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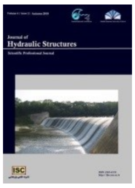

Developing Concept of Water-energy Productivity to Evaluate Dez Dam Operation

Ebrahim Zallaghi [1]
Ali Mohammad Akhoond-Ali[2]
Seyed Mohammad Ashrafi [3]

Abstract

The “concept of productivity” in the context of WEN (water-energy nexus) is a new outlook to evaluate dam and power plant operation policies. Understanding and modeling the complicated nature of water-energy nexus (WEN) are essential to increase productivity. The performance of dams and hydropower plants is mostly evaluated by the amount of energy generated and/or meeting downstream demands. The present study investigates the historical operation efficiency of Dez dam and hydropower plant from 1972 to 2018 by defining the productivity indices of water footprint (WF) of electricity, energy economics, water-energy performance, WEN, and energy sustainability. Then, the correlation between the obtained results and Streamflow Drought Index (SDI) is evaluated. The results indicated that wet years, despite generating more energy, do not show necessarily the highest productivities, since two years with moderate drought and almost similar discharges (i.e., 2007-2008 and 2010-2011) showed the highest and lowest productivities during the operation period of Dez Dam, respectively. Such difference arises from overlooking full supply levels (FSL) in from 2008 to2017. The FSL of water years in 2007-2008 was calculated to be 325.13 masl while it was 350.91 masl for water years of 2010-2011. One can, therefore, conclude that maximum productivity can be achieved even during droughts by adopting an optimal operation policy.

Keywords: Water-energy nexus (WEN); Hydropower generation; Integrated modeling; Water productivity.

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[1] Department of Hydrology and Water Resources, Faculty of Water & Environmental Engineering, Shahid Chamran University of Ahvaz, Ahvaz, Iran. ezallaghi@yahoo.com

[2] Department of Hydrology and Water Resources, Faculty of Water & Environmental Engineering, Shahid Chamran University of Ahvaz, Ahvaz, Iran. aliakh@scu.ac.ir
(Corresponding Author)

[3] Department of Civil Engineering, Faculty of Civil Engineering and Architecture, Shahid Chamran University of Ahvaz, Ahvaz, Iran. ashrafi@scu.ac.ir

1. Introduction

Water and energy should be considered inseparable in modeling and performance analysis. Water is needed to generate energy (hydropower and cooling systems in thermal power plants) while energy is needed to extract, treat, and distribute water; so, challenges in both fields must be addressed together. Energy and water are closely intertwined and are crucial not only for the economy, but also for the health and well-being of all the human beings [1].

Case studies conducted in Australia, Europe, and the United States aimed at identifying a comprehensive understanding of WEN applying integrated management systems and policies and determine how more prudent programs, processes, frameworks, and technologies can be adopted to reduce water and energy footprints [2].

Hydropower reservoirs demonstrate a strong WEN ([3, 4]). Although water reservoirs have the potential to generate hydropower, evaporations from lake surface and water seepage from reservoirs cause water losses, leading to water footprint in hydropower generation [5]. As global concerns over water and energy security increase, investigative study of WEN has recently attracted great attention. It is believed that WEN analysis can help manager to optimize water and energy operation [6].

Lee et al. [7] evaluated water and energy exchanges at regional and national scales using an integrated model. They developed the integrated global change assessment model (GCAM) to analyze the economic, energy, agricultural and land use, as well as water and climate systems in water and electricity systems of the United States. The results showed an optimal amount of water harvesting and consumption to generate electricity in the United States and changes in water harvesting in future scenarios.

On the other hand, successive droughts in different regions around the world can lead to fundamental changes in WEN. The occurrence of such droughts in arid and semi-arid regions, such as Iran, has received greater attention from researchers (Adib et al., [8]). Uncertainties governing models used in design and operation of water resource systems [9] have highlighted the need to examine WEN in complex water resource systems.

The present study defines a water and energy productivity index in order to analyze WEN for hydropower reservoirs. Considering the fact that Dez Dam is the only reservoir in Dez watershed that regulates National Power Grid Frequency and supplies downstream water demands [10], it was selected as a suitable case study in this research.

