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Impacts of Ignored Evaporation and Sedimentation Fluxes at Planning on Reservoir Performance in Operation

Murat Pinarlik[1,2] · **Adebayo J. Adeloye**[2] · **Zeliha Selek**[1]

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Abstract
Inevitable evaporation and sedimentation will influence reservoir operational performance if the two fluxes have been ignored when sizing reservoir systems. While this is to be expected, very few studies have quantified this influence. This study has analysed the effects of evaporation and sedimentation on reservoirs operational performance. It used seven reservoirs in Yesilirmak Basin, Turkey as case studies. The Dams serve a variety of purposes including irrigation, domestic and industrial, hydropower generation and flood control. Performance with regard to meeting these needs was characterized using reliability (time-based and volume-based), resilience, vulnerability and sustainability. The results showed that while ignoring both the evaporation and sedimentation during planning does affect subsequent operational performance, the influence of evaporation was more significant. Possible reasons are provided for the outcome and ways by which both can be accommodated during planning analyses thus mitigating the operational effects are suggested.

Keywords Reservoir Operation Performance · Sequent Peak Algorithm (SPA) · Behaviour Analysis · Evaporation · Sedimentation

1 Introduction

Stream flow varies with time making it impossible to always rely on natural river flows for meeting consumptive water demands. Hence, during the past five decades, numerous reservoirs have been built across the world to regulate natural river flows (Zhao et al. 2016a).

Highlights

- Evaporation and sediment exclusion affects reservoir size
- During reservoir operation, evaporation effect is more significant
- Both effects will increase with higher sediment yield and net evaporation

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✉ Adebayo J. Adeloye
bayo.adeloye@gmail.com; a.j.adeloye@hw.ac.uk

[1] Civil Engineering Department, Faculty of Technology, Gazi University, Ankara, Turkey

[2] Institute for Infrastructure and Environment School of Energy, Geoscience, Infrastructure and Society (EGIS), Heriot-Watt University, Edinburgh EH14 4AS, UK

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). Besides, global environmental/anthropogenic phenomena such as climate change, land-cover/land-use change and population growth constitute additional challenges to most reservoir systems (Vörösmarty et al. 2000). More variable precipitation, constantly increasing temperatures, and more frequent floods and droughts are all threatening the sustainability of water resource management (Conway 1996; Zhao et al. 2016b). Meanwhile, water demand is increasing, driven by a fast-growing population and rising standard of living (Oki and Kanae 2006).

Understanding the magnitude of evaporation from water supply reservoirs is an important component of water resource management, necessitating a consideration of evaporation during the design of water supply reservoirs and subsequent reservoir yield investigations (Lowe 2009). The loss of stored water from surface water reservoirs through evaporation is inevitable and can be significant in arid and semi-arid climates. 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). In the Rio Grande Basin (USA, New Mexico), evaporation from a mid-sized reservoir (Elephant Butte) accounts for 15 to25% of the Rio Grande water consumption allotment each year and represents enough water to satisfy the water needs of Albuquerque for 2 to 4 years (Gupta et al. 2002). Annual evaporation from lakes and dams in Turkey is greater than the amount of pumped groundwater. 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; Sivapragasam et al. 2009). Climate change is expected to lead to an increase in evaporation, which will intensify these problems. Therefore, an estimate of reservoir evaporation is an important precursor to the design and ongoing operation of a water supply reservoir (Adeloye et al. 1999).

A further factor militating against the ability of reservoirs to perform as designed is the loss of active storage capacity due to sediment deposition. The worldwide water demand is rising but reservoir storage capacities across the globe are reducing due to sedimentation. 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; Tadesse and Dai 2019; Chaudhary et al. 2019). This major effect of sedimentation causes a serious impact on water resources development by reducing water supply, hydropower production, the supply of irrigation water, and the effectiveness of flood control schemes (Wang et al. 2005). In order to reduce the adverse effects of sediments and to increase the sustainability of dams, dead storage space is provided for sediment deposition, which should suffice if sediments only deposit in this space. However, since the sediment is carried in reservoir inflows, its deposition is not limited to the dead storage zone alone but occurs throughout the entire reservoir storage, implying that the active storage space is not spared, leading to the loss of this useful capacity space. Many studies on dam operational methods for controlling sedimentation have been reported in recent years (e.g. Wu et al. 2007; Yin et al. 2014; Wang and Hu 2009; Espa et al. 2016; Tate and Farquharson 2000; Araújo et al. 2006; Shokri et al. 2013) but land use change and poor catchment management 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 on subsequent operational performance, using seven existing reservoirs in Turkey as case studies. The outcome of the study is expected to inform reservoir operators on the magnitude of any performance deterioration problem and thus assist them in planning mitigating measures, e.g. improved soil management in the reservoir catchment to reduce soil loss, evaporation loss reduction practices, etc. The effects of ignoring evaporation and sedimentation considerations during planning on the effective operational performance of reservoirs will worsen as projected climate change and its effect on evaporation and soil loss become intensified. The characterization of these operational performance effects is the novelty offered by this work because as far as the authors are aware, this has not been attempted in such a comprehensive manner before.

2 Materials and Data

2.1 Study Area

The seven dams considered for the present analysis are located on various tributaries of Yesilimak River in Turkey. The dams are owned and operated by the General Directorate of State Hydraulic Works (SHW) who also provided all the data. Yesilirmak Basin is the third largest basin in Turkey in terms of surface area ($=38{,}387$ km^2) and extends between latitude 39°46′80.05"N to 41°37′26.86"N and between longitude 34°48′88.31"E to 39°80′62.13"E (see Fig. 1). 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. Yesilirmak Basin is relatively dry with average annual precipitation varying from a minimum of 377 mm at the Alaca Dam to a maximum of 847 mm at Hasan Ugurlu. Conversely, annual potential evaporation is high and exceeds the precipitation at most of the dams, except Hasan Ugurlu, implying net water loss (i.e. evaporation – rainfall) from the reservoir surfaces. Ignoring such positive net evaporation during planning will result in under-sizing of reservoir capacity and poor operational performance. Rainfall in the basin is in general seasonal with over 65% of the annual rainfall occurring during winter and spring (January to May). Very little rainfall occurs during summer when evaporation rates are highest.

Land use categorization in the Yesilirmak Basin, typified by the Corum sub-basin, is shown in Table 2 and reveals progressive land-use changes with time. For the Corum Sub-basin, there have recently been significant increases in land devoted to urbanization and agricultural cultivation, at the expense of pastures in 2011 compared to 1987. Converting pastures to arable cultivation will have implications for the sediment yield within the basin which according to available data averages about 279.7 t km^{-2} year^{-1}.

2.2 Data

Time series required for the study include runoff, evaporation, rainfall and sedimentation data. Monthly inflow runoff data at the reservoirs are available for various periods between 1968 and 2018, as shown in Table 3 (see also the Appendix A for the time series plots of the runoff). Unfortunately, these records are not synchronized and attempts to obtain more recent and longer runoff records were unsuccessful. The data were therefore used

