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Performance of Pumping Stations in Relation to Irrigation Management (Case Study: Khuzestan Province, Iran)

A. Sharifnezhad[1], and A. Parvaresh Rizi[1*]

ABSTRACT

Since water pumping stations supply most of the water for irrigation schemes and consume considerable percentage of energy in some countries, performance evaluation of these facilities, especially in relation to irrigation management, is essential. Therefore, definition and determination of some indices could be effective for evaluation process, planning for future, and optimal use of water and energy. Since there is no typical method for the assessment of irrigation pumping systems in the literature, in the present study, some evaluation indices in the areas of operation and maintenance, management, energy, and economic performance of the irrigation pumping stations are introduced. Some irrigation pumping stations in Khuzestan Province (Iran) and energy-water relations of these projects were evaluated based on the proposed integrated approach. According to the results, the first step in evaluating the performance of these facilities is the establishment of a system for monitoring and recording the information. Evaluation of the operation and maintenance of these pumping stations shows the average status. Therefore, the weakest parameters, i.e. required hydraulic equipment, periodic monitoring of hydraulic parameters and security against water hammer, have to be strengthened and pumping stations be equipped properly. It was also shown that to achieve the ideal management of the case studies, the profitability of operating company should be improved. Besides, due to high energy loss in irrigation pumping stations (up to 49% in this study), use of equipment for reducing energy consumption and proper selection of pump and electromotor should be a priority in the design and management phases. The required power of electromotor is overestimated by at least 25%.

Keywords: Irrigation schemes, Performance indicators, Productivity of water and energy.

INTRODUCTION

Iran has a low percentage of the world fresh water due to its special geographical and climatic conditions. Although agriculture is the largest consumer of fresh water resources (about 90%) in Iran, the statistics show that about 75 percent of the mean annual rainfall is received during non-agricultural seasons. According to some studies, efficiency of energy in the agricultural sector is less than 40%. To supply water for irrigation projects, more than 70 percent of energy consumed in agriculture is by pumping stations (Amin *et al*., 2006). Therefore, operation of pumping stations is of great importance in terms of energy consumption. Due to high costs imposed on an agricultural system during construction and operation of pumping stations, their design and operation methods have an imperative role in water and energy productivity. Nowadays, energy and its supply are among the main problems in many societies. Energy use in agriculture has increased in response to increasing populations, limited supply of arable land, and desire for an increasing standard of living (Pahlavan *et al.*, 2012). This issue becomes more important as the energy consumption for the purpose of water supply and its conveyance directly affects social, economic, and even political aspects. In recent years,

[1] Department of Irrigation and Reclamation Engineering, University of Tehran, Karaj, Islamic Republic of Iran.
* Corresponding author; e-mail: parvarsh@ut.ac.ir

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increasing the efficiency of energy consumption systems has been greatly emphasized by some researchers. This is because water conveyance systems using pumps are one of the highest energy-consuming industries. According to Fathimoghadam (2007), twenty percent of the electrical energy produced in the world is used in the water industry. Therefore, a slight increase in the efficiency of these systems can have considerable effect on saving the energy and reducing its associated costs. The importance of water and energy and their direct interaction with the pumping stations have led to the increasing significance of pumping stations. Despite this fact, as far as the authors are concerned, no study or research has been done about assessment criteria of the water pumping stations in the literatures. Even in establishing assessment standards for irrigation and drainage schemes, no attention has been paid to pumping stations. In Iran, high proportion of energy consumed by pumping stations is wasted due to the following reasons: (a) Lack of a specified and standard guideline in operation and maintenance, (b) Non-compliance with the existing criteria, and (c) No prediction of the operating conditions at the design process. Such issues have made the pumping systems to operate with low efficiency in supplying the irrigation water (Fathimoghadam, 2007). From among similar studies, Evans *et al*. (1996) assessed the pumping stations' performance in North Carolina. They found out that through using Nebraska Pumping Plant Performance Criteria (NPC), the pumps' efficiency increases through reducing the costs and energy consumption. Although pump price increases by increasing pump efficiency, its initial cost is compensated through savings in pumps' operating costs. Paulyluc *et al*. (2006) assessed the performance of 18 pumping stations in Tunisia. The results showed that a significant reduction in energy consumption can be achieved through proper management i.e., when the system operates in optimum efficiency. Based on their results, 22% of the stations had a potential of more than 50% reduction, and 50% of them showed less than 20% potential of reduction in their energy consumption. Moreno *et al*. (2007) developed a model for energy efficiency analysis for pumping stations in Spain. They reached a reduction of 16 percent in costs and 14 percent in energy consumption by using two-speeds impeller during the operation. This study indicated that simple hydraulic and electrical measurement device (flow meters, pressure and electrical sensors) and knowing the exact amount of demand in irrigation seasons had a significant effect on improving the energy management of pumping stations. Moreno *et al*. (2010) presented solutions for improving energy efficiency in pumping stations by calculating energy consumption indicators for 15 pumping stations in Spain. They achieved energy savings of 10.2%. Alegre *et al*. (2011) composed a manual to provide efficient operation and management of urban water system based on the performance indicators. They introduced performance indicators (PIs) in several groups consisting of water resources, personnel, physical and operational quality of services, and economic and financial indices. Garcíaa *et al*. (2014) used Variable Speed Drives to achieve maximum pumping efficiency by optimizing pressure head. Their results showed the optimal operation of irrigation networks and energy savings up to 26%. Kooij *et al*. (2015) reduced the energy consumption of a wastewater transport system up to 25% using performance indicators derived from data monitoring and model simulation. Cardoso *et al*. (2017) evaluated pump efficiency and its optimization potential in three water supply systems and 65 pumps groups by testing each pump group in different operational conditions. Most energy inefficiencies were identified because of oversized groups, valve problems and disagreement with working points. Their results showed energy saving potential of 331 MWh yr^{-1} by refurbishment of the pumps, impeller adjustments, and variable speed drive installation. In Iran, Amin *et al*. (2006) calculated energy loss and the efficiency of the pumping stations in Fars province. According to the obtained results, for all the studied pumping stations, the efficiency was less than 50% and the overall efficiency was 45.2 , signifying high energy loss under the present condition. Since the first step in improving the performance of a system is assessing its performance, the authors aimed to introduce an assessment method based on some performance assessment indices. These indices were utilized for the assessment and optimization of a number of pumping stations in the Khuzestan province during a 4-year period

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(from April 2007-March 2008 to April 2010-September 2010) for different irrigation seasons.