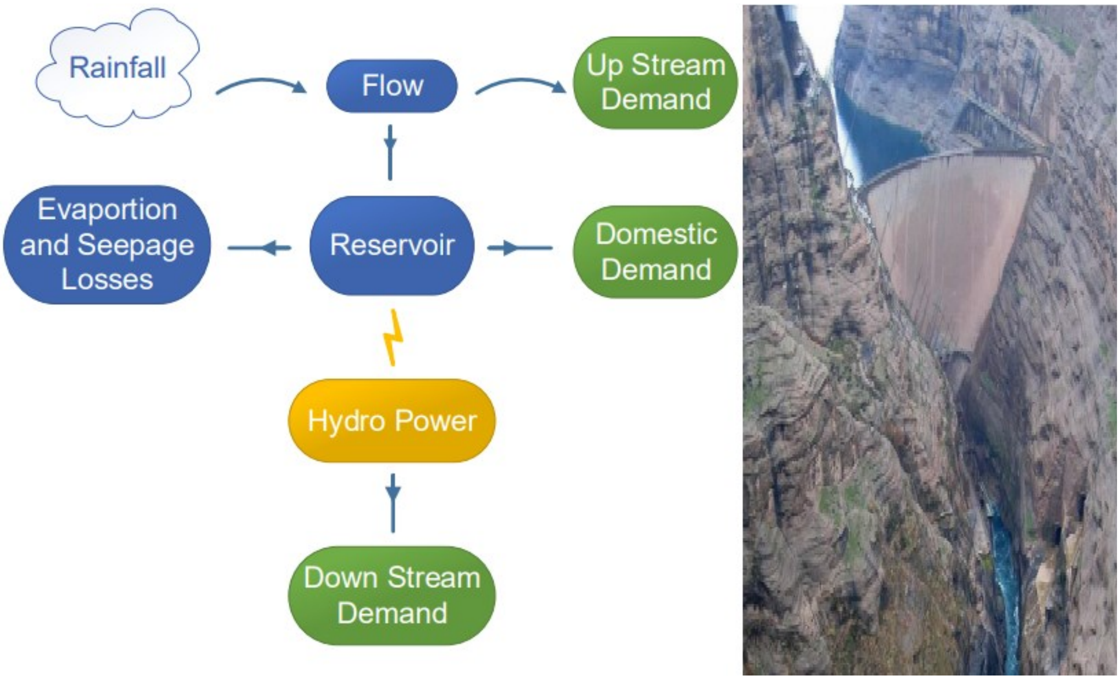


Figure 1. Conceptual design of WEN in Dez dam and hydropower plant

2. Study area and problem statement

Dez River is one of the most important tributaries in southwest of Iran. Dez reservoir began to operate in 1963 to supply drinking water and downstream industrial and agricultural demands. The original installed capacity of the hydropower plant is 520 MW. However, the capacity has been planned to be increased to 720 MW based on studies carried out in recent years. The design net head of Dez Hydropower Plant is 150 m consisting of 8 units each with a capacity 65 MW. The design flow rate of the plant is 380 m3/s. The mean annual flow of the river to Dez reservoir is approximately 7864 million m3/year of which approximately 5278 million m3/year is the required volume of Dez Hydropower Plant with full operation during design hours. As mentioned before, due to supplying downstream water demands, changing water release patterns in different months, and controlling National Power Grid Frequency, the power plant does not operate necessarily according to design hours. Table (1) presents technical specifications of Dez Reservoir and its power plant. Fig. (2) shows the dam and the power plant location.

Table 1. Specifications of Dez Reservoir and the Power Plant

	Parameter	Unit	Dez in the base state
Reservoir	**Normal level**	Masl	**352.0**
	Minimum operating level	Masl	**300.0**
	Total volume	MCM	**2698.5**
	Useful volume	MCM	**1868.9**

	Parameter	Unit	Dez in the base state
Hydropower	**Installed capacity**	MW	**520.0**
	Number of units	-	**8.0**
	Design flow rate	Cms	**357.0**
	Design head	M	**165.0**
	Efficiency	%	**90.0**
	Mean downstream level	Masl	**175.5**
	Hydropower peak time	Hour	**6.0**
	Mean falling head	M	**3.0**

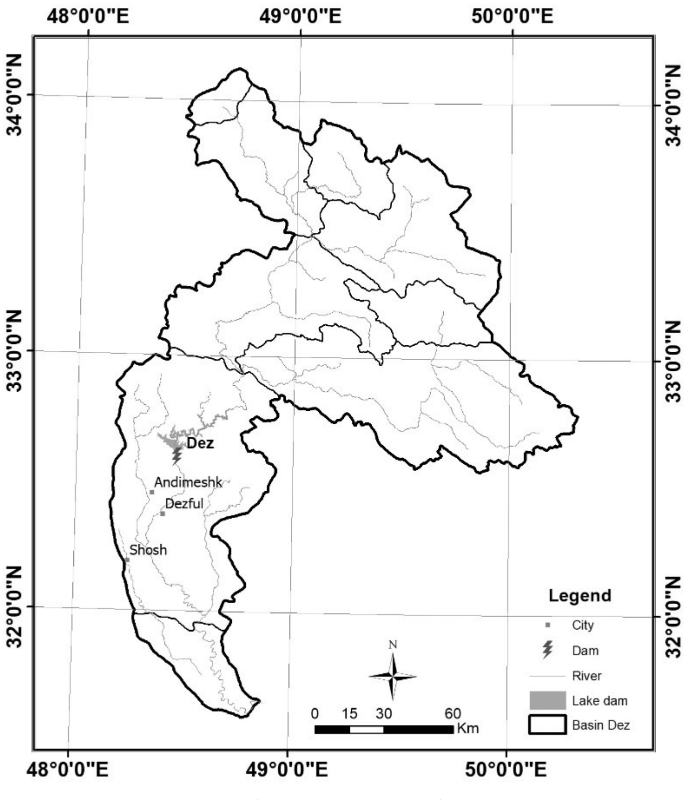


Figure 2. Dez Basin

3. Material and methods

Given that the purpose of this study is to evaluate the performance of reservoir and hydropower operation policies, a simulation model for water allocation must be applied (Ashrafi, 2019). WEAP model was selected due to its capabilities to consider both important processes affecting natural and human systems in water resources management (WRM across a river basin, its wide use to solve similar problems in different parts around the world and its ease of access.