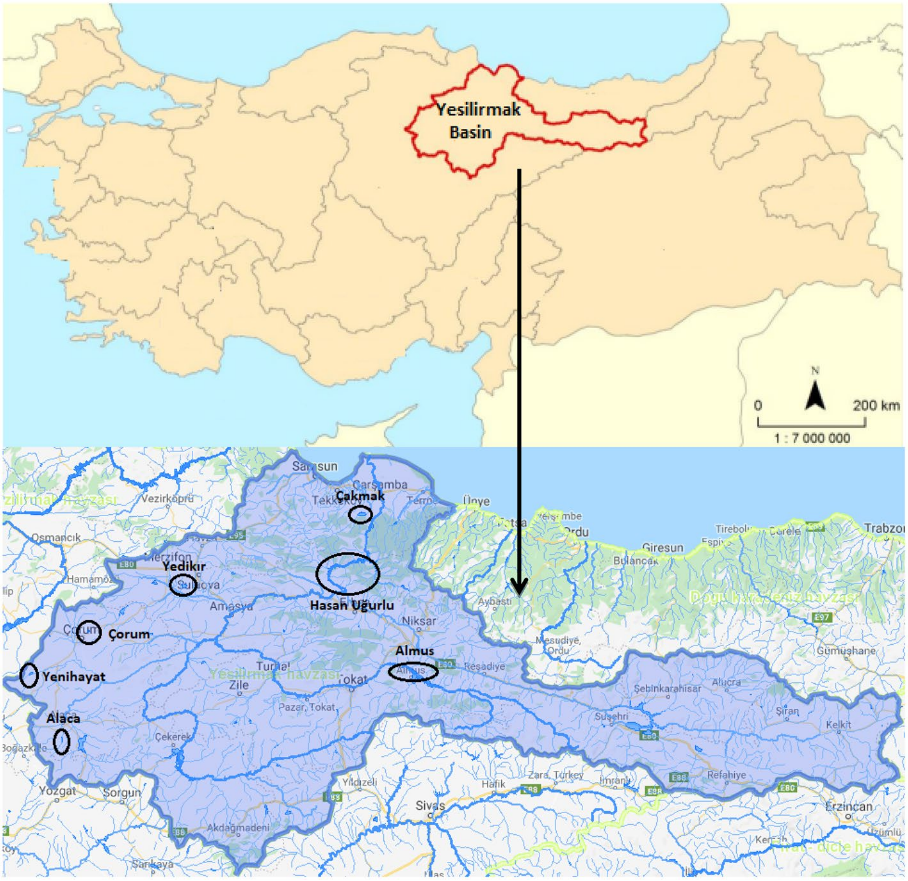

Fig. 1 Locations of Dams in Yesilirmak Basin (Republic of Turkey Ministry of Agriculture and Forestry Geodata 2019)

Table 1 Location and other characteristics of dams

Dam Name	Latitude	Longitude	Subcatchment	Sub-catchemnt 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	11,961	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

*Cakmak has no evaporation measurement and that for nearby Ugurlu was used instead

Table 2 Development in Land use of the Corum Subcatchment between 1987 and 2011

Years	Forest %	Pasture %	Agricultural %	Building Area %	Water Area %
1987	41.32	35.24	21.7	1.72	0.02
2011	47.5	6.98	37.09	8.28	0.15

as obtained. 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), is 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 Figs. 3, 4, 5, 6, 7, 8, 9.

The volumetric net evaporation data are shown in Appendix B (Tables 8, 9, 10, 11). Because they are already in volumetric units, they were used directly in reservoir mass balance equations. Apart from a few years, the annual net evaporation loss exhibits low interannual variability at all the dam sites. A further observation in Appendix B is the quantity of evaporation loss relative to the consumptive demands met by the seven reservoirs. For example, on an annual basis, the average volumetric evaporation loss is less than 10% of the irrigation water demand. Indeed, for some of the dams, e.g. Ugurlu, this fraction is below 1%. The implication of this is that any impact of the evaporation during planning or operation will be minimal. The mean seasonal distribution of the volumetric evaporation is also shown in Appendix B (Table 12) and confirms that net evaporation is always positive, i.e. evaporation exceeds the rainfall throughout the year at the dams. The same is true on an annual time scale by comparing the annual evaporation and rainfall in Table 1.

The sediment data are summarized in Table 4 from which its impact on the active storage capacity can be inferred. For example, the Yenihayat active storage capacity decreased by 2.74 hm^3 (10.8%) over 35 years, i.e. a sediment deposition (or active storage capacity reduction) of 0.08 hm^3/year. Although the sediment-induced capacity reduction at Alaca over the same 35 years was a higher percentage of its initial value when compared with Yenihayat, its rate of deposition was 0.04 hm^3/year. Both rates of annual deposition are low and would require over 300 years and 270 years to completely silt up the Yenihayat and Alaca reservoirs respectively. Even for the more sediment productive Ugurlu basin, it will

Table 3 Summary Statistics for the Runoff Data of Reservoirs

River Name (subbasin)	Period of Data	Mean Annual 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	13,534.11	33,710.12	2.49
Tersakan (Yedikir)	2010–2017	40.68	19.97	0.49

take over 200 years to completely silt up. These time horizons are much longer than the usual useful life of dam reservoirs of 50 to 100 years.

Since the simulation will be carried out using a monthly time scale, the average monthly rates of sedimentation that reflect the seasonality in the runoff (see Appendix A) are required. These were disaggregated as described later in Sect. 4.2, from the annual sedimentation rates in Table 4.

2.3 Methodology

The approach adopted for the study involved the following:

- Reservoir planning analysis using the sequent peak algorithm, SPA (McMahon and Adeloye 2005), to verify storage capacity quoted by the SHW (see also Table 5) and also establish whether or not evaporation and sedimentation had been accommodated in their sizing;
- Reservoir behavior simulation analyses to assess the operational performance of the reservoirs;
- Assessment of the impact of evaporation and sedimentation on the operational performance.

These are described briefly below.

2.4 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 Adeloye et al. 2001; McMahon and 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.

Table 4 Sediment Data

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

K_a = Active Volume of Reservoir, S_r = Sediment deposition rate

Table 5 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	12,759.84
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	21,970.38
Almus	Zoned embankment with clay core	Irrigation, energy and flood	1966	813	148.82	3130	807.5	311.17	974.92	18,997.12
Cakmak	Zoned embankment with clay core	Drinking water	1988	76,5	20.93	628	122.75	51.83	207.12	10,899.44
Hasan Ugurlu	Clay core and rockfill	Energy	1981	660	183.21	2266	191,5	1591.62	120,525.25	46,468.38
Yedikir	Zoned embankment with clay core	Irrigation	1985	54	1.51	593	517.57	16.15	79.85	7446.03

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 $C_{t+1} = \max\{0.0, (C_t + D_t — Q_t)$; $t = 1,2,3\ldots\ldots\ldots\ldots N$
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 $K_a = \max(C_{t+1})$ $t = 1,2,3,4\ldots\ldots\ldots,N$

2.5 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 K_a 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. (1) 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 less 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):

2.6 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).

2.7 Case b

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

$D_t^{'} = \mathrm{D_t}$ (i.e. supply target demand $\mathrm{D_t}$).

2.8 Case c

for $\mathrm{Z_t + Q_t \geq D_t + K_t}$ (available water is more than enough to meet full demand).

$D_t^{'} = \mathrm{Z_t + Q_t - K_t}$ (over supply $\mathrm{D_t}$ and leave reservoir full).

Once the behaviour simulation has been completed, the performance indices are then evaluated as follows (Hashimoto et al. 1982; McMahon and Adeloye 2005):

2.9 Time Based Reliability, $\mathrm{R_t}$:

$$R_t = \frac{N_s}{N} \tag{4}$$

R_t= time based reliability.

N_s= total number of intervals during which the demand was met (months).

N= total number of time intervals in the simulation (months).

2.10 Volumetric Reliability, $\mathrm{R_v}$:

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

R_v= volumetric reliability.

D_j= target demand during j$^{\mathrm{th}}$ failure period (hm^3).

$D_j^{'}$= actual supply from reservoir system during j$^{\mathrm{th}}$ failure period (hm^3).

f = number of failure periods (months).

N = number of periods in the simulation (months).

2.11 Resilience, φ:

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

φ= resilience.

f_s= number of continuous sequences of failure periods.

f_d= total duration of failures (months).

2.12 Vulnerability, η':

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

$\eta^{'}$= vulnerability (hm^3).

$max.\left(sh_k\right)$= maximum shortfall during k$^{\mathrm{th}}$ continuous failure sequence (hm^3).

f_s= number of continuous failure sequences in the simulation (months).

2.13 Dimensionless Vulnerability, η:

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

η= dimensionless vulnerability.
D= target demand during the failure (hm^3).

2.14 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

3.1 Verification of Quoted Active Storage Capacities

The results of the SPA analysis to size 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 former 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.

There were also discrepancies between the SHW quoted capacities and those estimated using the SPA. Due to the bias in the annual-data-based capacity estimates as discussed above, further comparisons will be limited to the monthly based SPA capacity estimates.