MATERIALS AND METHODS

Performance Assessment

A system performance is defined as the rate of access to produced objects (consumer satisfaction supply) and managing available resources (efficiency). To simplify this process, a manager must select a group of parameters (indices) to define and to assess the performance. In fact, by collecting information from the past activities and the results from these indices, right decisions can be made for future activities (National Committee on Irrigation and Drainage of Iran. 1996). In planning, implementation, and operation stages of irrigation systems, performance monitoring and assessment are of great importance. It provides for the managers the required information to make the right decisions. In addition, it can be effective in policy adjustment and future planning (National Committee on Irrigation and Drainage of Iran. 1997).

As mentioned in the literature review, in most previous researches, pumping stations have been evaluated based on consumed Energy per unit of pumped water and Cultivated area (EVI and ECI indices presented in this study, respectively). Also, reduction in energy consumption was often considered as a result of employing some equipment. Therefore, in this study, in order to achieve a more realistic evaluation, some effective parameters (and as a result, some new indices) were suggested for the first time.

Qualitative and *In-Situ* Methods in Assessing the Pumping Stations Performance

The performance of agricultural water pumping stations has a close relationship with the performance of their operation and maintenance management, as well as the performance of their efficiency. It also depends on the plans that have been made at the design phase. Operation is defined as continuous services that are performed for optimal use of the system. Maintenance is performing continuous operation such as inspection, provision of tools, machinery, and safety equipment that can provide the possibility of proper operation facilities in their useful lifetime. Therefore, regarding the importance of operation and maintenance factors in increasing the efficiency of pumping stations, and in order to achieve a distinct outcome, in this study, assessment of the performance was made using qualitative and in-situ methods. It should be noted that assessment of the design phase was not considered in this study (although it can affect the operation and maintenance phase). However, the focus was on the method which can present stations performance in a comprehensive and evaluable way, and can provide the conditions to compare the management status of each operational period with others in a single station as well as with operational periods for other stations. Since there was no prior or empirical model in the qualitative assessment of pumping stations, its assessment indices were introduced first. To calculate each index, the authors identified and valued effective parameters that were named S_i. Each parameter for each station, depending on the status of parameters, was valued from zero to four (Grade 4 for excellent, Grade 3 for good, Grade 2 for medium, Grade 1 for weak, and Grade 0 for very weak conditions). The numbers of effective parameters were shown with variable n. Since the importance of each effective parameter is not uniform in calculating each performance index, the Coefficient (C_i) was given to each of them (C_i has a value between zero and one). Thus, according to Equation (1), numerical value of each index would be between zero (the worst condition) and four (the best condition).

$$I = \frac{\sum_{i=1}^{n} S_i C_i}{\sum_{i=1}^{n} C_i} \qquad (1)$$

In the above equation, Siis effective parameter, nis the numbers of effective parameters and Ci is importance coefficient

The Effective Parameters

Therefore, the most important and effective parameters were defined based on the existing needs, deficiencies, and experiences of operation organizations as follows:

1. Required Measuring Equipment (S_1)

Without using measuring equipment, it is not possible to control the pressure and flow rates as the main hydraulic parameters in pumping stations. Measuring the outflow of the pump helps to provide accurate planning for water delivery, and, as a result, increases the water delivery efficiency. By recording the pressure before and after the pump, the performance conditions of the system are determined, and any probable danger for the pump is prevented on time. Therefore, lifetime and efficiency of pump will increase.

2. Suitable Water Level Sensor (S_2)

Water level sensor is one of the equipment which protects the pump against cavitation and corrosion; it does not allow the pumps to intake an inappropriate level of water. If the water level falls below the allowed limit in the pump suction, the sensor turns off the pump automatically. Thus, in addition to increasing the useful life and efficiency of the pump, maintenance cost is reduced and operation activities will be performed with greater safety.

3. Protection Equipment against Water Hammer (S_3):

Water hammer is the formation of pressure wave as a result of sudden changes in flow velocity in a piping system. This phenomenon commonly occurs because of different reasons such as turning on and off the pumps, sudden shut down of the pump, rapid opening or closing of a valve, using inappropriate check valves, and unexpected problems that happen in water conveyance system. In such situations, if the protective system is not utilized, the pump would be damaged. Therefore, protection equipment against water hammer is essential for safe and efficient operation.

4. Trash Rack Status (S_4):

Suction of trash by the pump can cause damage to the pump vanes, and as a result reduces lifespan and efficiency of the pump.

5. Cleaning and Lubricating the Pumps (S_5):

Regular cleaning, washing, and lubricating the pumps help prevent extra friction between moving metal parts, and removes dust and sand which may enter the engine. Negligence in performing this parameter can damage the pump.

6. Timely Repair and Replacement of the Pumps (S_6):

Any failure of the pump or its components will reduce the efficiency of the pump. Sometimes, operation and maintenance costs increase to an extent that replacing the pump is preferable to its repair. Regular inspections and timely identification of the pump problems lead to improvement of the efficiency of pump performance and reduce the operating costs.

7. Operator Efficiency (S_7):

If all the effective parameters are provided properly in a pumping station but the operator has not been essentially trained (in other words, if the operator is not efficient), system maintenance would not perform properly. It is essential for the operators to be trained so as to get acquainted with potential problems and their importance, and be able to have efficient management skills in operating the pumping stations.

8. Reports and Records of Operation and Maintenance Status (S_8):

In performance assessment of the pumping station, collecting accurate and timely information from operation and maintenance conditions is necessary to be able to identify the problems and reliable solutions.