In order to analyze Dez reservoir and Hydropower productivity, evaporation data, downstream demands, reservoir volume and levels, and hydropower plant energy generation records were collected on monthly basis over the operation period of 1972-2018. Then, based on the Dam monthly storage volumes, the simulation was performed considering the supply of agricultural demands, fish farming, and environmental flow requirements in Band-e Qir Area by WEAP model. The results were obtained for each year and analyzed using water-energy productivity and system sustainability indices. Finally, changes in water-energy productivity indices were analyzed as compared to drought index using SDI. In addition, due to lack of reservoir evaporation data from 1963 to 1971, this period was removed from the calculations.

3.1. Water and energy resource system assessment index

It is necessary to determine the appropriate index to assess operation scenarios and identify more favorable alternatives. In this section, the criteria to measure the efficiency of water and energy resource systems are presented. Also, the results of implemented system operation policies are compared in different conditions. Finally, the optimal scenario of water-energy productivity is recognized based on the index.

4. Water-energy productivity indices

In this section, some indices are defined to analyze Dez reservoir and Hydropower Plant productivity based on WEN**.**

4.1. Energy-water performance index (EWPI)

EWPI is the ratio of average monthly energy generation of the hydropower to average monthly flow release from power plant, suggesting the amount of water released per unit of energy. The hydropower generates different amounts of energy at different reservoir levels per unit volume of water released [11],[12]

$$EWPI = \frac{\text{Generated energy}}{\text{Volum of water released}} \quad \frac{GWH}{MCM} \tag{1}$$

4.2. Water footprint intensity (WFI) in hydropower plants

In power generation, WF is associated with the volume of water consumed and polluted at different stages of electricity generation. It is calculated similar to that of thermal power plants with fossil fuels, nuclear energy, and bioenergy. To define WF, water evaporation rate per unit of energy generated is defined in energy generation by power plants [5]. In some references, this process is defined as water consumption by a hydropower (Lee et al., [18. The inverse of WF equation was used in the composite index, called water footprint productivity index (WFPI), to increase productivity [13].

$$WFI = \frac{\text{Reservoir net evaporation}}{\text{Generated energy}} \quad \frac{MCM}{GWH} \tag{2}$$

$$WFPI = \frac{1}{\text{WFI}} \quad \frac{GWH}{MCM} \tag{3}$$

4.3. Energy economic index (EEI)

To calculate the economic index of energy generation revenues, the amount of revenues per unit of energy generated was defined [14],[15].

$$EEI = \frac{\text{Energy sales revenue}}{\text{Generated energy}} \qquad \$/GWH \tag{4}$$

4.4. WEN index

This index helps the decision-makers to determine the efficiency and effectiveness of the intended operation and management policy according to water and energy perspectives. Eq. (5) is defined for the composite index of WEN [16].

$$WENI = \frac{\sum_{i=1}^{n} w_i X_i}{\sum_{i=1}^{n} w_i} \tag{5}$$

Considering that water and energy productivity indices have different aspects, min-max normalization technique was used to normalize the data. Based on the significance of maximum and minimum values, Eqs. (6) and (7) are used, respectively:

$$X_i = \frac{x_i - Min(x_i)}{Max(x_i) - Min(x_i)} \tag{6}$$

$$X_i = \frac{Max(x_i) - x_i}{Max(x_i) - Min(x_i)} \tag{7}$$

where, X_i is normalized value of the actual value of the index x_i, n is the number of productivity indices, Min(x_i) and Max(x_i) are the minimum and maximum values of the index, and w_i is the weight considered per index.

5. Performance assessment index of water resources system

In order to analyze the system performance, and compare results from implementation of system operation policies under different scenarios, the criteria to measure the efficiency of water resources systems are presented. These indices are used as a complement to water-energy productivity indices.

Many studies have often measured the performance of water resources systems by simple criteria such as mean and variance of benefits or operation variables. Although these criteria are useful in many cases, they are not technically sufficient and provide no important description of system behavior when failure occurs [17]. In system efficiency analysis, the focus is on system failure which is defined as system efficiency exceeding the threshold or inability of the reservoir system to provide sufficient discharge.

Hashimoto et al. [18], evaluated system performance from three viewpoints, including (1) how often the system fails (reliability), (2) how quickly the system returns to its satisfying state once failure occurs (resiliency), and (3) how much is the system maximum failure (vulnerability)?

