes related to the scenarios is almost constant. Most of the efficiency belongs to pumps with VSDs, and the lowest of it belongs to the P3 scenario where the changes of required discharge are regulated monthly.

Required pressure of the system

Producing excessive pressures, which causes water losses, affects the pump’s useful life, and, most importantly, consumes energy wastefully, is a major issue in pumping stations equipped with constant-speed pumps. Since closing

flow control valves increases energy loss, pumping stations with constant-speed pumps supply more pressures than the system needs.

Figures 12, 13, and 14 show that the pressure needed by the system is highest when the system is operated using the P1 scenario. Since in this scenario a flow control valve is used, the system performance in terms of water loss is reasonable. However, high-pressure values cause high pump power, resulting in high energy consumption.

According to Figures 12, 13, and 14, the lowest required pressure is obtained in pumps with VSD. In the scenario P1, although water consumption is on-demand and there is no water loss, more pressure is required for this achievement and the consecutive closure of the discharge valve needs more pumping head (pressure). The scenario of P3 appears to require less pressures during the irrigation season, but when we put this result together with Fig. 11 (which has less efficiency), we cannot be sure that energy consumption in this scenario would be desirable.

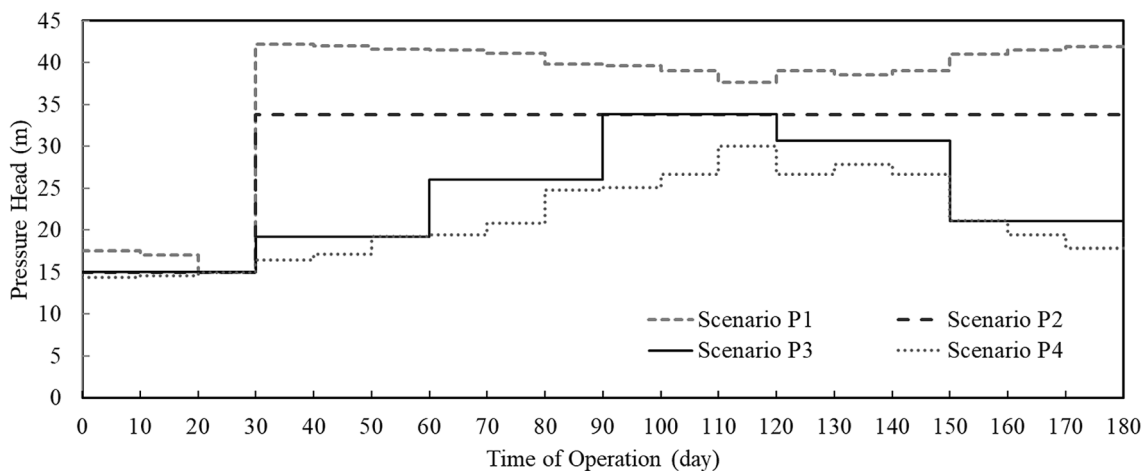


Fig. 12 The pressure produced in the pumping station in each scenario (district I1)

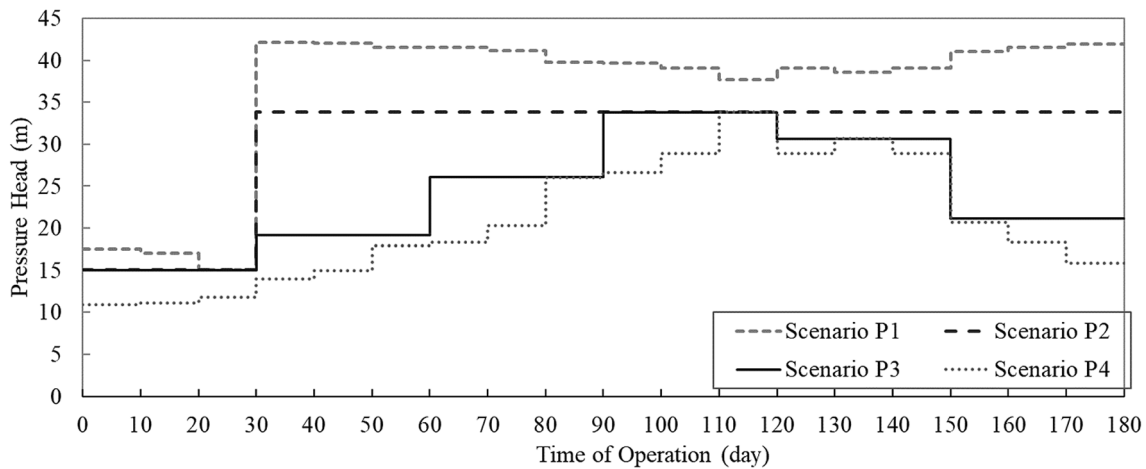


Fig. 13 The pressure produced in the pumping station in each scenario (district I2)