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 to build in sufficient safety factor against numerous uncertainties e.g. projected climate change, future demand growth and failure to accommodate evaporation and sediment considerations in the planning analyses. As noted earlier, the volumetric evaporation at the Almus site is very low compared to the consumptive irrigation demand and the sediment yield in the basin is also relatively modest. Consequently, it is unlikely that the over-design at Almus has been caused by a consideration of both the evaporation and sedimentation. Indeed, the sufficiency of the much smaller SPA capacity estimate will be further tested later on when its performance with and without evaporation and sedimentation is evaluated. 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 hm^3 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.

In an attempt to aid decision making in relation to e.g. capacity expansion for additional demands, the complete storage-yield functions for the reservoirs were developed. This involved repeated implementation of the SPA for different demand levels. The results are shown in Fig. 2 for all the reservoirs. As expected, the monthly storage-yield function is always to the right of the annual function; the difference at a given demand being the within-year storage requirement. For the low to medium variability streams (Yenihayat, Alaca, Almus, Cakmak, Yedikir), the two functions are distinct meaning that significant within-year storage needs exist for these reservoirs. Indeed, as revealed by the storage-yield functions for these reservoirs, the required capacity is nil for up to 0.5MAR (MAR = mean annual runoff) demand when based on annual analysis whereas using monthly analysis, stored water will be required to meet demand as low as 0.1MAR. For the high annual variability rivers (Corum and Ugurlu), the two functions are indistinguishable even at low demand ratios, implying that reliable capacity estimates for these rivers can be obtained using annual runoff data records.

Another important use of the storage-yield functions, apart from capacity expansion at the respective sites, is as a regional tool for reservoir planning. The similarity of the low-medium variability storage-yield functions is an indication that they can be used to plan new reservoirs in the region, if the demand and mean annual runoff are known. To do this, the demand will be scaled by the mean annual runoff. Entering either figure with the scaled demand, the scaled active storage capacity can be read off. Given the underestimate produced by the annual function, it will be better to use the monthly function so as to accommodate both the within-year and over-year storage requirements. To obtain the volumetric capacity estimate, the scaled capacity will be multiplied by the known mean annual runoff. Thus, the planned ideal active volume of the new dam can be easily obtained or the amount of water demanded from the dam with the active volume can be calculated.

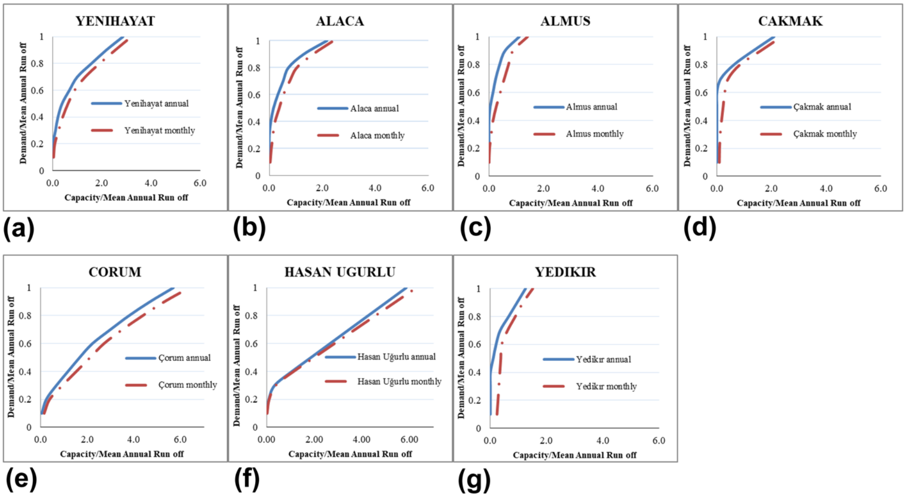

Fig. 2 Storage-yield Functions for Reservoirs

3.2 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 (see Table 8–11) were used directly.

For the sedimentation, monthly sedimentation rates that reflect the seasonality in the inflows were obtained from the annual sedimentation rates using a simple disaggregation scheme given by:

$$S_{r,m} = S_{r(annual)}\left(\frac{MR_m}{MAR}\right); m = 1,2,..,12 \tag{11}$$

where $S_{r,m}$ is the sedimentation rate for month m (hm^3), $S_{r(annual)}$ is the mean annual sedimentation rate in Table 4 (hm^3), MR_m is the mean runoff for month m (hm^3) and MAR is the mean annual runoff in Table 3 (hm^3). The disaggregated sedimentation rates are presented in Appendix B together with the MR_m values (see Table 13).

The time series plots of the storage states with evaporation and sedimentation are shown in Appendix C. Regions where the reservoir is empty (i.e. zero content) represent failures. If the reservoir capacity estimate is correct and the demand has not increased, one would expect the behaviour simulation to produce no such failures. However, the fact that failures are occurring in Figures 10, 11, 12, 13, 14, 15, 16 is an indication that additional stressors, in this case evaporation and sedimentation, are at play.

The full array of the obtained performance indices are 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.

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)	98.8	99.93	0.33	0.26	0.19	64.6	64.69
Monthly with sediment effect (SHW)	99.2	100.00	0.5	0.02	0.01	78.88	78.99
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	2.65	0.05	98.25	98.38
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	99.79	1.00	1.91	0.30	88.63	88.75
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	0.02	0.08	97.19	97.32
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

Table 7 (continued)

ALACA	Mnth Rel %	Vol Rel %	Resiliency	Vulnerability (hm^3)	Dim Vul	Susta. (1)	Susta. (2)
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	99.93	1.00	119.57	0.11	96.2	96.33
Monthly with sediment effect (SHW)	99.31	100.00	1	43.07	0.04	98.58	98.71
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 effect (SPA)	98.96	99.98	1.00	0.02	0.01	99.69	99.82
Monthly with sediment effect (SHW)	95.80	98.9	0.50	0.77	0.21	73.34	73.46
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	0.35	0.21	92.45	92.57
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

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.

Where there are differences between the SPA-based and SHW quoted capacity estimates such as at Almus, Corum and Cakmak reservoirs, however, the estimated reliability was different from unity if the capacity was an under-design. For example, the SHW capacity at Corum only produced a time-based reliability of 75.5% which when compared to the 99.73% reliability for the SPA-based capacity estimate is a confirmation of the gross under-design of the Corum dam by the SHW. The estimated vulnerability with the SHW capacity is equally high at 12% whereas the corresponding vulnerability for the SPA capacity was zero. Another interesting aspect of the result in Table 7 concerns the Almus reservoir. As noted earlier, the SHW quoted capacity of 813 hm^3 is more than twice the SPA estimated capacity of 380 hm^3. However, as seen in Table 7, both capacities produced reliability close to 100%, implying that the SHW estimate is indeed a gross over-design for meeting the irrigation demand placed on the reservoir. The performance of Cakmak reservoir is similar to that of Almus in that the apparent over-design represented by the SHW quoted capacity did not produce a higher reliability in comparison to the much smaller SPA-based capacity estimate.

When the effect of sedimentation was considered in the simulation, the reliability either decreased marginally or remained unchanged at all the reservoirs. Thus, for example, the reliability for the SHW quoted capacity was 100% (without sedimentation) or 99.2% (with sedimentation); the corresponding performance of the SPA-based capacity was 99.21% (without sedimentation) or 98.8% (with sedimentation). At Corum where the SHW grossly under-sized the capacity as noted previously, the consideration of sedimentation also did not cause the performance to further deteriorate as the reliability remained 75.5% with or without sedimentation. Because the inclusion of sedimentation has not resulted in further failures, the estimated vulnerability without sedimentation was the same as without sedimentation. Additionally, the vulnerability with and without sedimentation was moderate, ranging between 0 and 25%, which for most water users especially for irrigation are tolerable (Adeloye et al. 2016).

The inclusion of evaporation on the other hand produced higher impacts in both the reliability and vulnerability when compared to the effect of sedimentation. Full details of this are also shown in Table 7; however, the results for Yenihayat and Alaca for which the SWH and SPA-based capacity estimates agreed will be used for illustration purposes. For example at Yenihayat, the time-reliability dropped from 100% without evaporation to 96.4% with evaporation, although the volumetric reliability was still 99%. The Alaca analysis produced similar outcome, with the time-reliability dropping from 100% to 98.4%, although the volume reliability was barely unchanged. The dimensionless vulnerability at Alaca deteriorated to 29% with evaporation, which is a significant escalation from the 19% recorded with sedimentation. Vulnerability at Yenihayat with evaporation was similar to that with sedimentation.