5.1. Reliability

The relative frequency of success in achieving a goal is called reliability. It refers to the probability of a system succeeding in achieving the intended goals in long run. In water resources systems, failure threshold is often defined as meeting 100% downstream water demands. However, this is a matter of convention and other factors need to be considered [18],[19]:

$$\mathrm{Rel} = \left(1 - \frac{\mathrm{NDe_f}}{\mathrm{T}}\right) \times 100 \text{ ، } \mathrm{NDe_f} = \mathrm{No, of\,times}(\mathrm{De_t} > \mathrm{Re_t}) \tag{8}$$

$$\alpha_v = \frac{\mathrm{Re_{Total}}}{\mathrm{De}_{Total}} \times 100 \tag{9}$$

When long periods of data are used in calculations of a natural series, the above equation may be applied to calculate system reliability. Probability risk is defined as system performance under undesirable conditions.

In Eq. (8), $\alpha_v$is volumetric reliability, $\mathrm{De_t}$ is the target demand in current time steps, $\mathrm{Re_t}$ is water release rate from reservoir, $\mathrm{NDe_f}$ is the number of times in which, $\mathrm{De_t} > \mathrm{Re_t}$, and $\mathrm{Def_t}$ is the amount of downstream consumption scarcity in the study time step.

5.2. Resiliency

Resiliency refers to how quickly a system can return to its satisfying state when a failure occurs. If TF is the number of periods a system remains in failure mode, then, the inverse of this parameter can indicate the speed, at which the system returns to its original state. In general, resiliency can be defined as follows [18],[19]:

$$\mathrm{Res} = \frac{\overset{\mathrm{T}}{\underset{\mathrm{t=1}}{\mathrm{N}}} \;(\mathrm{Def_{t+1}} = 0 \mid \mathrm{Def_t} > 0)}{\overset{\mathrm{T}}{\underset{\mathrm{t=1}}{\mathrm{N}}} \;(\mathrm{Def_t} > 0)} \times 100 \quad , \; \mathrm{t} = 1,2, \dots, \mathrm{T} \tag{10}$$

5.3. Vulnerability

Vulnerability shows the severity of occurred failures. Various definitions of vulnerability have been proposed in literature. Vulnerability is often assessed according to two criteria of maximum and average vulnerability. The most commonly used criteria are defined based on monthly distribution of demands over a long period of time.

Maximum monthly vulnerability is defined as the ratio of maximum rate of scarcity in each month to demands of that month which is calculated as follows [18],[19]:

$$\mathrm{Val} = \max\left\{\frac{(\mathrm{De_t} - \mathrm{Re_t})}{\mathrm{De_t}}\right\} \times 100 \quad , \quad \mathrm{t} = 1,2, \ldots \mathrm{T} \tag{11}$$

5.4. Sustainability index

Sandoval et al. [20] proposed sustainability index to gather the performance criteria of water resources systems in a single index and facilitate comparison and decision-making among different options for water resources management and planning

$$\mathrm{SI}^i = \left\{\mathrm{Rel}^i \times \mathrm{Res}^i \times (1 - \mathrm{Vul}^i)\right\}^{1/3} \tag{12}$$

The indices for water resources system performance were employed for hydropower energy and environmental flow

5.5. SDI index

The computational principles of SDI (Streamflow Drought Index) are similar to those of SPI. The monthly flow rates of each hydrometric station fit a suitable statistical distribution [21].

$$SDI_{ik} = \frac{v_{ik} - v_k}{S_k} \qquad i = 1,2 \ldots \quad k = 1,2,3,4,5,6 \tag{13}$$

where v_k and S_k are mean total flow volume rate and standard deviation of cumulative flow volume in the base period k, respectively, and v_{ik} is the cumulative streamflow volume in the base period, k.

6. Measurement results of the historical period of operation 1972-2018

Figs. 3 and 4 present the rule curve using standard operating procedure (SOP) and monthly operating time series of Dez reservoir and Hydropower Plant based on the observed data.

