The Effect of Ignored Evaporation and Sedimentation Secondary Processes during Reservoir Planning Analysis on Eventual Operational Performance

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Abstract: This study has analysed the effects of evaporation and sedimentation on the operational performance of reservoirs if these effects had been neglected while dimensioning the reservoirs. It used seven reservoirs operated by the Turkish Republic General Directorate of State Hydraulic Works (SWH) in Yesilirmak Basin, Turkey as case studies. The dams serve a variety of purposes including irrigation, domestic and industrial supplies, hydropower generation and flood control. First, reservoir planning analysis using the sequent peak algorithm, SPA, was carried out to verify capacity for the reservoirs quoted and also establish whether or not evaporation and sedimentation had been accommodated in their sizing. Reservoir behaviour simulation analyses were then used to assess the operational performance (i.e. reliability (time-based and volume-based), resilience, vulnerability and sustainability) with and without the effects of evaporation and sedimentation. The results of the SPA showed that capacity quoted by the SWH at some of the reservoirs could have been grossly oversized, which is not bad given the cushioning effect of against future water shortages. However, some of the reservoirs also appeared to have been undersized, which is undesirable because of the likelihood of frequent failures of such systems. On the impacts of evaporation and sedimentation on operational performance, the results showed that both would cause performance to deteriorate, albeit marginally, if they were ignored when dimensioning the reservoirs. However, the impact of evaporation appeared bigger than that of sedimentation for the seven reservoirs. The fact that the impacts were marginal could be attributed to the relatively low evaporative demand when compared to the consumptive irrigation demand, and the low sediment yield of the basins. These caveats are important and should be borne in mind when using these results. Finally, regional storage-yield tools were developed which could form the basis for planning new reservoir developments in the region.

Keywords: Reservoir Operation Performance; Sequent Peak Algorithm (SPA); Behaviour Analysis; Evaporation; Sedimentation.

1. Introduction

River flow varies with time and hence water should be stored in reservoirs when available in plenty for use later (Neelakantan and Sasireka, 2013). These reservoirs serve a variety of purposes such as flood control, irrigation, drinking/industrial water supply, and hydropower generation (World Commission on Dams, 2000). The storage contents of reservoirs vary greatly over time due to variations in water use and hydrologic conditions that range from severe multiple-year droughts to floods (Wurbs and Ayala, 2014). Because of these reasons and the unreliability of stream flow in arid and semi-arid regions, performance evaluation of reservoir operation is important and particularly difficult (Moradi-Jalal et al., 2007). The standard operating policy (SOP) is known as the simplest rule for reservoir operation ((Maass et al. 1962; Loucks et al. 1981).

In the water balance of reservoir system, evaporation plays a crucial role particularly so for the reservoir systems of located in the semi-arid or arid regions (Sivapragasam et al., 2009). Annual evaporation from lakes and dams in Turkey is greater than the amount of groundwater pumped. It was also reported that more water is lost by evaporation than is used for domestic and industrial purposes, a quantity greater than one fifth of irrigation water use (Gökbulak and Özhan, 2006). The studies also show significant effects of evaporation on reservoir yields (Recaa et al., 2015; You and Cai, 2008; Campos, 2010).One way of compensating for this inevitable loss is to explicitly include the evaporation process in the reservoir planning analysis, thus ensuring that the resulting capacity estimate will be capable of meeting both the intended consumptive demands and the evaporative losses (Montaseri and Adeloye, 2004).

A further factor militating against the ability of reservoirs to perform as designed is the loss of active storage capacity due to sediment deposition. Although the worldwide water demand is rising, the reservoir storage capacities across the globe are reducing due to sedimentation, making it difficult to meet these rising needs. For example, it is estimated that the worldwide average annual rate of storage loss due to reservoir sedimentation is between 0.5 and 1% of the total storage capacity (Mahmood, 1987; White, 2001). In order to reduce the adverse effects of sediments and to increase the sustainability of dams, dead storage space is provided for sediment deposition but unfortunately, the dynamics of the sediment transport is such that deposition occurs throughout the entire storage, including the active storage zone. Many studies have been carried out on dam operation methods in the past years that help to control sedimentation (Wu et al., 2007; Yin et al., 2014; Wang and Hu, 2009; Espa et al., 2016; Tate and Farquharson, 2000; Araújo et al., 2006; Shokril et al., 2013); however, land use change and poor catchment plans have rendered such efforts ineffective in most of the cases.