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 to 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 Conclusion

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.

Finally, regional storage-yield tools were developed which could form the basis for planning new reservoir developments both at gauged and non-gauged sites in the region. For example, using these tools at gauged sites will save significant analysis time, which is important during preliminary evaluation of potential reservoir sites. For non-gauged sites, these tools provide a feasible option for obtaining the needed reservoir storage-yield information.

Appendix A

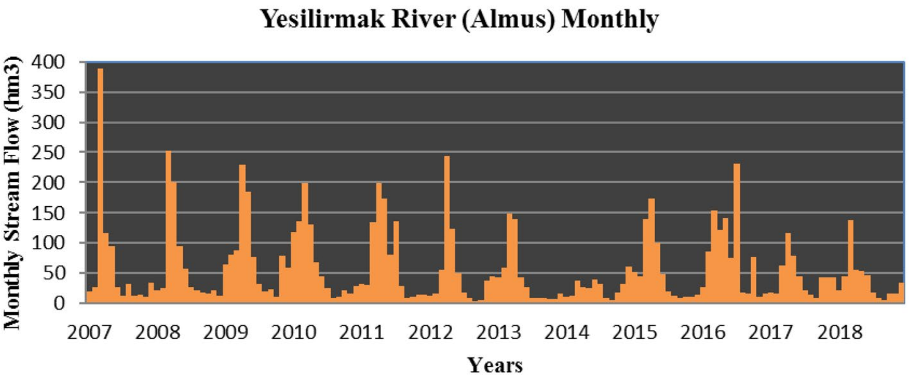

Fig. 3 Time Series Plots of the Runoff of Almus Reservoir

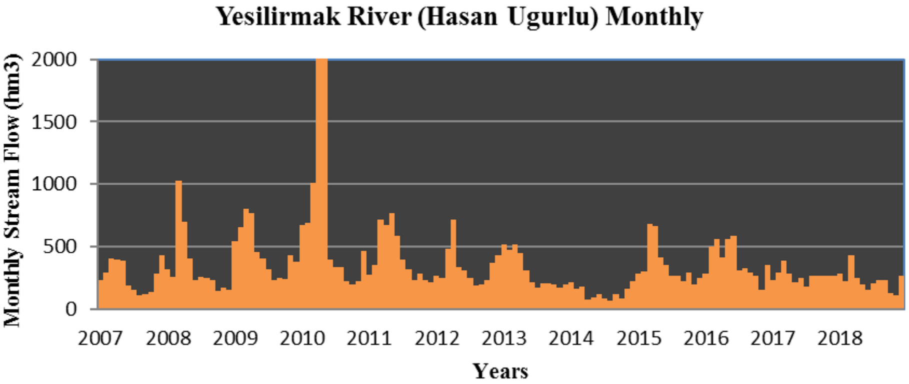

Fig. 4 Time Series Plots of the Runoff of Hasan Ugurlu Reservoir

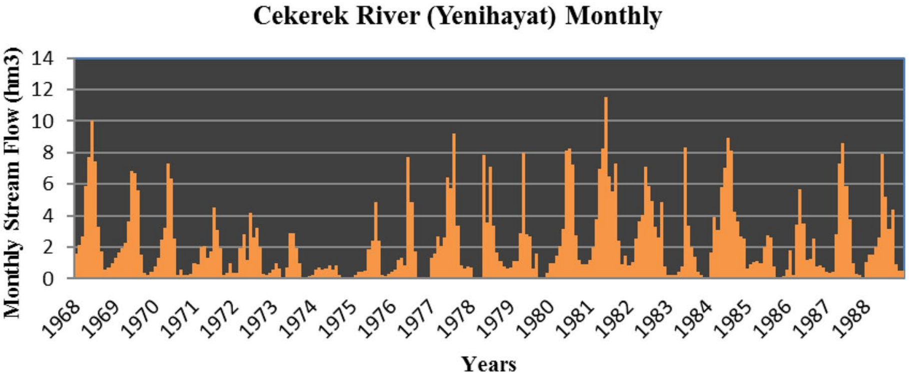

Fig. 5 Time Series Plots of the Runoff of Yenihayat Reservoir

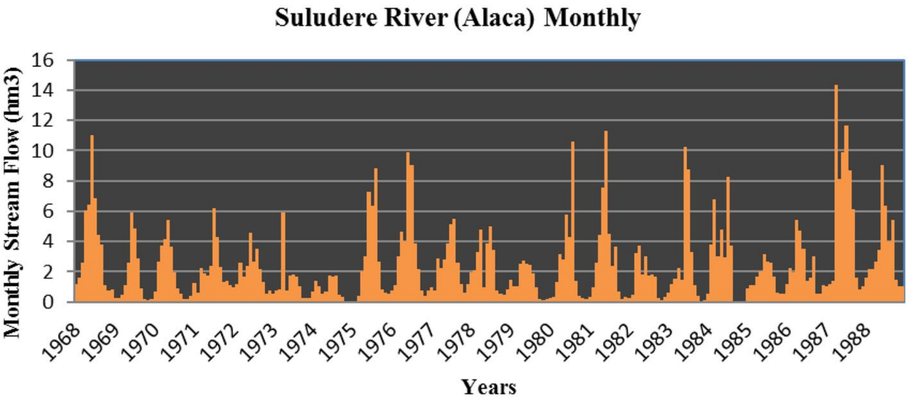

Fig. 6 Time Series Plots of the Runoff of Alaca Reservoir

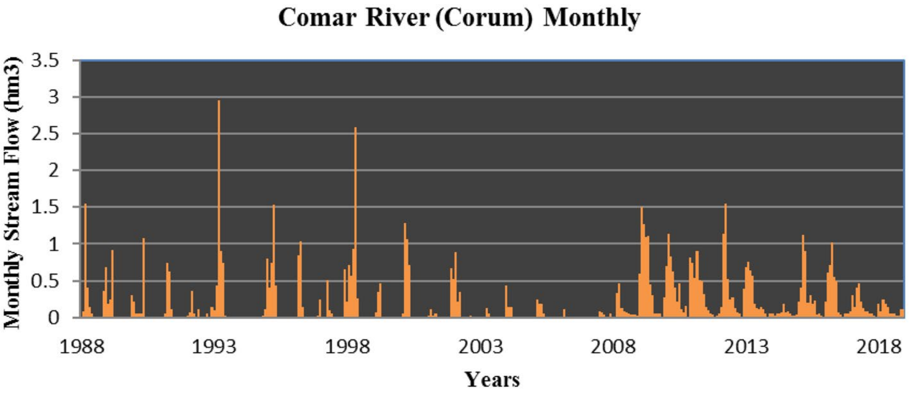

Fig. 7 Time Series Plots of the Runoff of Corum Almus Reservoir

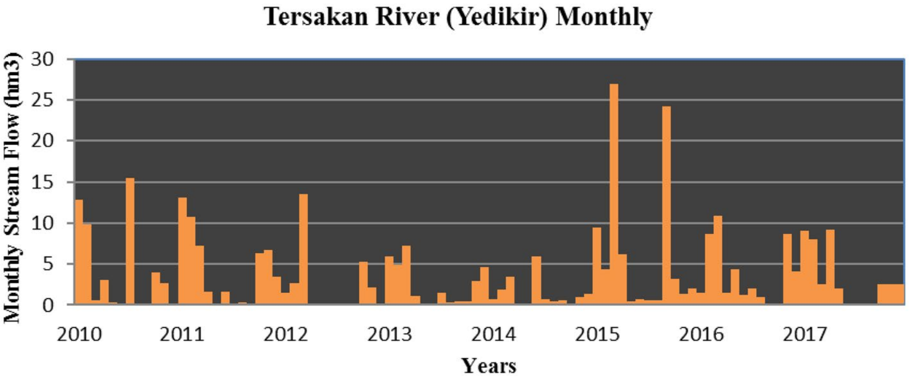

Fig. 8 Time Series Plots of the Runoff of Yedikir Reservoir

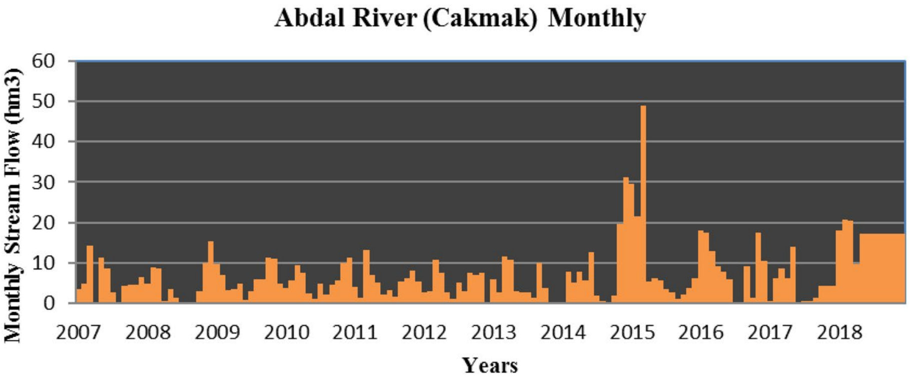

Fig. 9 Time Series Plots of the Runoff of Cakmak Reservoir

Appendix B

Table 8 Annual Volumetric Evaporation Data of Yenihayat and Alaca Dams

	Yenihayat			Alaca		
Years	Volumetric Evaporation (hm^3)	Demand (hm^3)	Vol. Evaporation /Demand %	Volumetric Evaporation (hm^3)	Demand (hm^3)	Volumetric Evaporation (hm^3)
1968	1.34	21.4	6.26	0.54	16	3.38
1969	1.34	21.4	6.26	0.54	16	3.38
1970	1.31	21.4	6.12	0.54	16	3.38
1971	1.34	17.8	7.53	0.54	19.6	2.76
1972	1.34	15.45	8.67	0.54	21.1	2.56
1973	1.34	16.6	8.07	0.42	16.99	2.47
1974	0.7	19	3.68	0.278	13.73	2.02
1975	0.63	15.25	4.13	0.54	17.68	3.05
1976	0.72	19	3.79	0.54	18.94	2.85
1977	1.23	21	5.86	0.562	16.4	3.43
1978	1.34	21.4	6.26	0.54	16	3.38
1979	1.34	21.4	6.26	0.54	16	3.38
1980	1.34	21.4	6.26	0.54	16	3.38
1981	1.34	21.4	6.26	0.54	16	3.38
1982	1.34	21.4	6.26	0.54	16	3.38
1983	1.34	21.4	6.26	0.54	16	3.38
1984	1.34	21.4	6.26	0.54	16	3.38
1985	1.31	21.4	6.12	0.54	16	3.38
1986	1.31	21.4	6.12	0.54	16	3.38
1987	1.35	21.4	6.31	0.54	16	3.38
1988	1.35	21.4	6.31	0.54	16	3.38

Table 9 Annual Volumetric Evaporation Data of Almus, Cakmak and Hasan Ugurlu Dams

Years	Almus			Çakmak			Hasan Uğurlu		
	Volumetric Evaporation (hm^3)	Demand (hm^3)	Vol. E/D%	Volumetric Evaporation (hm^3)	Demand (hm^3)	Vol. E/D %	Volumetric Evaporation (hm^3)	Demand (hm^3)	Vol. E/D %
2007	63.27	824.51	7.67	5.26	54.71	9.61	20.82	3122.27	0.67
2008	23.33	781.68	2.98	5.63	49.11	11.46	9.11	4283.29	0.21
2009	67.64	933.12	7.25	5.63	64.64	8.71	46.71	5477.89	0.85
2010	74.86	846.98	8.84	5.63	65.13	8.64	37.58	120,543.86	0.03
2011	117.91	733.6	16.07	5.63	63.7	8.84	36.9	5090.95	0.72
2012	23.67	701.32	3.38	5.63	84.88	6.63	15.01	3943.28	0.38
2013	23.69	445.46	5.32	5.63	69.2	8.14	11.63	3820.41	0.30
2014	37.57	319.08	11.77	4.01	70.46	5.69	10.8	1351.18	0.80