9. Monitoring Hydraulic Parameters (S_9):

In order to achieve the maximum efficiency of the pumping station, controlling the system performance and monitoring, and measuring hydraulic parameters (such as pump-produced pressure and discharge), pump operation efficiency, and produced power are required. The role of monitoring is demonstrating the system condition through changes that may occur over time.

10. Methods of Flow Control in Pump Stations (S_{10}):

Controlling the system discharge is a method to reduce energy loss in the pumping stations. Some equipment such as control valves, parallel pumping systems, and variable speed pumps can be used to control the discharge. Disregarding the suitable flow

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control method results in the highest energy loss, while using variable speed pump control method leads to the least energy loss and the best performance management.

To calculate each performance index, the researchers have attributed a weighted coefficient to each parameter proportional to the intended index. Finally, by calculating these indices, operation status of the pumping stations can be evaluated.

Indices of Pumping Stations Operation and Maintenance

In this study, some indices to evaluate the operation and maintenance performance of pumping stations based on the available conditions in Iran were identified as follows:

Operation Safety Index (OSI)

This index shows the operations desirability of the safety of the pumping stations performance. The higher this index value, the higher the operation reliability and performance efficiency, and the lower the costs of maintenance. In calculating this index, the parameters that increase the pumping station operation and maintenance safety, and prevent the possible problems, have higher importance. Equation (2) is used to calculate this index:

$$OSI = \frac{S_1C_1 + S_2C_2 + S_3C_3 + S_4C_4 + S_5C_5 + S_6C_6 + S_7C_7 + S_9C_9}{C_1 + C_2 + C_3 + C_4 + C_5 + C_6 + C_7 + C_9} \quad (2)$$

Operation Desirability Index (ODI)

This index represents the desirability of the pumping station performance regardless of its safety and operation efficiency. In order to calculate this index, parameters related to pump failure and to prevent pumping process are more important. Equation (3) is used to calculate *ODI*:

$$ODI = \frac{S_1C_1 + S_2C_2 + S_3C_3 + S_4C_4 + S_6C_6 + S_7C_7}{C_1 + C_2 + C_3 + C_4 + C_6 + C_7} \quad (3)$$

Decision-Making and Crisis Management Index (DMI)

This index calculates the performance of the pumping station in management and decision-making in critical conditions. The higher this index value, the better the management performance, the more the pumping stations' useful life, and the lower the operation and maintenance costs. This index is calculated by Equation (4):

$$DMI = \frac{S_1C_1 + S_2C_2 + S_3C_3 + S_6C_6 + S_7C_7 + S_8C_8 + S_9C_9}{C_1 + C_2 + C_3 + C_6 + C_7 + C_8 + C_9} \quad (4)$$

To calculate the defined index, at first, an importance Coefficient (Ci) was attributed to each effective parameter based on their importance in the calculation of each index. For example, the importance coefficient of S_1 parameter in *DMI*, *ODI*, and *OSI* indices are 0.5, 0.4, and 0.8, respectively (Table 1). This table can be used for any station at any time.

Pumping Stations Operation Management Indices

The defined management indices allow the pumping station management to be aware of the efficiency of the pumping station in different periods of irrigation. So, the necessary requirements can be provided in

Table1. Coefficients for effective parameters in calculation of pumping station performance indices.

Effective parameter	C_{OSI}	C_{ODI}	C_{DMI}
S_1	0.8	0.4	0.5
S_2	1	0.4	0.5
S_3	1	0.2	0.5
S_4	0.6	0.2	0
S_5	0.5	0	0
S_6	0.5	0.5	0.8
S_7	0.6	0.3	1
S_8	0	0	1
S_9	0.6	0	1
S_{10}	1	0	0.5

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proper times using these indices to increase the farmers' satisfaction with the pumping station management. Two important management indices are as follows:

Sufficient Water Supply Reliability Index (SWI)

This index shows the pumping station's ability to supply adequate water for the scheme with suitable pressure. This index is the ratio of the Pumped water Volume in an irrigation period (V_P) to the Requested water Volume of the scheme (V_R). Ideally, its value equals one; any value less than one indicates lack of sufficient water supply. Decrease in this index depends on several parameters such as the source of water supply (quality and quantity of the available water), mechanical problems (pumps, pipes, and protection equipment failure), hydraulic problems (sediment accumulation and sudden decrease in water-level elevation), etc. In such conditions, the optimum value of 0.9 to 1 is recommended for this index. Values higher than one indicate extra water supply and undesirable situation.

$$SWI = \frac{V_p}{V_R} \qquad (5)$$

Timely Water Supply Reliability Index (TWI)

Timely Water supply reliability is the pumping stations' ability to deliver adequate water at the appropriate time, that is, when the scheme needs a known volume of water. This index shows that not only supplying adequate water, but also its timely delivery is of great importance. This index is obtained by dividing the Volume of water delivered to the farm unit (V_d) to the Volume of water needed for that farm unit (V_r). It is equal to one in ideal condition. Because of the importance of energy, it is not acceptable for this index to be more than one. Also, due to the importance of adequate water supply and its timely delivery, the desired value for this index is slightly lower than the *SWI* index; it is recommended to be around 0.8 to 1.

$$TWI = \frac{V_d}{V_r} \qquad (6)$$

As mentioned above, when *SWI* and *TWI* indices are closer to one, the pumping station performance will be increased to supply the operation safety, water productivity, and higher production per unit area; thereby ideal and desirable conditions will be achieved for the pumping station. Here, because of the lack of data related to the water requirement during the irrigation seasons, *SWI* and *TWI* indices were not calculated for the studied stations.

Pumping Stations Energy Indices

Energy indices enable us to assess energy consumption of the pumping system realistically and regularly. Also, it helps manager to make better decisions about the operation and maintenance of the system and reduces its system costs. Some important management indices are presented below:

Energy Consumption per Unit Volume of Pumped Water Index (EVI)

This index indicates the amount of consumed energy per cubic meter of the pumped water. Increase in the index value reflects more energy consumption, and as a result, increase in the system costs. This index is related to the pump performance and must have a constant value. Increase in this index value for a specific period of time indicates additional energy consumption which must be corrected by proper management.

$$EVI = \frac{E_{wr}}{V_p} \qquad (7)$$

Energy Consumption per Hectare of Cultivation Index (ECI)

This index is calculated by dividing the amount of consumed energy (watt-hour or kilowatt-hour) to the cultivated acreage (ha). If the value of this index is high in a period or a season, with a constant crop pattern, one can consider more cultivation areas for that period.