The aim of this study is to systematically assess the effect of ignoring evaporation and sedimentation during reservoir planning has on subsequent operational performance, using seven existing reservoirs in Turkey as Case Studies.

2. Study Area and Methods

The seven dams are located in Yesilirmak Basin which is third largest basin in Turkey in terms of surface area (= 38387 km^2) and extends between latitude 39°46'80.05"N-41°37'26.86"N and longitude 34°48'88.31"E-39°80'62.13"E (see Fig. 1).

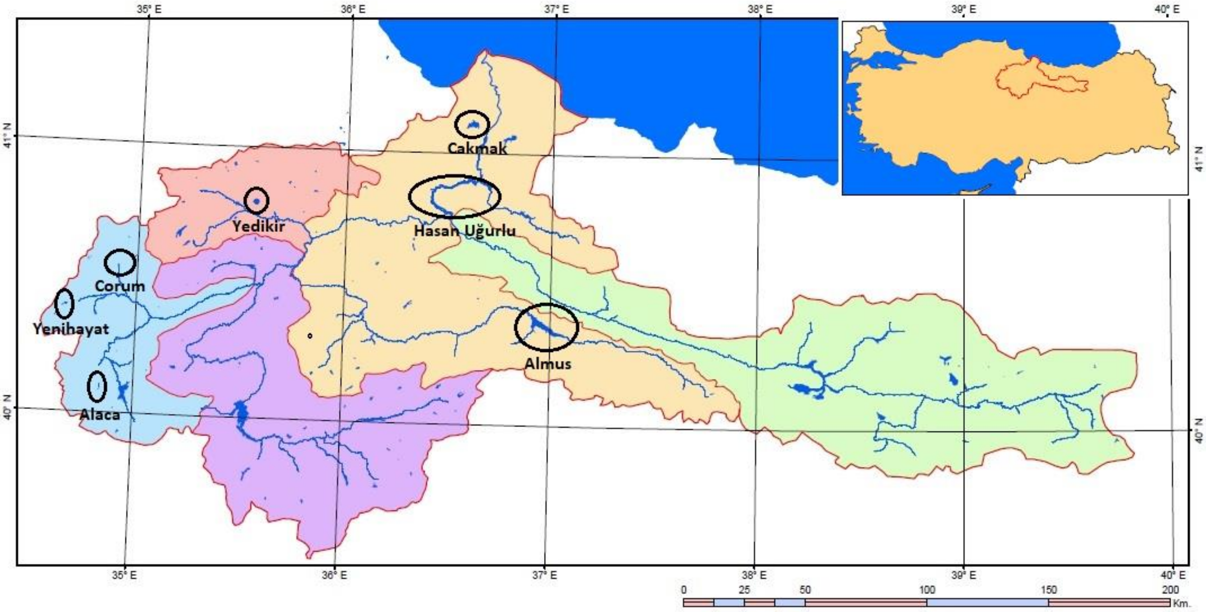

Figure 1. Locations of Yesilirmak Basin and Dams in Turkey

Precise information about the location of the seven dams is summarized in Table 1. Collectively, the seven dams drain three sub-basins namely the Corum, Yesilirmak and Tersakan with a total area of 18, 569 km^2, i.e. about 48% of the entire Yesilirmak Basin. Also, general informations about these dams are given in Table 2. The dams are owned and operated by the General Directorate of State Hydraulic Works (SWH) and they provided all the data used in the analyses.

Table 1. Location and other characteristics of Dams

Dam Name	Latitude	Longitude	Subbasin	Subbasin Area (km^2)	Annual Potential Evaporation (mm)	Annual Precipitation (mm)
Alaca	40°10'80.09"N	34°83'86.67"E	Corum	3827	1022.6	377
Corum	40°58'25.44"N	34°99'19.99"E			920.01	416.74
Yenihayat	40°39'31.55"N	34°66'70.27"E			1022.6	583
Almus	40°38'66.95"N	36°92'92.19"E	Yesilirmak	11961	938.3	492.7
Cakmak	41°10'87.80"N	36°60'88.38"E			722.4	617.8
Hasan Ugurlu	40°91'77.52"N	36°64'53.06"E			722.4	847.4
Yedikir	40°77'74.77"N	35°56'82.93"E	Tersakan	2781	920.01	416.74