2015	32.33	648.7	4.98	7.38	118.72	6.22	13.16	4334.78	0.30
2016	303.14	630.22	48.10	5.73	105.48	5.43	17.74	4666.29	0.38
2017	65.12	547.88	11.89	5.63	78.86	7.14	17.62	2561.28	0.69
2018	65.8	538.86	12.21	5.63	93.1	6.05	12.91	2806.32	0.46

Table 10 Annual Volumetric Evaporation Data of Yedikir Dam

Years	Yedikir		
	Volumetric Evaporation (hm^3)	Demand (hm^3)	Vol. Eva/Demand %
2010	5.545	57.2	9.69
2011	5.645	39.55	14.27
2012	5.645	28.51	19.80
2013	5.645	37.19	15.18
2014	4.73	36.71	12.88
2015	5.89	52.62	11.19
2016	5.46	53.28	10.25
2017	5.97	51.22	11.66

Table 11 Annual Volumetric Evaporation Data of Corum Dam

Years	Corum		
	Volumetric Evaporation (hm^3)	Demand (hm^3)	Vol. Eva/Demand %
1988	0.708	4.04	17.52
1989	0.708	5.14	13.77
1990	0.708	4.94	14.33
1991	0.708	4.22	16.78
1992	0.708	1.73	40.92
1993	0.708	4.49	15.77
1994	0.708	3.03	23.37
1995	0.708	4.89	14.48
1996	0.708	3.41	20.76
1997	0.708	2.23	31.75
1998	0.708	3.59	19.72
1999	0.708	3.95	17.92
2000	0.708	3.26	21.72
2001	0.708	0.28	252.86
2002	0.708	2.66	26.62
2003	0.708	0.99	71.52
2004	0.708	0.95	74.53
2005	0.708	1.57	45.10
2006	0.708	3.12	22.69
2007	0.668	0.86	77.67
2008	0.48	2.3	20.87
2009	0.646	3.09	20.91
2010	0.812	3.99	20.35
2011	0.747	6.31	11.84
2012	0.706	3.27	21.59
2013	0.914	2.51	36.41
2014	0.554	3.59	15.43
2015	0.447	3.46	12.92
2016	0.96	0.38	252.63
2017	0.66	3.32	19.88
2018	0.362	2.18	16.61

Table 12 Monthly 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

Table 13 Monthly Mean Runoff and Monthly Mean Sediment Load

Months	Dam Names													
	Alaca		Corum		Yenihayat		Almus		Cakmak		Hasan Ugurlu		Yedikir	
	Run off (hm^3)	Sediment Load (hm^3)	Run off (hm^3)	Sediment Load (hm^3)	Run off (hm^3)	Sediment Load (hm^3)	Run off (hm^3)	Sediment Load (hm^3)	Run off (hm^3)	Sediment Load (hm^3)	Run off (hm^3)	Sediment Load (hm^3)	Run off (hm^3)	Sediment Load (hm^3)
January	0.84	0.00560	0.21	0.00179	0.72	0.00661	36.80	0.03405	8.41	0.02276	346.57	0.07597	6.77	0.02106
February	1.29	0.00502	0.28	0.00234	1.05	0.01086	48.55	0.04493	8.97	0.02428	371.91	0.08153	6.38	0.01984
March	2.21	0.00838	0.59	0.00498	1.57	0.01599	150.3	0.13907	13.93	0.03772	601.18	0.13178	9.04	0.02811
April	3.73	0.00740	0.51	0.00434	2.35	0.01313	146.1	0.13521	5.71	0.01545	56,331	1.23480	2.85	0.00886
May	3.35	0.00584	0.35	0.00299	3.86	0.01028	98.60	0.09124	7.03	0.01903	4827.3	1.05818	0.93	0.00291
June	5.58	0.00318	0.11	0.00091	5.68	0.00612	51.58	0.04773	5.01	0.01355	317.70	0.06964	1.18	0.00368
July	4.93	0.00102	0.06	0.00054	4.67	0.00221	48.71	0.04507	3.61	0.00978	245.29	0.05377	1.50	0.00465
August	3.89	0.00065	0.04	0.00032	3.65	0.00197	16.42	0.01519	2.60	0.00704	233.76	0.05124	0.35	0.00110
September	2.12	0.00084	0.02	0.00019	2.18	0.00169	11.22	0.01038	5.61	0.01518	215.35	0.04721	3.18	0.00989
October	0.68	0.00126	0.02	0.00018	0.78	0.00203	21.11	0.01953	5.74	0.01554	206.22	0.04520	2.76	0.00859
November	0.44	0.00193	0.02	0.00019	0.70	0.00296	25.15	0.02327	9.49	0.02568	232.07	0.05087	3.49	0.01085
December	0.56	0.00332	0.15	0.00123	0.60	0.00441	31.41	0.02906	9.46	0.02560	303.64	0.06656	2.27	0.00705