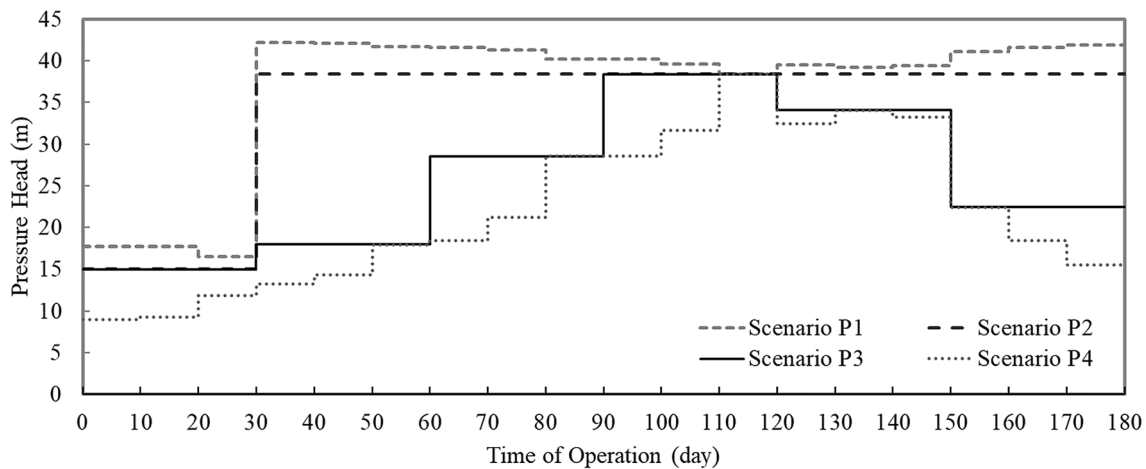


Fig. 14 The pressure produced in the pumping station in each scenario (district I3)

Energy consumption during the irrigation season

Using Eq. 2 and the values of pressure head and discharge, the energy consumption in each scenario was calculated (Table 4). It is obvious that the energy consumption is lowest when the P4 scenario is used to operate the system. So, P4 was considered as the optimum scenario in terms of energy saving and the percentages of energy saved by using this scenario was calculated. The results are presented in Table 5. It is seen that using the P4 scenario can result in 44 to 55% reduction in energy consumption. The energy consumption indicator, ECI, (the amount of consumed energy per unit of pumped irrigation water) is also reported in Table 5.

In present research, some energy-saving strategies for constant-speed pumps are considered (P1, P3 scenarios). Also in designing of this irrigation system, zoning method for distribution of pressure and discharge in the network is

utilized which in itself has potential to decrease water and energy consumption. Furthermore, irrigation scheduling has been determined in 10-day periods that the system requirements would be closer to the real-time values. (In many of pressurized irrigation schemes, the main criterion for design is the maximum value of required flow rate and the pressure. Also, the potential of the constant-speed pumps to reduce the water and energy consumption is not taken into account.) However, it is obvious that the use of VSDs has caused considerable improvement in consumption reduction. This percentage (44–54%) is certainly not generalized to all pressurized irrigation systems (in the references, there are different numbers for different systems as well), since the determinant parameters vary greatly. But the results of this scenario are so remarkable that they should be respected as an design alternative and the methodology of this paper be considered. Sometimes

Table 4 Energy consumed by the pumping station in different scenarios

Scenario			Energy consumption ^a (KWh)					
			April	May	June	July	August	September
P1	1st decade	District I1	140	1460	1808	2229	2318	1952
		District I2	140	1460	1808	2229	2318	1952
		District I3	125	730	880	1069	1126	964
	2nd decade	District I1	163	1561	1928	2318	2384	1808
		District I2	163	1561	1928	2318	2384	1808
		District I3	133	768	940	1114	1148	880
	3rd decade	District I1	206	1784	2206	2492	2318	1636
		District I2	206	1784	2206	2492	2318	1636
		District I3	178	868	1069	1203	1137	806
	Total energy consumption (KWh)		76,560					
P2	1st decade	District I1	206	2492	2492	2492	2492	2492
		District I2	206	2492	2492	2492	2492	2492
		District I3	206	1203	1203	1203	1203	1203
	2nd decade	District I1	206	2492	2492	2492	2492	2492
		District I2	206	2492	2492	2492	2492	2492
		District I3	206	1203	1203	1203	1203	1203
	3rd decade	District I1	206	2492	2492	2492	2492	2492
		District I2	206	2492	2492	2492	2492	2492
		District I3	206	1203	1203	1203	1203	1203
	Total energy consumption (KWh)			94,648				
P3	1st decade	District I1	206	1784	2206	2492	2384	1952
		District I2	206	1784	2206	2492	2384	1952
		District I3	206	868	1069	1203	1148	964
	2nd decade	District I1	206	1784	2206	2492	2384	1952
		District I2	206	1784	2206	2492	2384	1952
		District I3	206	868	1069	1203	1148	964
	3rd decade	District I1	206	1784	2206	2492	2384	1952
		District I2	206	1784	2206	2492	2384	1952
		District I3	206	868	1069	1203	1148	964
	Total Energy Consumption (KWh)			82,515				
P4	1st decade	District I1	108	452	734	1340	1525	900
		District I2	75	369	684	1426	1660	882
		District I3	49	172	332	724	901	474
	2nd decade	District I1	133	520	870	1525	1678	734
		District I2	97	441	846	1660	1855	684
		District I3	56	204	429	863	980	332
	3rd decade	District I1	205	710	1297	1962	1525	577
		District I2	161	655	1372	2220	1660	504
		District I3	120	315	724	1202	940	241
	Total energy consumption (KWh)		43,106					