Table 2. Characteristics of Dams

Dam Name	Type of Dam	Benefits of Dam	Start-up	Active Storage Capacity (hm^3)	Dead Storage Capacity (hm^3)	Surface Area at Full Capacity (km^2)	Elevation at Top of Dam (m)	Minimum Annual Flow (hm^3)	Maximum Annual Flow (hm^3)	Height above River Bed (m)
Alaca	Rockfill	Irrigation	1985	10.3	2.2	0.988	1025	10.17	66.02	12759.84

Corum	Zoned Earthfill	Irrigation, drinking water	1977	6.1	0.051	0.59	917.13	0,12	6,8	2872.19
Yenihayat	Zoned Earthfill	Drinking Water	2000	25.36	1.34	1.307	942.42	5.41	57.89	21970.38
Almus	Zoned embankment with clay core	Irrigation, energy and flood	1966	813	148.82	3130	807.5	311.17	974.92	18997.12
Cakmak	Zoned embankment with clay core	Drinking water	1988	76,5	20.93	628	122.75	51.83	207.12	10899.44
Hasan Ugurlu	Clay core and rockfill	Energy	1981	660	183.21	2266	191,5	1591.62	120525.25	46468.38
Yedikir	Zoned embankment with clay core	Irrigation	1985	54	1.51	593	517.57	16.15	79.85	7446.03

Rainfall in the basin is in general seasonal with over 65% of the annual rainfall occurring during the winter and spring (months of January–May). Very little rainfall occurs during the summer when evaporation rates are highest. Available data averages show that sediment yield within Yesilirmak Basin is about 279.7 t km^{-2}year^{-1}.

Time series used for the study include runoff, evaporation, rainfall and sedimentation data. The summary statistics for the annual runoff data are shown in Table 3. The runoff also exhibits significant seasonality as expected from the seasonality of the rainfall. The variability of the annual runoff as characterized by the coefficient of variation, Cv (std/mean) are generally below 0.5, signifying a medium variability situation (McMahon et al., 1992). As shown by McMahon and Adeloye (2005), reservoir systems situated on such rivers will be expected to exhibit both within-year and over-year behaviours, with the within year requirement being most pronounced at low (relative to the mean annual runoff) yield ratios.

Table 3. Runoff Data of Reservoirs

River Name (subbasin)	**Period of Data**	**Mean Runoff (hm^3)**	**Standard Deviation**	**C$_v$**
Suludere (Alaca)	1968-1988	29.61	12.45	0.42
Comar (Corum)	1988-2018	2.36	1.85	0.78
Cekerek (Yenihayat)	1968-1988	27.81	13.66	0.49
Yesilirmak (Almus)	2007-2018	685.94	207.56	0.30
Abdal (Cakmak)	2007-2018	85.56	46.61	0.54
Yesilirmak (Hasan Ugurlu)	2007-2018	13534.11	33710.12	2.49
Tersakan (Yedikir)	2010-2017	40.68	19.97	0.49

The volumetric evaporation data were obtained by SHW and they were used in reservoir mass balance equations directly. The mean seasonal distribution of the volumetric evaporation is also shown in the Table 4 and confirms that net evaporation is always positive, i.e. evaporation exceeds the rainfall throughout the year at the dams.

Table 4. Seasonal Volumetric Evaporation Data

	Yenihayat	Alaca	Almus	Cakmak	H.Ugurlu	Yedikir	Corum
Months	Vol. Eva. (hm^3)	Vol. Eva. (hm^3)	Vol.Eva. (hm^3)	Vol.Eva. (hm^3)	Vol. Eva. (hm^3)	Vol.Eva. (hm^3)	Vol. Eva. (hm^3)

January	0.10	0.92	0.99	0.47	0.66	0.46	0.06
February	0.10	0.92	2.22	0.47	0.49	0.46	0.06
March	0.10	0.92	2.96	0.47	0.77	0.46	0.06
April	0.01	0.88	4.37	0.47	1.14	0.29	0.04
May	0.03	0.25	3.05	0.33	1.70	0.48	0.06
June	0.12	1.06	3.49	0.52	3.87	0.69	0.08
July	0.20	1.80	35.68	0.73	4.40	0.80	0.09
August	0.20	1.57	6.14	0.75	1.67	0.58	0.07
September	0.12	1.13	3.68	0.36	2.19	0.29	0.06
October	0.04	0.25	8.71	0.40	2.60	0.18	0.05
November	0.10	0.92	1.83	0.19	0.76	0.42	0.01
December	0.10	0.92	1.75	0.47	0.57	0.46	0.06

The sediment data are summarized in Table 5 from which its impact on the active storage capacity can be inferred. Since the simulation will be carried out using a monthly time scale, the average monthly rates of sedimentation are also reported in the table.