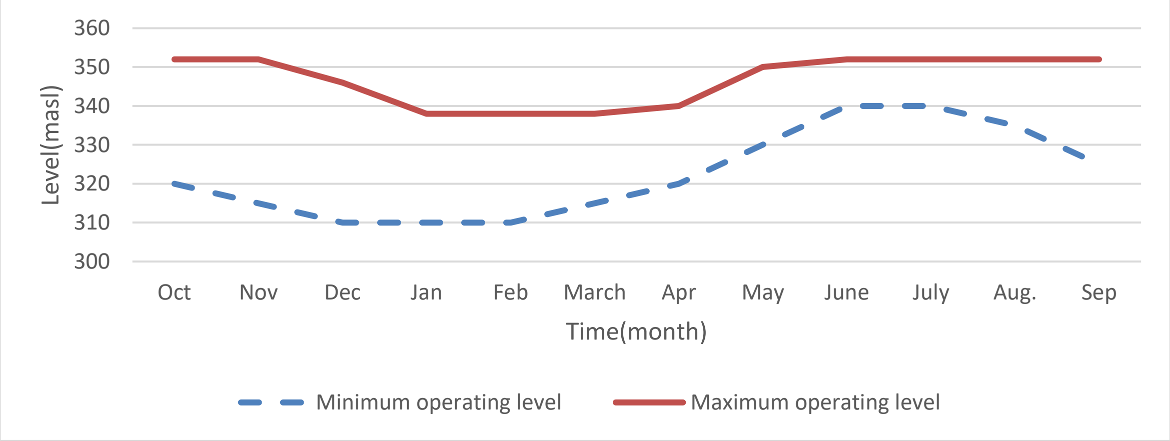
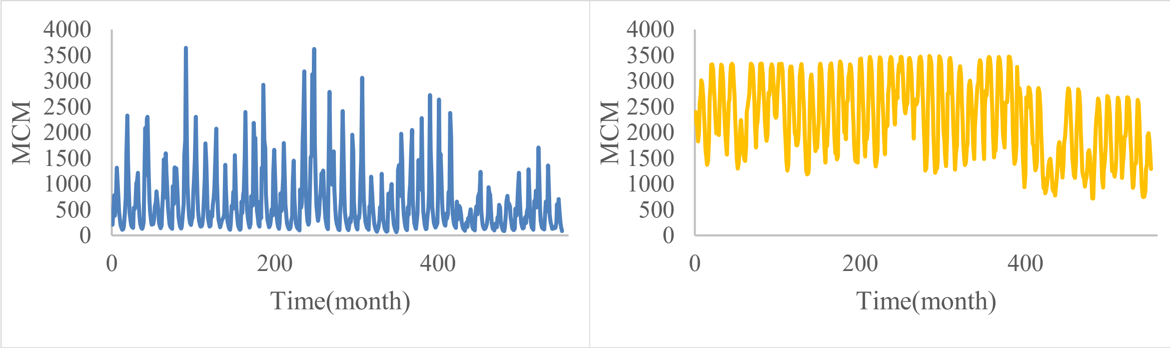
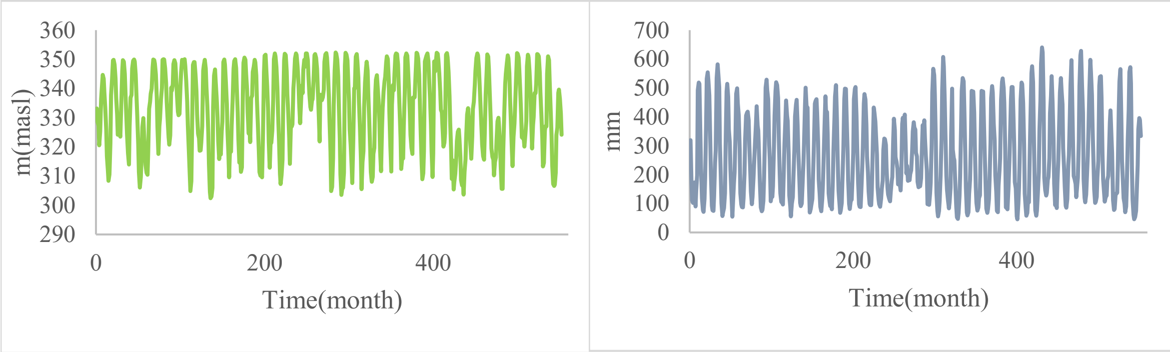


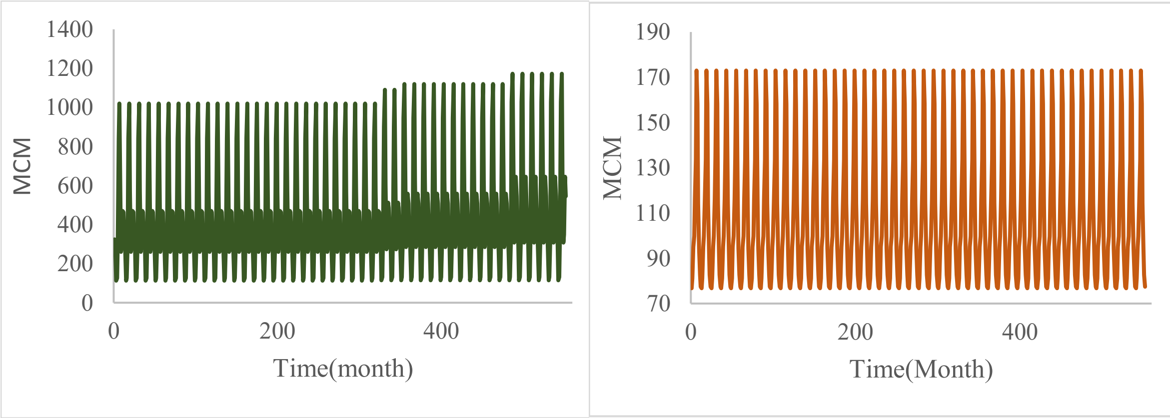
Figure 3. Rule curve of Dez reservoir operation