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This index value usually increases in seasons with more water requirement and decreases in seasons with low water requirements.

$$ECI = \frac{E_{wr}}{A_h} \quad (8)$$

Pumping Discharge per Hectare of Cultivation Index (PCI)

This index can be obtained by dividing the discharge of pumped water (cubic meter per hour) to its cultivated acreage in a month or a year. This index value depends on the type of cultivated crop and the quantity of available water. It is expected that a constant discharge is pumped per month for a special crop per hectare. Therefore, this index is inversely related to the cultivated area and decreases with increase in the cultivated area.

$$PCI = \frac{Q_p}{A_h} \quad (9)$$

Percent Surplus Energy of Pumping System Index (PSI)

This index is obtained from the ratio of the difference between Energy supplied by the pump (E_{ws}) and the Energy requirements of the system (E_{wr}) to the energy requirements of the system; it is an appropriate index for managing energy consumption in the pumping station. Calculation of this index in each month enables us to identify and explain the energy loss.

$$PSI = \frac{E_{ws} - E_{wr}}{E_{wr}} \quad (10)$$

Electric Motors' Proportionality of Pumping System Index (EPI)

This index shows what percentage of power generated by the pump is used by the system and/or how much (%) of the selected electric motor is proportional to the operating system conditions.

$$EPI = \frac{P_{wr}}{P_{ws}} \quad (11)$$

Where, P_{wr} is scheme Power requirement at each irrigation period and P_{ws} is the selected electric motor Power of the pumping stations.

Economic Indices of Pumping Stations

A pumping station is economically profitable if its revenue is higher than its costs. In order to analyze the economic conditions of the studied pumping stations, all information about their revenues and costs is required. This information includes water sale income, income from the sale of agricultural products, electricity costs, repair and maintenance costs, personnel costs, etc. It must be noted that the effective parameters in calculating incomes and costs are different, depending on local conditions, operation type, and legal culture of each zone. There are 8 considered pumping stations in the studied region. Veis (P1), Sabily main station (P2), Sabily no.1 substation (P3), Sabily no.2 substation (P4), Sabily no.3 substation (P5), Sabily no.4 substation (P6), Evan no.1 station (P7) and Evan no.2 station (P8). In this study, economic data for both Sabily and Evan No.1 Stations are presented in Tables 2 and 3 Defined economic indices according to the available data are as follows:

Volume of delivered water per unit of cultivated acreage (A)

Water sale incomes per unit volume of delivered water (B)

Maintenance costs per unit volume of delivered water (C)

Maintenance costs per hour of pump operation (D)

Operators' salary per unit of cultivated area (E)

Operator salary per unit volume of delivered water (F)

Operator salary per hour of pump operation (G)

Electricity costs per unit of cultivated area (H)

Electricity costs per unit volume of delivered water (I)

Electricity costs per hour of pump operation (J)

Profitability of Pumping Station for Farmer (PFF) and Operator (PFO) Indices

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Table 2. Required data for economic assessment of the Sabily Main Pumping Station.

Year	Cultivated area (ha)	Volume of delivered water (m^3)	Hours of pump performance (hr)	Water sale income($)	Maintenances cost ($)	Electricity cost ($)	Operator salary ($)
2011	-	-	-	-	-	1630.48927	74.86020
2010	8540	-	-	62190	-	466.30699	67.86918
2009	7319	145670400	14188	49910	17889.6774	284.26013	58.35172
2008	5413	68999040	13125	37720	2843.28304	269.28341	53.55857
2007	8813	180835200	30553	59260	20435.9408	213.07000	46.06841
2006	8929	133116480	-	53760	3756.90145	-	-
2005	8666	12810530	-	49290	3368.20308	-	-
2004	8534	133300253	-	42580	11415.9757	-	-
2003	8277	123248563	-	40860	3343.73967	-	-
2002	7848	127780070	-	11946	3296.23357	-	-
2001	7358	112329240	-	28200	3153.47316	-	-

Table 3. Required data for economic assessment of Evan Number 1 Pumping Station.

Year	Cultivated area (ha)	Volume of delivered water (m^3)	Water sale income ($)	Maintenances cost ($)	Electricity cost ($)	Operator wage ($)
2011	3498	-	-	-	401.55826	74.8602
2010	1675	-	-	-	95.41986	67.86918
2009	3854	32971190	24430	1537.1142	27.92091	58.35172
2008	2498	28244419	14030	1414.39362	23.70671	53.55857
2007	5054	76931350	24910	1213.59583	104.62000	46.06841
2006	-	-	24640	1426.74493	-	-
2005	-	-	21740	1737.40569	-	-
2004	-	-	24540	1530.58398	-	-
2003	-	-	-	1051.05696	-	-
2002	-	-	-	985.67044	-	-
2001	-	-	-	1112.79228	-	-

Farmer's income comes from the cultivated area and its crop yield. Farmers must pay for the pumped water volume costs and other costs at different stages of planting and harvesting. Regardless of the miscellaneous costs (due to the unavailability of data),and through defining farmers' income index per cost of purchased water, an analysis of the farmers economic profitability of the pumping station can be carried out (Equation 12). Also, the index of operator profitability per unit volume of the pumped water can be obtained through Equation (13):

$$PFF = \frac{C_w}{A_w} \quad (12)$$

$$PFO = \frac{A_w}{B_w} \quad (13)$$

Where, A_W is the Water selling income, B_W is the total current costs (i.e., electricity, maintenance and personnel costs), and C_w is the product-selling income. They are

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determined for each unit volume of the pumped water.