Table 5. Sediment Data

Dam Name	**K_a (1980) hm^3**	**K_a (2014) hm^3**	**Reduction hm^3**	**Sr (annual) hm^3**	**Sr (monthly) hm^3**
Alaca	10.3	9.12	1.18	0.033	0.0028
Corum	6.1	5.424	0.676	0.02	0.0017
Yenihayat	25.36	22.62	2.74	0.08	0.01
Almus	813	790.78	22.22	0.63	0.05
Cakmak	76,5	70.48	6.02	0.23	0.02
Hasan Ugurlu	660	556.16	103.84	2.97	0.25
Yedikir	54	49.57	4.43	0.13	0.01

K_a= Active Volume of Reservoir, S_r= Deposition rate

Sequent Peak Algorithm (SPA)

The SPA is a convenient technique for estimating reservoir active storage capacity if secondary processes such as evaporation and sedimentation are not considered. The method estimates capacity as described in the following steps (see also McMahon & Adeloye, 2005):

C_t = the cumulative sequential deficit at the beginning of period t in a record of N periods;

C_{t+1} = the corresponding deficit at the end of t, i.e., at the beginning of t+1;

D_t = demand in period t;

Q_t = the inflow during t

1. Step 1: set C_0 = 0, no deficit in storage to start with , i.e. reservoir is initially considered to be full)

2. Step 2: determine sequentially C_{t+1}=max{0.0, (C_t + D_t - Q_t); t= 1,2,3…………N

3. Step 3: Check if $C_0 = C_N$; if yes, then go to step 4; else if this is the first iteration, then set C_0= C_N and go to Step 2; else Stop: SPA has failed because gross demand is higher than the average inflow.

4. Step 4: Estimate reservoir active storage capacity, K_a as K_a= max(C_{t+1}) t=1,2,3,4………,N

Behaviour Analysis and Performance Evaluation

Operation performance evaluation was carried out using behaviour analysis based on reservoir mass balance as follows:

$$Z_{t+1} = Z_t + Q_t - D'_t - EV_t - S_t \; ; \tag{1}$$

$$0 \leq Z_{t+1} \leq K_t \tag{2}$$

Where;

Z_{t+1} = active storage (hm^3) at time t+1

Z_t= active storage (hm^3) at time t

Q_t= inflow to the storage (m^3) during time t

D'_t = release (hm^3) during time t

EV_t= net evaporation loss (hm^3) during time t

S_t= sediment load (hm^3) into active storage space during time t

K_t= active storage capacity (hm^3) remaining at t.

In general, K_t is related to the original active storage capacity Ka by:

$$K_t = K_a - S_t \tag{3}$$

Where sedimentation effect is being ignored, $S_t = 0$, implying that $K_t = K_a$.

The inequality constraint in Eq. (2) ensures that water in storage can neither exceed the active storage capacity nor be negative. The implication of this is that on occasions, the water released D'_t may actually be lesser that the consumptive use demand, D_t; when this happens, the reservoir is adjudged to have failed. The determination of how much water to release is accomplished using the operating policy for which the default standard operating policy (SOP is assumed in this work. The SOP stipulates supplying the full demand if there is sufficient water in storage; otherwise, the reservoir should be emptied to supply all that is available as follows (Moran, 1956):

Case a
for $Z_t + Q_t < D_t$ (insufficient water in storage to meet full demand)

$D'_t = Z_t + Q_t$ (i.e. supply all available water and leave reservoir empty)

Case b
for $D_t < Z_t + Q_t < D_t + K_t$ (water available is sufficient to meet full demand)

$D'_t = D_t$ (i.e. supply target demand D_t)

Case c
for $Z_t + Q_t \geq D_t + K_t$ (available water is more than enough to meet full demand)

D_t' = $Z_t + Q_t - K_t$ (over supply D_t and leave reservoir full)

Once the behaviour simulation has been completed, the performance indices are then evaluated as follows:

Time based reliability, R_t:

$$R_{\boldsymbol{t}} = \frac{N_s}{N} \tag{4}$$

$R_{\boldsymbol{t}}$= time based reliability

N_s= total number of invertal during which the demand was met

N= total number of time intervals in the simulation

Volumetric reliability, R_v:

$$R_v = 1 - \frac{\sum_{j\in f}\left(D_j - D_j'\right)}{\sum_{j\in N} D_j} \tag{5}$$

R_v= volumetric reliability

D_j= target demand during jth failure period

D_j'= actual supply from reservoir system during jth failure period

f= number of failure periods

N= number of periods in the simulation

Resilience, φ:

$$\varphi = \frac{f_s}{f_d}\ ; \quad 0 \le \varphi \le 1 \tag{6}$$

φ= resilience

f_s= number of continuous sequences of failure periods

f_d= total duration of the failures

Vulnerability, η':

$$\eta' = \frac{\sum_{k=1}^{f_s} max.(sh_k)}{f_s} \tag{7}$$

$max.(sh_k)$= maximum shortfall during kth continuous failure sequence

f_s= number of continuous failure sequences in the simulation

η'= vulnerability

Dimensionless Vulnerability, η:

$$\eta = \frac{\eta'}{D}\ ;\ \ 0 \le \eta \le 1 \tag{8}$$

η= dimensionless vulnerability

D= target demand during the failure

Sustainability, γ:

$$\gamma_1 = \left(R_t \varphi(1-\eta)\right)^{1/3} \tag{9}$$

$$\gamma_2 = \left(R_v \varphi(1-\eta)\right)^{1/3} \tag{10}$$

γ_1= sustainability index using R_t

γ_2= sustainability index using R_v

3. Results and Discussion

3.I. Verification of quoted active storage capacities

The results of the SPA analysis to dimension the active storage capacity without consideration of both evaporation and sediment deposition are shown in Table 6. The analyses used alternatively annual and monthly data in order to assess the impact of data temporal scale on the estimated capacity. Also shown in Table 6 for comparison are the capacities as quoted by the General Directorate of State Hydraulics (SHW). As seen in Table 6, reservoir capacity estimates based on annual data analyses were much lower than their monthly-data-based counterparts. This is because while the latter estimates the total (within-year and over-year) storage capacity, the latter only estimates the over-year capacity. Based on the observation made earlier regarding the medium variability of the annual runoff at the sites, one would expect significant within-year storage requirements at the respective reservoir sites.

Table 6. SPA-based Active Capacities of Reservoirs

Reservoirs	**Active Capacity (SHW) hm^3**	**Active Capacity (annual) hm^3**	**Active Capacity (monthly) hm^3**
Alaca	10.3	4.71	9.83
Almus	813	111.91	380.45
Çakmak	76.5	40.79	57.94
Çorum	6.1	24.55	25.61
H. Uğurlu	660	225.48	583.5
Yedikır	54	33.85	57.38
Yenihayat	25.36	19.6	25.95

Estimates at three of the reservoirs: Alaca, Yedikir and Yenihayat almost perfectly match the SHW quoted capacities and although the details about how the SHW arrived at the quoted capacities are unknown, this may be taken as indication that consideration of secondary processes had not been considered while estimating capacity for these reservoirs. The capacity estimate at Almus was 380 hm^3, which is a mere 47% of the 813 hm^3 quoted by the SHW. The cause of this huge discrepancy is not immediately obvious apart from perhaps an inclination towards a generous oversizing. Overdesign discrepancies between SHW quoted capacities and corresponding SPA estimates also exist at both Cakmak and Ugurlu but these are not as high as that at Almus and could also be attributed to a tendency towards generous oversizing by the SHW. The only reservoir that appears to be undersized by the SHW is the Corum dam whose quoted capacity of 6.1 hm3 is only a quarter of what will be required based on the SPA capacity estimation. Whilst over-sizing may be tolerated because of its inherent safety factor, gross undersizing as revealed at Corum is not desirable because of its negative impact on the ultimate performance of any reservoir.

3.II. Performance evaluation

Reservoir behaviour simulations to assess performance were implemented as described previously. Due to discordance between the SPA-estimated capacity and the capacity quoted by the SWH for some of the reservoirs, simulations were implemented assuming either capacity prevailed. This will also help to confirm whether or not the observed over- or under-design was having any notable effects on reservoir performance. The volumetric evaporation data provided by SHW were used directly. For the sedimentation, the annual and monthly deposition rates S_r used are as reported previously in Table 5. Ideally, one would expect a seasonally varying sediment deposition rate given that the runoff in the catchments is seasonal as remarked previously. However, given the lumped nature of the sediment data available for the study, it was decided to use of a constant monthly rate in order to eliminate any uncertainty regarding the true seasonal pattern of sediment deposition in the catchments. Nonetheless, the behavior simulation formulation presented herein is robust that it will readily accommodate seasonality in the sediment deposition rate if the information is available.