^aCalculated from Eq. 2.

to create irrigation zones does not guarantee that irrigation pumping sets work in the most efficient manner, despite the use of VSDs (Jiménez-Bello et al. 2010). In this situation, it may be possible to link optimization model with irrigation designing model and pump sets' condition to

achieve the best efficient. In present study, employing VSDs has aided to improve pump efficiencies noticeably.

Results of present study, by showing the process of hydraulic design, reveal the effects of different parameters on the evaluation of different scenarios of operation of common

Table 5 Percentage of energy savings of each scenario compared to each other

Scenario	Energy consumption during irrigation season (kWh)	ECI (kWh/m ³)	Percentage of energy savings of each scenario compared to each other			
			Scenario P1	Scenario P2	Scenario P3	Scenario P4
Scenario P1	76,560	0.158	*	19%	7%	−44%
Scenario P2	94,648	0.136	−19%	*	−13%	−54%
Scenario P3	82,515	0.147	−7%	13%	*	−48%
Scenario P4	43,106	0.089	44%	54%	48%	*
Maximum energy saving			44%	54%	48%	*

pumps against the use of VSPs. It can be understood that by changing any of these factors (such as the number and size of pumps, irrigation scheduling, irrigation network layout, the amount of change in water requirements during the irrigation season), the evaluation results may change in favour of or to the detriment of each defined scenarios.

The operation scenarios defined here may be employed in any pressurized irrigation projects. This paper will aid to assess the use of VSPs against other existing scenarios while designing the irrigation project and planning for pumping stations. If the conservation rate in water and/or energy was significant in this assessment, the hydraulic design method described in this paper can be a good way to choose between different designing options, regarding proposed details about the employments of VSPs in a pressurized irrigation project. So the irrigation system under VSPs feeding will operate in on-demand pattern and water and energy consumption will be managed simultaneously.

Conclusion

Adjusting the speed of pumps can be used as an efficient way to achieve a wide range of flows that may be required in an irrigation system, making it possible to minimize water loss in the system, reduce total energy consumption in electric motors, and increase the lifetime of pumps. The use of improved irrigation management measures such as a flow meter, irrigation scheduling, and/or regular maintenance and upgrades typically reduces the amount of water pumped over the course of a growing season (Zhang et al. 2013). The amount of reduction in energy consumption in different management scenarios is important in constant-speed pumps as well. In this paper, these scenario which are common in many regions have been compared with VSPs. However, the results obtained in the present study showed that, depending on operational condition, the energy consumed by an irrigation water pumping system operated using variable-speed drives (with emphasizing on the existence of the irrigation scheduling) could be 44 to 54% less than that of a system with constant-speed pumps. Moreover, hydraulic design of these pumps due to the details of the irrigation scheme and its comparison with operation of

constant-speed pump has been considered in this study. It has been shown that despite the simultaneous decrease in energy and water consumption in scenario 4, ECI has experienced significant decrease and has not remained constant. Since in Iran the cost of energy is growing and the agriculture sector of the country could experience an energy crisis in the near future, using variable-speed pumps could be an important step to optimize water consumption use as well as to minimize the costs of operating irrigation pumping stations.

In assessing the performance of an irrigation pumping station, it should be considered whether the operating point of pumps is as close as possible to the best efficiency point, making it possible for the pump to satisfy the water demand of the system using the minimum amount of energy. One major goal of the present study was to quantify how pump operation scenarios could affect the efficiency of pumping station. Through considering different operating scenarios, it was concluded that using variable-speed pumps not only improves the pump efficiencies, but also satisfies the irrigation water demand at minimum energy consumption, showing that the optimal performance of the pumping station occurs when variable-speed pumps are used.

Acknowledgements This research received Research Project Grant Funding from the Iran National Science Foundation (INSF). The Research Grant Agreement No. is 87041044. The authors acknowledge the support of the INSF.

Funding This study was funded by Iran National Science Foundation (INSF), Grant Number 87041044.

Availability of data and material Data are available based on the request of the readers.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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