Case Studies

Several pumping stations in Khuzestan province were selected, as they are important sources for supplying irrigation water in the region. In these agricultural regions, there is a high density of pumping stations. These stations are good samples in operation conditions, thus the results can be considered as a basic model for planning and optimizing water pumping in the country (Fathimoghadam, 2007). The eight studied pumping stations are as follows: Veis Pumping Station, which is located in north east of Ahvaz Irrigation Scheme (P1); five Sabily Pumping Stations including the Main Sabily Station (P2), four Sabily Pumping Substations (P3 to P6 located in Dez Irrigation Scheme), and two Evan Pumping Stations [Numbers 1 and 2 (P7 and P8)], which are located in Evan Irrigation District.

- North East Irrigation and Drainage Scheme of Ahvaz: This scheme includes Veis, Molasani, Salamat, Abufazel, and East of Gargar Units, covers 23,470 hectares of command area. Veis' Pumping Station supplies water for this scheme. Its total pumping capacity is 12.5 $m^3 s^{-1}$ includes 5 vertical pumps with 2.5 $m^3 s^{-1}$ capacity, 11 m head, and 512 kW power.

- Dez Irrigation and Drainage Scheme: Approximately, 14,000 hectares of this area are irrigated using pumped water, therefore, pumping stations play a vital role in the scheme. Nearly 2,600 hectares of this area are irrigated by the Main Sabily Station and its four pumping substations. The total flow entering the Sabily Irrigation Scheme is about 15 $m^3 s^{-1}$.

- Evan Irrigation and Drainage Scheme: The area of this scheme is 13,000 hectares; Evan Number 1 Pumping Station having 7 submerged pumps with 10 $m^3 s^{-1}$ capacity, supplies water from Karkheh River. Evan Number 2 Pumping Station with 20 centrifugal pumps and 20 $m^3 s^{-1}$ capacity is located in 14 km distance from Evan Number 1 Pumping Station. In this study, Sabily Station zone was assessed because of its vast command area, and Evan Number 1 Pumping Station was assessed because of its acceptable database.

RESULTS

Calculation of Pumping Stations Operation and Maintenance Indices

Based on the presented method and the current conditions of the studied stations, effective parameters (S_1 to S_{10}) were valued for each pumping stations (Table 4), then the performance indices were calculated for them using the Equations (2), (3), and (4) (Figure 1).

According to the results, Pumping Station Evan No. 2 (P_8 with Grade 3) had the best operation and maintenance performance. Overall, the average performance of the studied pumping stations shows medium operation and maintenance conditions (with Grade 2).

DMI, *ODI*, and *OSI* indices can help to improve the operation and maintenance status

Table 4. Assigned values to determine the effective parameters of evaluation process.

Parameters	P_1	P_2	P_3	P	P_5	P_6	P_7	P_8
S_1	1	0	0	0	0	0	1	0
S_2	4	0	1	2	2	2	4	0
S_3	4	0	0	0	0	0	0	0
S_4	3	3	2	3	3	2	2	3
S_5	3	3	4	4	4	4	3	2
S_6	4	3	3	3	3	3	4	2
S_7	3	4	3	2	2	2	3	3
S_8	3	3	2	2	2	2	3	3
S_9	2	1	1	1	1	1	2	0
S_{10}	3	3	3	3	3	3	3	2

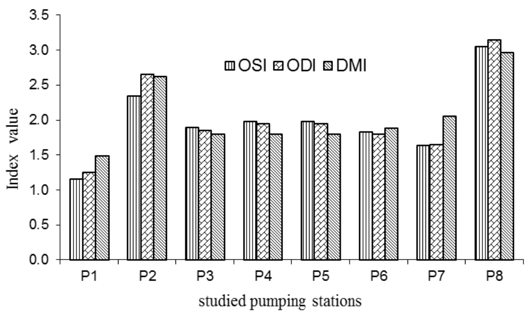

Figure 1. Pumping stations operation and maintenance indices **v**alues.

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by evaluating the operation conditions and comparing the results in each pumping station. It leads to increase the energy consumption efficiency. The use of these indices depends on the management purpose and expectations of the pumping station performance.

Calculation of Pumping Stations Energy Indices

In order to calculate the energy indices, after collecting the necessary data, the authors calculated and compared the defined indices for each station for a 4-year period (from April 2007-March 2008 to April 2010-September 2010). It is notable that the *EVI* and *ECI* indices were calculated only for the Main Sabily Station due to the lack of available pump data (Figures 2 and 3). *PCI* index was calculated only for the Main Sabily Station and its substations (Figures 4 to 7). Also, *PSI* and *EPI* indices were calculated for the two pump groups of the Main Sabily Station (4 small pumps and 4 large pumps) (Table 5).

EVI index changes during different months showed that deviation from a specific value happened more in the warm months. Usually, in the warmer months of the year, the pump uses its maximum power and, subsequently, its energy consumption increases. Decrease in this index in August 2010 and 2009 was due to the reduction in water levels and, as a result, decrease in the pump operation hour and consumed energy. By assuming no changes in crop patterns in different years, this index is expected to be the same in different months of the year. Generally, this index decreased from 2007 to 2010. These changes must be economically justifiable. As shown in Figure 3, if the cultivated area is fixed throughout the different years, it would be expected to have the same trend in *ECI* index, except for a few cases.

One of these exceptions is the increase of this index in July 2007, which seems to be due to the small cultivated area in this month. In the optimal operation, it is expected that pumping station operates at maximum efficiency, but according to the results and on average, this index showed different trends in different years, among which the second period (April 2008-March 2009) had the highest performance. Knowing the *EVI* index and the delivered volume of water to farmers, according to their land area, one could assess

Table 5. Calculated *PSI* and *EPI* indices: Main Sabily Station (September 2010).