The full array of the obtained performance indices is presented in Table 7 for all the reservoirs; however, further discussions will be limited to the reliability (time-based and volume-based) indices and the vulnerability. As expected, without consideration of the additional stressors of evaporation and sedimentation, the reliability was close to unity, i.e. no failure whatsoever, for either reservoir capacity assumption especially when there is no discordance in the two capacity estimates. Additionally with no failures, the estimated vulnerability is zero for these situations.

Table 7. Behaviour Analysis Results

ALACA	**Mnth Rel %**	**Vol Rel %**	**Resiliency**	**Vulnerability (hm^3)**	**Dim Vul**	**Susta. (1)**	**Susta. (2)**
Monthly (SPA)	99.21	100.00	0.50	0.00	0.00	79.26	79.37
Monthly (SHW)	100.00	100.00	-	-	-	-	-
Monthly with sediment effect (SPA)	99.21	99.93	0.50	0.25	0.18	74.17	74.27
Monthly with sediment effect (SHW)	100.00	100.00	-	-	-	-	-
Monthly with evaporation effect (SPA)	98.41	99.77	0.25	0.40	0.29	56.15	56.22
Monthly with evaporation effect (SHW)	98.80	99.90	0.33	0.26	0.19	64.60	64.69

ALMUS	**Mnth Rel %**	**Vol Rel %**	**Resiliency**	**Vulnerability (hm^3)**	**Dim Vul**	**Susta. (1)**	**Susta. (2)**
Monthly (SPA)	99.31	100.00	1.00	0.00	0.00	99.87	100.00
Monthly (SHW)	100.00	100.00	-	-	-	-	-
Monthly with sediment effect (SPA)	99.31	99.98	1.00	1.53	0.03	98.94	99.07
Monthly with sediment effect (SHW)	100.00	100.00	-	-	-	-	-
Monthly with evaporation effect (SPA)	88.89	94.63	0.38	5.25	0.09	69.67	69.76
Monthly with evaporation effect (SHW)	98.60	99.50	0.50	33.16	0.60	58.50	58.57
CAKMAK	**Mnth Rel %**	**Vol Rel %**	**Resiliency**	**Vulnerability (hm^3)**	**Dim Vul**	**Susta. (1)**	**Susta. (2)**
Monthly (SPA)	99.31	100.00	1.00	0.00	0.00	99.87	100.00
Monthly (SHW)	100.00	100.00	-	-	-	-	-
Monthly with sediment effect (SPA)	99.31	99.86	1.00	1.24	0.20	92.88	93.01
Monthly with sediment effect (SHW)	100.00	100.00	-	-	-	-	-
Monthly with evaporation effect (SPA)	94.44	96.63	0.38	1.88	0.30	64.06	64.14
Monthly with evaporation effect (SHW)	97.20	98.40	0.50	2.41	0.38	67.58	67.67
CORUM	**Mnth Rel %**	**Vol Rel %**	**Resiliency**	**Vulnerability (hm^3)**	**Dim Vul**	**Susta. (1)**	**Susta. (2)**
Monthly (SPA)	99.73	100.00	1.00	0.00	0.00	99.87	100.00
Monthly (SHW)	75.50	79.50	0.14	0.03	0.12	50.05	50.11
Monthly with sediment effect (SPA)	99.73	99.99	1.00	0.01	0.04	98.55	98.68
Monthly with sediment effect (SHW)	75.50	79.50	0.15	0.03	0.10	51.58	51.65
Monthly with evaporation effect (SPA)	75.81	87.15	0.14	0.02	0.07	51.11	51.18
Monthly with evaporation effect (SHW)	59.90	70.20	0.15	0.01	0.06	51.79	51.86
HASAN UGURLU	**Mnth Rel %**	**Vol Rel %**	**Resiliency**	**Vulnerability (hm^3)**	**Dim Vul**	**Susta. (1)**	**Susta. (2)**
Monthly (SPA)	99.31	100.00	1.00	0.00	0.00	99.87	100.00
Monthly (SHW)	100.00	100.00	-	-	-	-	-
Monthly with sediment effect (SPA)	99.31	99.98	1.00	27.94	0.02	99.03	99.17
Monthly with sediment effect (SHW)	100.00	100.00	-	-	-	-	-
Monthly with evaporation effect (SPA)	97.92	99.92	0.67	26.88	0.02	86.54	86.66
Monthly with evaporation effect (SHW)	98.60	100.00	1.00	14.27	0.01	99.44	99.58
YEDIKIR	**Mnth Rel %**	**Vol Rel %**	**Resiliency**	**Vulnerability (hm^3)**	**Dim Vul**	**Susta. (1)**	**Susta. (2)**
Monthly (SPA)	98.96	100.00	1.00	0.00	0.00	99.87	100.00
Monthly (SHW)	95.80	99.00	0.50	0.71	0.19	73.86	73.96
Monthly with sediment	98.96	99.98	1.00	0.06	0.02	99.32	99.46