Appendix C

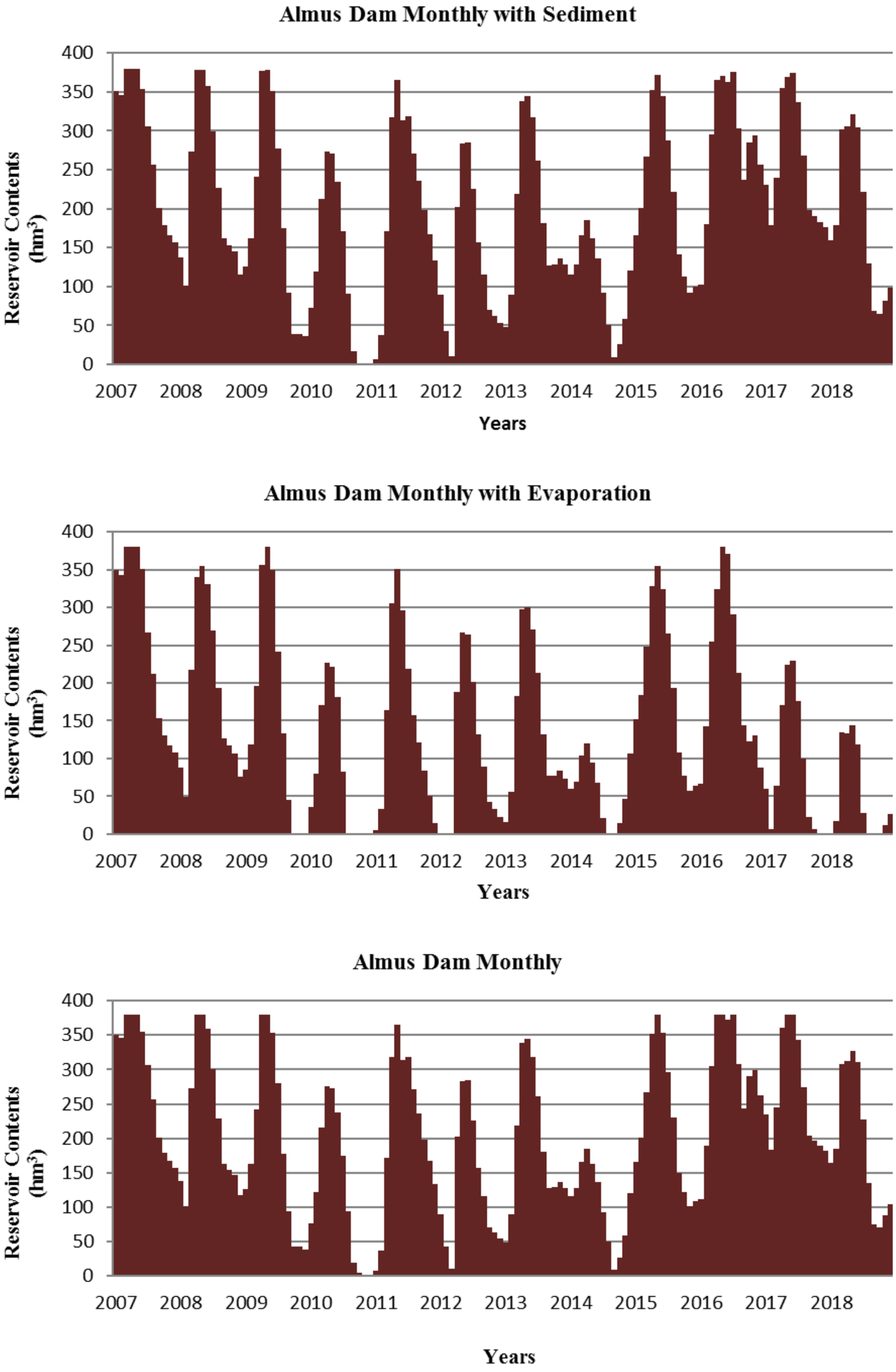

Fig. 10 The Time Series Plots of the Almus Reservoir Contents with Evaporation and Sedimentation

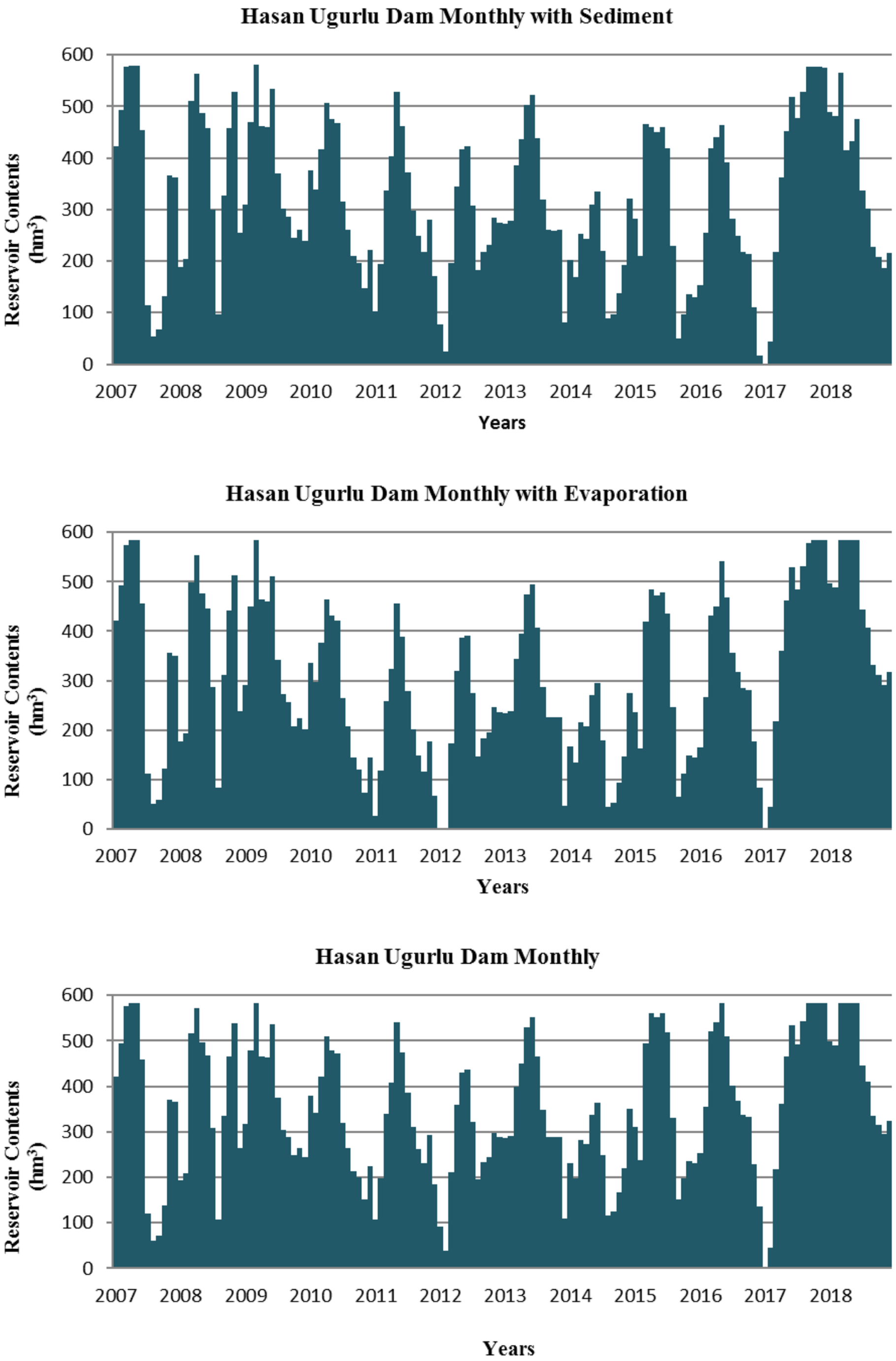

Fig. 11 The Time Series Plots of the Hasan Ugurlu Reservoir Contents with Evaporation and Sedimentation