	Energy Consumption (KWh)	Energy Production (KWh)	Power Consumption (KW)	Power production (KW)	*PSI* (%)	*EPI* (%)
Larger pumps	226320	1541000	740	1000	35.1	74.0
Smaller pumps	56133	325090	195	290	48.7	67.2

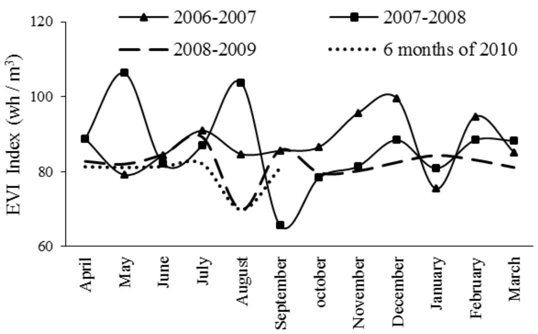

Figure 2. *EVI* index changes (Main Sabily Station).

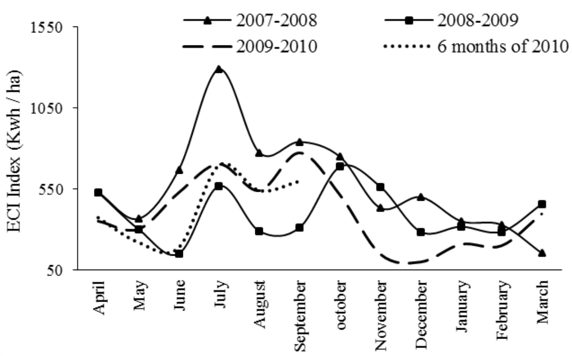

Figure 3. *ECI* index changes (Main Sabily Station).

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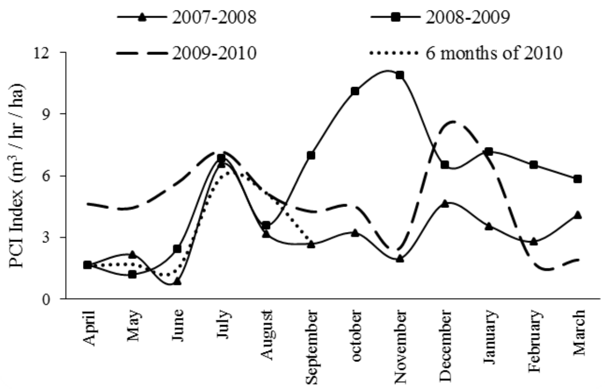

Figure 4. *PCI* index changes (Main Sabily Station).

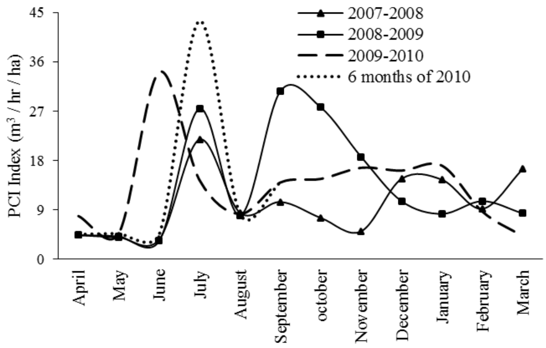

Figure 5. *PCI* index changes (Sabily Station No. 1).

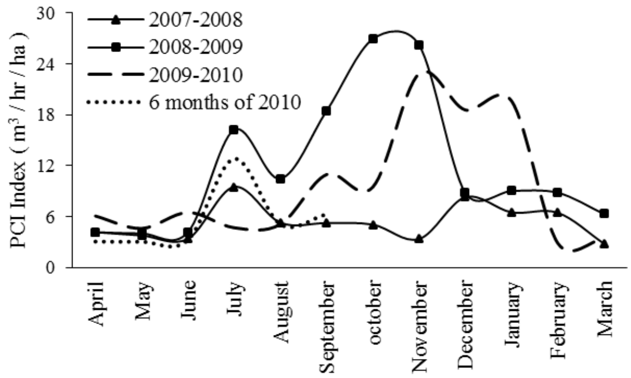

Figure 6. *PCI* index changes (Sabily Station No. 2).

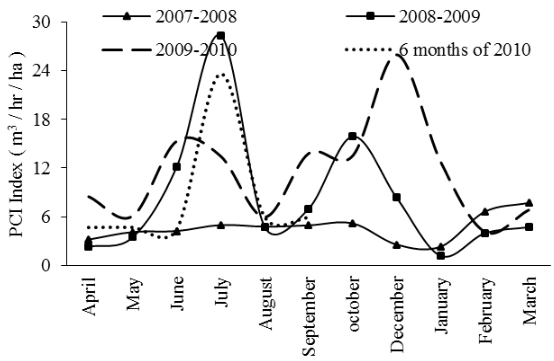

Figure 7. *PCI* index changes (Sabily Station No. 3).

the quantity and amount of water and energy consumption per unit of production. According to the results, the *PCI* index showed the same trend in the Main Sabily Station in different years. Its increase in September and October 2008 is due to the reduction in cultivated area (Figure 4). In Sabily No. 1 Substation, increase in this index in all months in 2008 and June 2009 was due to the reduction in cultivated area and pumping hours, respectively (Figure 5). This index increased in Sabily No. 2 in the same months (Figure 6). By assuming constant crop pattern in each station, the main Sabily Station had the lowest water consumption per unit of area and the best water consumption management (average annual values of this index were lowest for the Main Sabily Station).

It is notable that Sabily Substation 3 had no data in November; therefore, this month was removed from the analysis. The *EPI* and *PSI*, the other two energy indices, were calculated only for the Main Sabily Pumping Station due to the lack of information in other pumping stations. The values of the *PSI* and *EPI* indices showed that 35.1% and 48.7 percent of energy was lost in large and small pumps of the Sabily Stations, respectively. Therefore, energy loss in small pumps was more than large pumps; in other words, the higher the *EPI* index value, the lower the energy loss was.

Calculation of Profitability of Pumping Station (PFF and PFO)

Many parameters were required to calculate the *PFF* and *PFO* (Profitability of pumping stations For Farmer and Operator respectively) indices that were available only during winter planting in the Sabily Station in 2009 (Tables 6 and 7). Water sale in the Sabily Scheme was not volumetric, and its income per cubic meter for the operators was considered as the cost of buying a cubic meter of water by the farmers. To calculate the aforementioned indices, the authors obtained electricity, maintenance, and

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Table 6. Parameters used to calculate *PFO* and *PFF* (for 1 m^3 of pumped water) (winter 2010).