effect (SPA)							
Monthly with sediment effect (SHW)	95.80	98.70	0.50	0.92	0.25	72.03	72.12
Monthly with evaporation effect (SPA)	87.50	89.26	0.33	1.20	0.33	60.73	60.81
Monthly with evaporation effect (SHW)	87.50	88.30	0.33	1.41	0.38	58.97	59.05
YENIHAYAT	**Mnth Rel %**	**Vol Rel %**	**Resiliency**	**Vulnerability (hm^3)**	**Dim Vul**	**Susta. (1)**	**Susta. (2)**
Monthly (SPA)	99.60	100.00	1.00	0.00	0.00	99.87	100.00
Monthly (SHW)	99.60	99.90	1.00	0.59	0.35	86.58	86.70
Monthly with sediment effect (SPA)	99.60	99.91	1.00	0.37	0.22	91.99	92.11
Monthly with sediment effect (SHW)	98.80	99.80	0.33	0.63	0.37	59.30	59.38
Monthly with evaporation effect (SPA)	96.43	99.04	0.22	0.36	0.21	55.89	55.97
Monthly with evaporation effect (SHW)	96.00	98.90	0.20	0.37	0.22	53.83	53.90

These results tend to prove that while the argument continues to rage over the impact of secondary process such as evaporation and sedimentation in reservoir planning and operational analyses, the effect of their inclusion is limited. While evaporation has dented the performance of the two reservoirs, the sedimentation effect on performance was barely noticeable. The sediment yield characteristics of the two basins may have played a part here, with their extremely low rate of sediment deposition which as noted previously is unlikely to consume a considerable part of the active storage capacity over the typical 50 – 100 years useful life of reservoirs. It is possible, however, that perhaps with a basin exhibiting a much higher sediment yield, e.g. as observed for a semi-arid basin in Brazil by Araujo et al. (2006), the outcome might be different.

Although evaporation has produced larger effects on performance than those produced by sedimentation, these effects are not huge either. Two possible reasons could be adduced for this. First is that as noted earlier, the evaporative demands are much less than the consumptive demands served by the two reservoirs; hence failure to include the evaporative demands in the planning analysis has not produced large effects on the subsequent performance. Another reason is that in this analysis, the net evaporation rather than the gross evaporation has been considered. The net evaporation tempers the gross evaporation by deducting the direct rainfall on the reservoir surface and is the correct approach for handling evaporation fluxes on reservoir surface. Without such tempering, the evaporation loss will be too high (see e.g. Araujo et al., 2006) and erroneous.

4. Conclusions

This study has analysed the effects of evaporation and sedimentation on the operational performance of water supply reservoirs. Seven Turkish reservoirs were analysed and reservoir performance was characterized using reliability, vulnerability and sustainability. The results showed that the quoted capacity at some of the reservoirs could have been grossly oversized, which is not bad given the cushion such provides against future severe droughts as caused by e.g. projected climate change. Conversely, some of the reservoirs appeared to have been undersized which is undesirable because of the likelihood of frequent failures of such systems.

On the impacts of the secondary processes of evaporation and sedimentation on system performance, the results showed that both would cause performance to deteriorate, albeit marginally, if they were ignored during the planning analysis for the reservoirs. However, the impact of evaporation appeared bigger than that of sedimentation for the seven reservoirs. The fact that the impacts were marginal could be attributed to the relatively low evaporative demand when compared to the consumptive irrigation demand, and the low sediment yield of the basins. These caveats should be borne in mind when using these results.

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