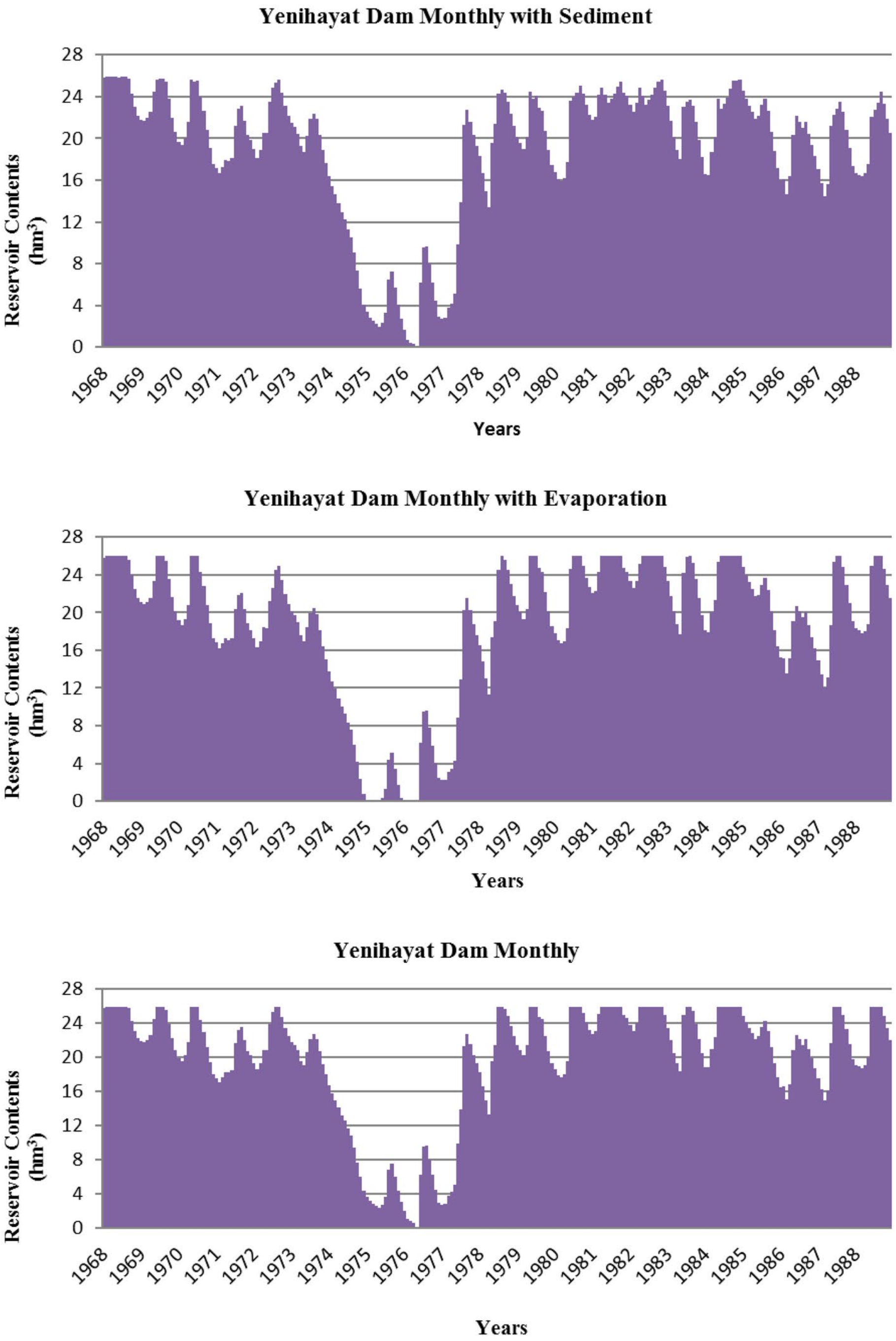

Fig. 12 The Time Series Plots of the Yenihayat Reservoir Contents with Evaporation and Sedimentation

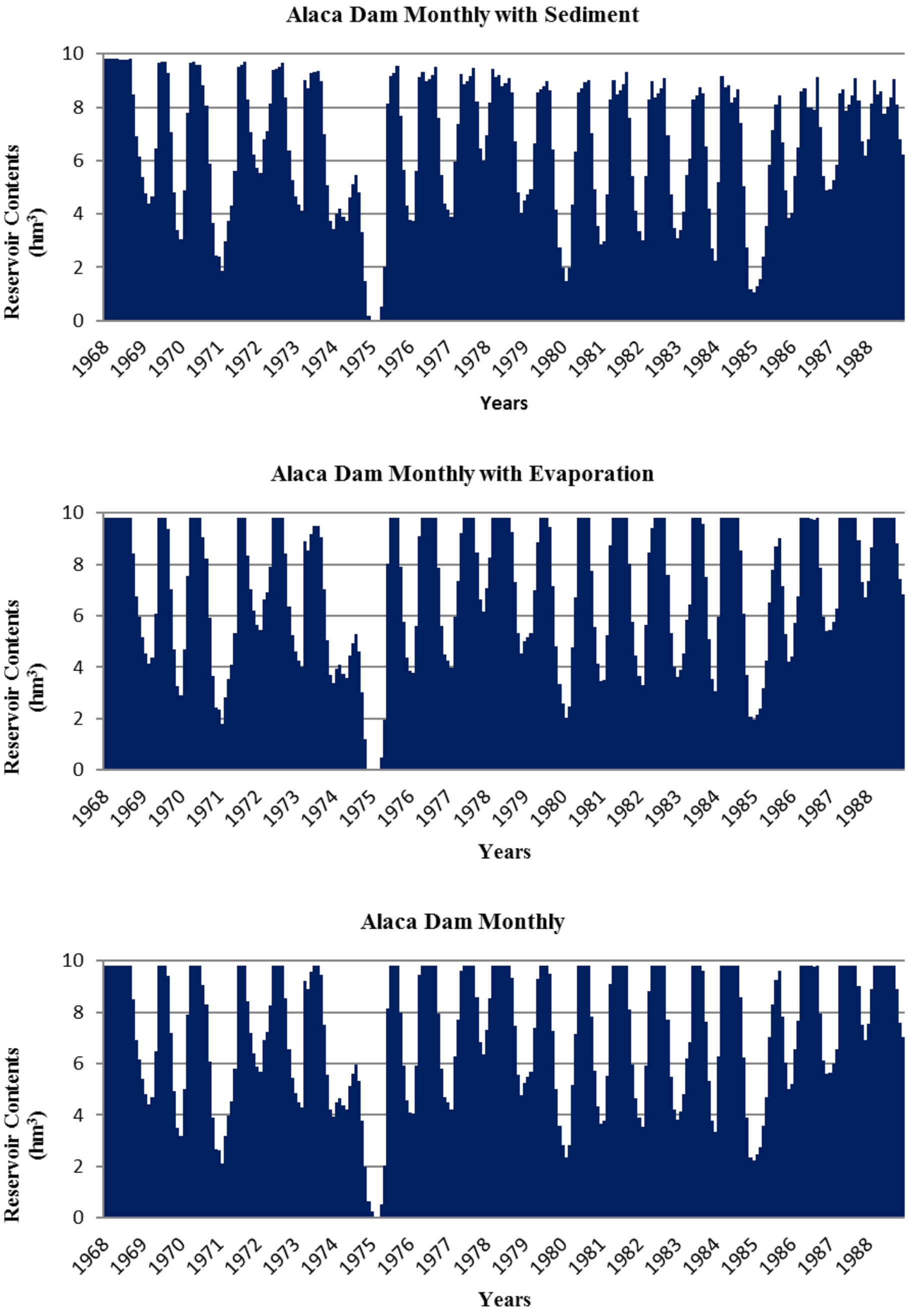

Fig. 13 The Time Series Plots of the Alaca Reservoir Contents with Evaporation and Sedimentation