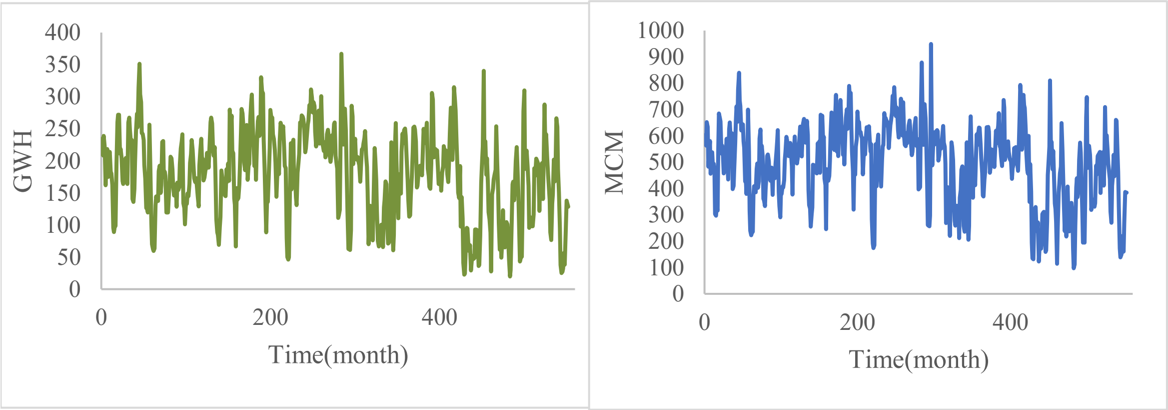
a) Inflow **b) Volume**



c) Elevation **d) Evapration**



e) Demand **f) environmental flow requirements**



g) Power Generate **h) Turbine Outflow**

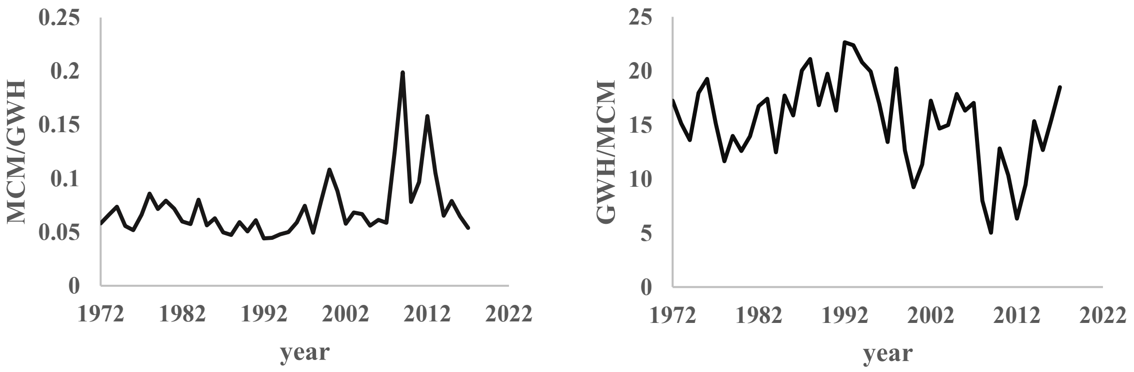
Figure 4. Time-series diagram of Dez Dam datasets a) inflow (MCM), b) volume (MCM), c) elevation (MASL), d) evaporation (mm)), e) Demand (MCM), f) environmental flow requirements-Tennant method (MCM), g) power generate (Gwh), h) Turbine outflow (MCM)

7. Results of calculating WEN productivity and SDI indices in the operation period

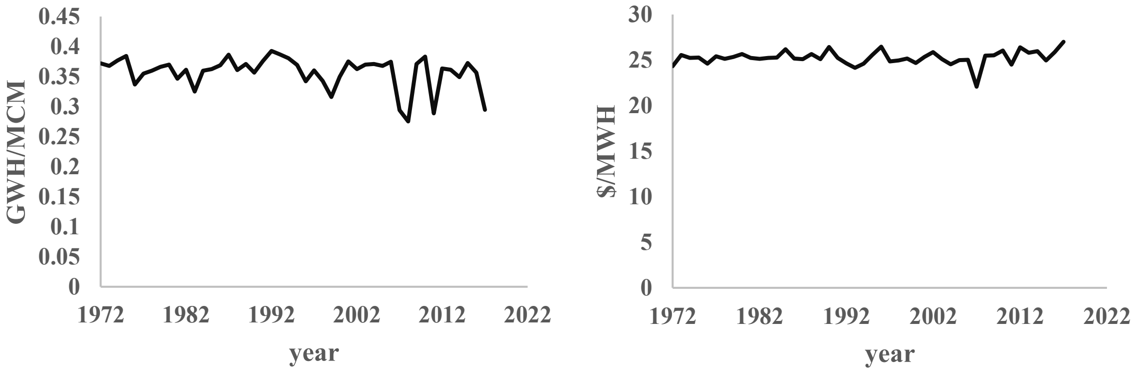
Fig. (5) and Table. (2) present the results of productivity index calculations and SDI index in the operation period of 1972-2018 based on the measured data considering the definition of WEN productivity indices in section 4.