Total revenue of Products sales ($)	Sales revenue ($×10^3)	Electricity costs ($×10^3)	Maintenance costs ($×10^3)	Personnel costs ($×10^3)
1.78850	34.26	0.2	12.28	0.4

Table 7. Calculated *PFO* and *PFF* indices.

A_w	B_w	C_w	*PFO*	*PFF*
34.26	12.88	8552.22	2.66	249.63

personnel costs per cubic meter of pumped water by analyzing the economic parameters (Table 6). In addition, to calculate the products' sale income, some other parameters such as crop pattern, cultivated area, and products' sale prices were driven. Besides, crop performance during the irrigation season was calculated. It should be noted that in the time of this study, one dollar was considered equal to 100,000 Rials (Iranian Currency). Obviously, in similar studies it could be justified based on the updated currency value. According to the results presented in Table 7, the economic benefit of a pumping station for the operator was negligible compared with that of the farmers. It seems that the economic benefit is not important for the operator (maybe, because of public management), which leads to decrease in performance of the pumping stations.

Calculation of Economic Indices of Pumping Stations

The required data for the economic analysis are presented in Tables 2 and 3. Based on the available data, economic indices were calculated to achieve a comprehensive economic analysis (Tables 8 and 9). To calculate these indices, hydraulic parameters such as annual pump operating hours, annual cultivated area, and annual pumped volume of water were used.

Figure 8 shows the comparison of the economic index *C* between two stations in which the repairs' cost in the Sabily Pumping Station per unit volume of pumping was much more than that of the Evan Station in the first (April 2007-March 2008) and the third financial year (April 2009-March 2010). This difference is reasonable regarding Sabily's bigger pumps and higher station lifetime (approximately 2.5 times more). However, in the second year (April 2008-March 2009), the value of this index was higher in the Evan Station. This increase was due to the increase in maintenance costs and decrease in the cultivated area.

Figure 9 depicts the comparison of the

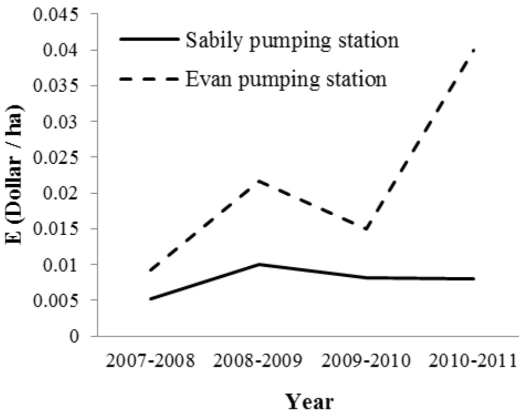

Figure 8. Comparison of *C* index changes.

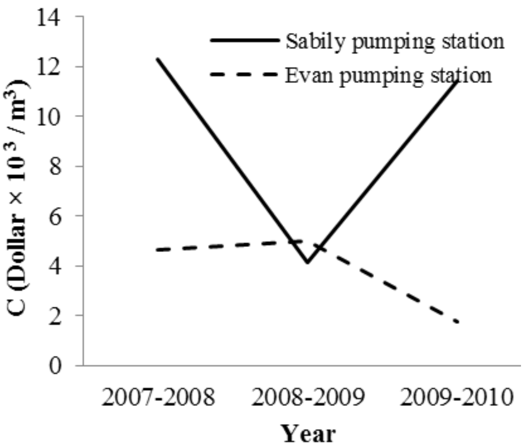

Figure 9. Comparison of *E* index changes.

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Table 8. Calculated economic indices for Evan No. 1 Station.

Year	*I* ($\$\times10^3$)	*H* ($)	*F* ($\$\times10^3$)	*E* ($)	*C* ($\$\times10^3$)	*B* ($\$\times10^3$)	*A* (m^3 ha^{-1})
2011	-	0.11479	-	0.02140	-	-	-
2010	-	0.05696	-	0.04051	-	-	-
2009	0.08	0.00724	1.77	0.01514	4.66	74.09	0.86
2008	0.08	0.00949	1.9	0.02144	5.01	49.67	1.13
2007	0.14	0.02070	0.6	0.00911	1.58	32.38	1.52

Table 9. Calculated economic indices for the Main Sabily Station.

year	*J* ($)	*I* ($\$\times10^3$)	*H* ($)	*G* ($\$\times10^3$)	*F* ($\$\times10^3$)	*E* ($)	*D* ($)	*C* ($\$\times10^3$)	*B* ($\$\times10^3$)	*A* (m^3 ha^{-1})
2011	-	-	-	-	-	-	-	-	-	-
2010	-	-	0.0546	-	-	0.0079	-	-	-	-
2009	0.200	0.2	0.0388	0.041	0.4	0.0079	1.260	12.28	34.26	1.99
2008	0.205	3.9	0.0497	0.040	7.8	0.0098	0.2166	4.12	54.67	1.27
2007	0.069	1.2	0.0241	0.015	2.5	0.0052	0.6688	11.30	32.77	2/05
2006		-	-	-	-	-	-	2.82	40.39	1.49
2005	-	-	-	-	-	-	-	2.79	40.80	1.39
2004	-	-	-	-	-	-	-	8.56	31.94	1.56
2003	-	-	-	-	-	-	-	2.71	33.15	1.49
2002	-	-	-	-	-	-	-	2.58	93.49	1.63
2001	-	-	-	-	-	-	-	2.81	25.10	1.53

economic index *E* between two stations. In the Evan Pumping Station during the first to the fourth years (2007-2010), the operator's salary costs per unit of the cultivated area were more than that of the Sabily Station. This could be acceptable considering that the Sabily Station had more cultivated area (approximately twice more) during those years.