Table 2. Results of calculating normalized productivity indices

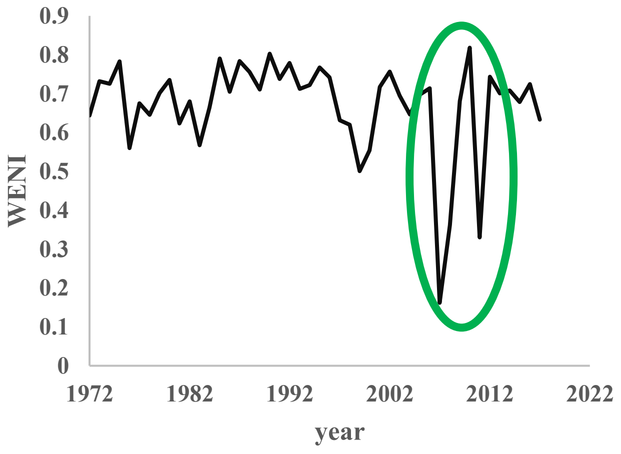
Year	WF	WFPI	EWPI	EEI	WENI	SD index	Situation	Year	WF	WFPI	EWPI	EEI	WENI	SD index	Situation
1973	0.01	0.75	0.82	0.45	0.64	-0.20	Normal	1996	0.01	0.88	0.80	0.71	0.77	0.52	Gentle wet
1974	0.02	0.65	0.79	0.70	0.73	0.44	Normal	1997	0.01	0.74	0.57	0.89	0.74	-0.29	Normal
1975	0.03	0.58	0.87	0.64	0.73	-0.23	Normal	1998	0.03	0.58	0.72	0.56	0.63	0.79	Gentle wet
1976	0.01	0.78	0.93	0.65	0.78	1.46	Medium wet	1999	0.01	0.89	0.58	0.58	0.62	-0.98	Gentle dry
1977	0.01	0.84	0.52	0.51	0.56	-1.02	Medium dry	2000	0.03	0.54	0.35	0.62	0.50	-1.35	Medium dry
1978	0.02	0.65	0.68	0.68	0.67	0.48	Normal	2001	0.06	0.38	0.64	0.53	0.55	-0.77	Gentle dry
1979	0.04	0.49	0.72	0.62	0.65	0.17	Normal	2002	0.04	0.48	0.85	0.67	0.72	0.72	Gentle wet
1980	0.03	0.60	0.78	0.66	0.70	1.47	Medium wet	2003	0.01	0.75	0.74	0.77	0.76	0.29	Normal
1981	0.03	0.54	0.80	0.73	0.73	0.81	Gentle wet	2004	0.02	0.63	0.80	0.62	0.69	0.72	Gentle wet
1982	0.03	0.60	0.61	0.64	0.62	-0.01	Normal	2005	0.02	0.65	0.81	0.50	0.65	0.51	Gentle wet
1983	0.02	0.73	0.73	0.62	0.68	0.52	Gentle wet	2006	0.01	0.78	0.79	0.60	0.70	0.77	Gentle wet
1984	0.01	0.76	0.43	0.64	0.57	-0.86	Gentle dry	2007	0.02	0.71	0.85	0.60	0.71	0.58	Gentle wet
1985	0.04	0.53	0.72	0.65	0.66	-0.26	Normal	2008	0.01	0.74	0.16	0.00	0.16	-1.46	Medium dry
1986	0.01	0.77	0.74	0.84	0.79	0.54	Gentle wet	2009	0.08	0.32	0.00	0.69	0.36	-1.95	Severe dry
1987	0.02	0.69	0.80	0.63	0.70	0.90	Gentle wet	2010	0.15	0.19	0.82	0.70	0.68	-0.38	Normal
1988	0.01	0.88	0.95	0.61	0.78	1.35	Medium wet	2011	0.03	0.55	0.92	0.80	0.82	-1.15	Medium dry
1989	0.00	0.93	0.73	0.73	0.76	-0.05	Normal	2012	0.05	0.43	0.11	0.49	0.33	-1.82	Severe dry
1990	0.01	0.73	0.81	0.61	0.71	0.18	Normal	2013	0.11	0.25	0.75	0.88	0.74	-1.04	Medium dry
1991	0.01	0.87	0.69	0.88	0.80	-0.84	Gentle dry	2014	0.06	0.39	0.73	0.76	0.70	-0.71	Gentle dry
1992	0.02	0.71	0.86	0.64	0.74	1.51	Very wet	2015	0.02	0.66	0.63	0.79	0.71	-0.85	Gentle dry
1993	0.00	1.00	1.00	0.52	0.78	2.62	Very wet	2016	0.03	0.54	0.83	0.58	0.68	0.13	Normal
1994	0.00	0.99	0.95	0.42	0.71	0.19	Normal	2017	0.02	0.67	0.69	0.77	0.72	-0.69	Gentle dry
1995	0.00	0.91	0.90	0.51	0.72	1.42	Medium wet	2018	0.01	0.81	0.17	1.00	0.63	-1.77	Severe dry



a) WFI **b) WFPI**



c) EWPI **d) EEI**



e) WENI

Figure 5. (A) WFI, (B) WFPI, (C) EWPI, (D) EEI, and (E) WEN Productivity Index for Historical Operation of Dez Dam and Hydropower Plant

According to Figs. (5)- A) and (5-B), the lowest WFI (0.044 MCM/GWH) was noticed in water year1992-1993, which is considered severely humid, and the highest WFI was related to water year 2009-2010, equal to 0.2 MCM/GWH. The WFI ranged from +177% to -38%.

The water year 2009-2010 was normal. Yet other normal years may be noticed across the time series. However, the evaporation rates were similar over normal years, decreased hydropower generation in 2009-2010 lead to increased water footprint since the average energy generation in normal years was 2273 GWH, it was 1983 GWH in 2009-2010. The reason for the minimum footprint in wet periods can be obviously attributed to the higher energy generation in wet period than normal years. The wide range of footprint changes confirms the result. Although Dez reservoir evaporations were not significant compared to reservoir inflow volume, WFI is very effective for productivity in reservoirs with large area or high evaporations.

WFPI was the inverse of WFI equation following the above rule. The range of changes in WFI productivity was from +67% to -47% and the highest and lowest productivity rates were for years 1992-1993 and 2009-2010, respectively.

As can be seen in Fig. (5-C), EWPI, which is the amount of energy generated per unit volume of water released, ranging from +10% to -23%. The lowest productivity rate belonged to 2008-2009 with severe drought of 0.27 GWH/MCM while the highest productivity rate was observed in 1992-1993 with severe wetness of 0.39 GWH/MCM. This behavior seems to be normal for EWPI, because this index depends greatly on the reservoir level and, in severely wet periods, the reservoir normally releases water at high levels, so it has higher productivity.

The EEI diagram in Fig. 5-D showed that the severe drought years 2017-2018 had the highest productivity rate of EEI (27 $/MWH) while the moderate drought year had the lowest EEI (22 $/MWH).

The results showed that water years 1992-1993, despite having the highest WFPI and EWPI rates, lost the first possible rank in EEI due to its failure to generate a sufficient amount of energy in months when the highest revenues can be obtained from electricity sales. Also, the years 2017-2018, despite the occurrence of severe drought, had the highest economic productivity in energy generation. Therefore, a sole wet period cannot ensure the highest economic productivity. The years 2007-2008, with less severe drought than years 2017-2018, i.e., higher inflow, had the lowest economic productivity, the reason for which can be attributed to the lack of proper dam impounding. Finally, even with severe drought, it is possible to achieve maximum productivity with proper operation in accordance with a well-framed operation policy.

As seen in Fig. (5-E), in green areas, water years of 2007-2008, with inflow rate of 3842.5 MCM are classified as moderate drought periods while previous year was considered mildly wet and the next year was classified as severe drought. The lowest water-energy productivity was observed from January to December. However, the water years of 2010-2011, with almost similar conditions (2010-2011 as the moderate drought period while previous year to be a normal year, and next year as severe drought) and inflow rate of 4446.4 MCM, had the highest productivity from January to December. According to the history of operation, the minimum and maximum levels of operation in 2007-2008 were 305.38 and 325.97 masl, respectively, while the minimum and maximum levels of operation in 2010-2011 were 315.66 and 351.71 masl, respectively. Therefore, Dez Dam impounding was incomplete in 2007-2008 and the maximum operation levels were mot reached. In this study, system sustainability as well as water resource assessment indices were developed to evaluate energy sustainability and environmental flow. Table (3) presents the results of assessment indices for water resource system, energy generation, and environmental flow of Dez Dam and Hydropower Plant in Band-e Qir Area. As seen from results, the sustainability index of supplying water, energy, and environmental demands is assessed as good.

Table 3. Results of calculations of system assessment indices

Index	Demand supply	Environmental demands	Energy generation
Reliability	83.02	100.00	86.11
Resilience	48.41	100.00	16.67
Vulnerability	79.05	0.00	80.20
Sustainability	43.83	100.00	30.52
V_Reliability	89.03	100.00	93.49

8. Conclusion

In this study, a 46-year period (1972-2018) of Dez reservoir operation was evaluated using WEN approach, WFPI, EWPI, EEI, system performance assessment indices, and drought index. The results showed that EEI was a function of time and amount of energy generation; despite the drought, the maximum economic productivity can be achieved by proper reservoir planning. Also, in case of failure to generate sufficient energy in years with similar inflow rate, especially during months with highest evaporation rates, WF increases. This is of outmost importance especially in dams with large reservoirs and high evaporation levels. The best and worst productivity rates were observed in two years with moderate drought under almost similar conditions, suggesting the important role of proper operation and planning in productivity. It is recommended to perform further studies on productivity index of reservoir dams with higher evaporation volumes and evaluate the effects of climate change on dam productivity.

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