Also, a comparison between the two stations regarding the economic index *H* is shown in Figure 10. In the Sabily Pumping Station, *E* index was about twice more than that of the Evan Station in the second and third financial years, which is reasonable because the electric power of the Sabily Station was two times more than that of the Evan Station. But, remarkably, this index was almost the same in the first and the fourth financial years for both stations.

However, the increase of this index value for

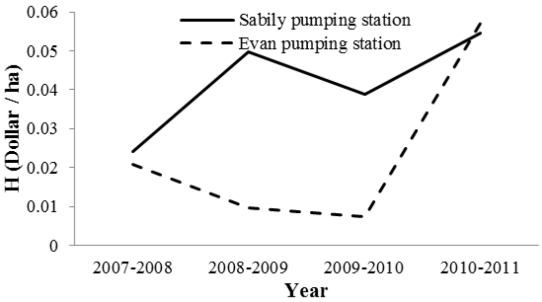

Figure 10. Comparison of *H* index changes.

Evan Station had no proper explanation. Considering the lack of accessible or measured data, pumping stations need to be periodically monitored and assessed. Therefore, the first step in the performance assessment of these facilities is to establish a monitoring system for maintenance.

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CONCLUSIONS

The assessment of pumping station and determination of its performance indices in various aspects (operation, management, energy, and economy) enables us to compare the pumping stations performance in different irrigation periods and regions. In addition, this can directly affect the overall performance of the irrigation scheme, and as a result, the product efficiency and productivity of water and energy. The more accurate and complete the effective parameters are defined, the more complete evaluation of pumping system condition will be done. Based on the results, the average of the operation, performance, and maintenance of the studied pumping stations indicates a moderate condition (Grade 2). Therefore, all of the identified parameters in the pumping stations need to be improved, specifically the parameters S1, S2, and S9, due to their weakest conditions. In surface irrigation schemes, the original purpose of the pumping station is to supply the water requirement in sufficient quantities and at the optimal time. Achieving this goal can be assessed by defining, calculating, and controlling the *SWI* and *TWI* indices periodically. To achieve the maximum energy efficiency, the pumping system electric motors must be selected proportional to the system power required. Therefore, selection criteria of electric motors power of the pumping stations should be modified. Calculating the energy consumption indices (EPI and PSI) shows the high percentage of energy loss in pumping stations (on average 40%). Due to the importance of energy saving, the following efforts must have the priority in the planning stages: (a) Using proper equipment to reduce the energy consumption, (b) Appropriate pump-electromotor selection, (c) Developing a pump operation schedule adapted to the water requirement of the irrigation command area. According to the results of energy indices, Sabily Pumping Station had the maximum energy efficiency in the first six months of 2010 (according to EVI index) and in the period April 2008-March 2009 (according to ECI index). Also, calculation of *PCI* for studied stations shows that the Main Sabily Station had the lowest water consumption per hectare, and as a result, the best water consumption management. The economic optimal model for each station in different periods is defined by calculation of *PFF* and *PFO* indices. Thus, costs and revenues of pumping station would be managed and controlled. On the other hand, the economic benefit of operators is much less than that of the farmers, which should be increased in order to achieve better management. However, the time trend of each index may show the instability in decision-makings or could be interpreted as variations of related factors (such as crop pattern, water requirement, management issues, costs, pumping station facilities, etc.) during each cultivation. In both cases, the temporal changes of indices can give us good information on how to manage the pumping station in terms of irrigation management.

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ارزیابی عملکرد ایستگاههای پمپاژ با هدف مدیریت آبیاری (مطالعه موردی: استان خوزستان، ایران)

ا. شریف نژاد، و ع. پرورش‌ریزی

چکیده

از آنجاکه ایستگاههای پمپاژ آب کشاورزی، بخش عمده‌ی آب مورد نیاز طرحهای آبیاری را تأمین می‌کنند و در برخی کشورها درصد بالایی از انرژی را مصرف میکنند، ارزیابی عملکرد آنها، به ویژه در

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ارتباط با مدیریت آبیاری لازم است. بنابراین تعریف و تعیین برخی شاخصها میتواند در فرایند ارزیابی، برنامه ریزیهای آتی و کارایی و استفاده بهینه از آب و انرژی مؤثر باشد. با توجه به اینکه روش مشخصی برای ارزیابی سامانه‌های پمپاژ آبیاری در منابع علمی وجود ندارد، در تحقیق حاضر، برخی شاخص‌های ارزیابی عملکرد در بخش‌های بهره‌برداری و نگهداری، مدیریت، انرژی و اقتصاد معرفی شدند. سپس عملکرد چندین ایستگاه پمپاژ واقع در استان خوزستان (ایران) و روابط آب-انرژی در آنها بر اساس این رویکرد جامع ارزیابی شد. طبق نتایج نخستین گام در ارزیابی عملکرد این تأسیسات، راه‌اندازی سیستم‌های پایش و نگهداری اطلاعات است. نتایج ارزیابی عملکرد در مطالعه موردی، عملکرد متوسط این ایستگاه‌ها را نشان می‌دهد. بنابراین، در بخش مدیریت بهره‌برداری، پارامترهایی که در وضعیت ضعیف قرار دارند (تجهیزات هیدرولیکی مورد نیاز، پایش دوره ای پارامترهای هیدرولیکی و میزان امنیت در مقابل ضربه قوچ) باید با رعایت اولویت‌بندی بدست آمده در نتایج، تقویت شوند. در محاسبه بهره‌مندی اقتصادی بهره برداران و کشاورزان از ایستگاه پمپاژ، باید بهره اقتصادی بهره‌برداران برای دستیابی به مدیریت بهینه افزایش یابد. همچنین در بخش ارزیابی انرژی، با توجه به محاسبه تلفات انرژی تا حدود ۴۹ درصد در برخی از پمپ‌ها، بکارگیری تجهیزات کاهش مصرف انرژی و انتخاب صحیح پمپ و الکتروموتور باید در اولویت طراحی و مدیریت قرار گیرد. در هنگام طراحی، توان مورد نیاز الکتروموتورها در این تحقیق، حداقل ۲۵٪ بیش از نیاز برآورد شده است.

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