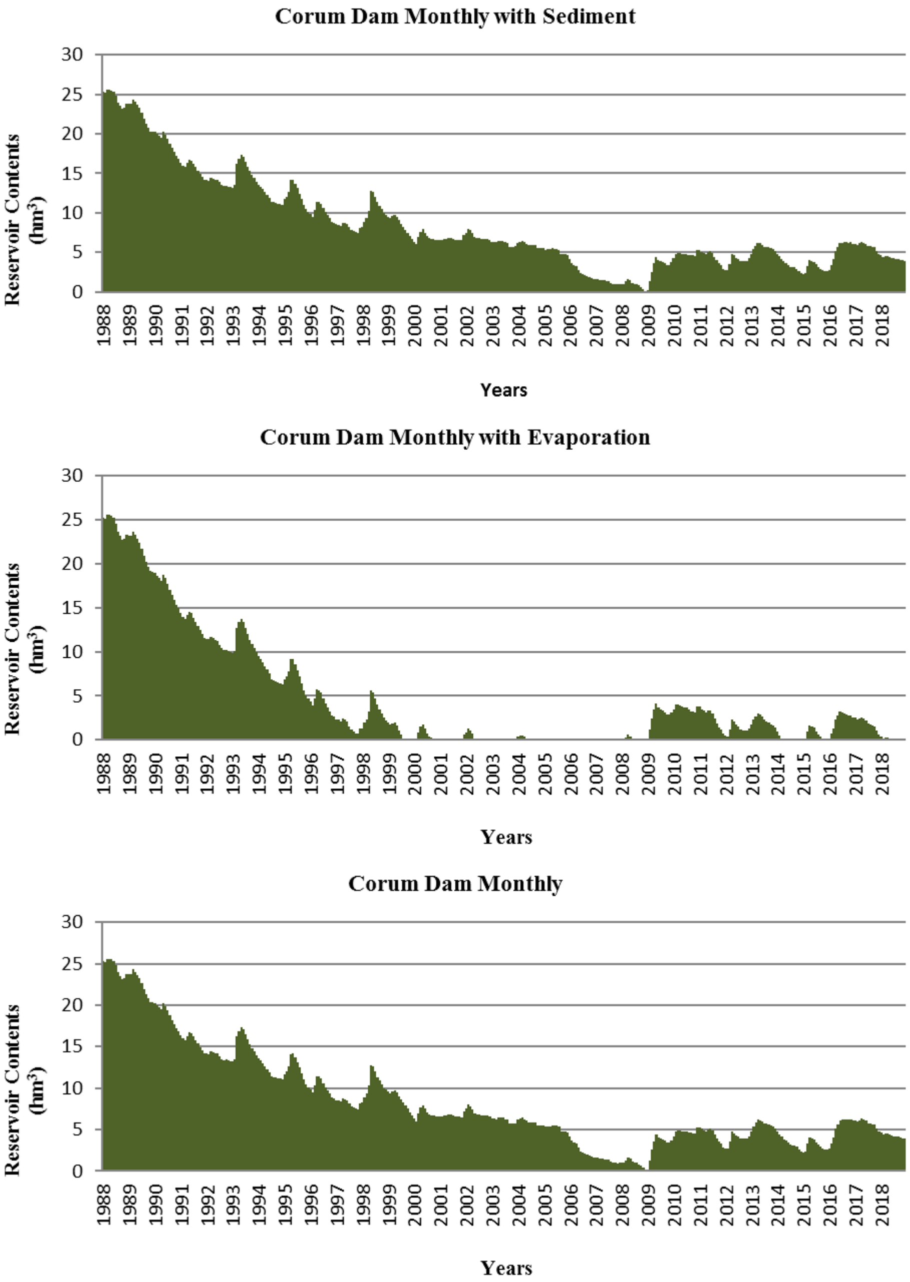

Fig. 14 The Time Series Plots of the Corum Reservoir Contents with Evaporation and Sedimentation

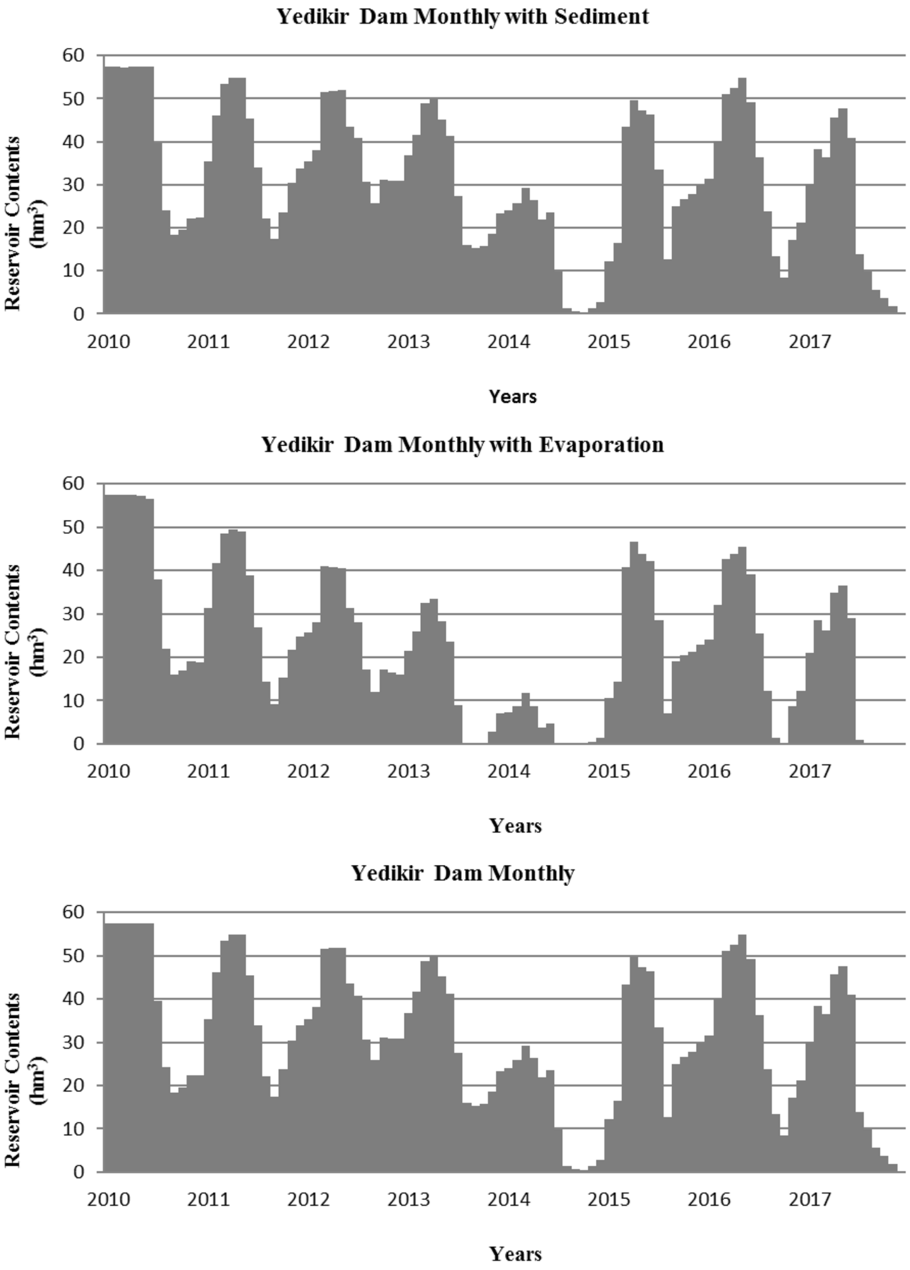

Fig. 15 The Time Series Plots of the Yedikir Reservoir Contents with Evaporation and Sedimentation

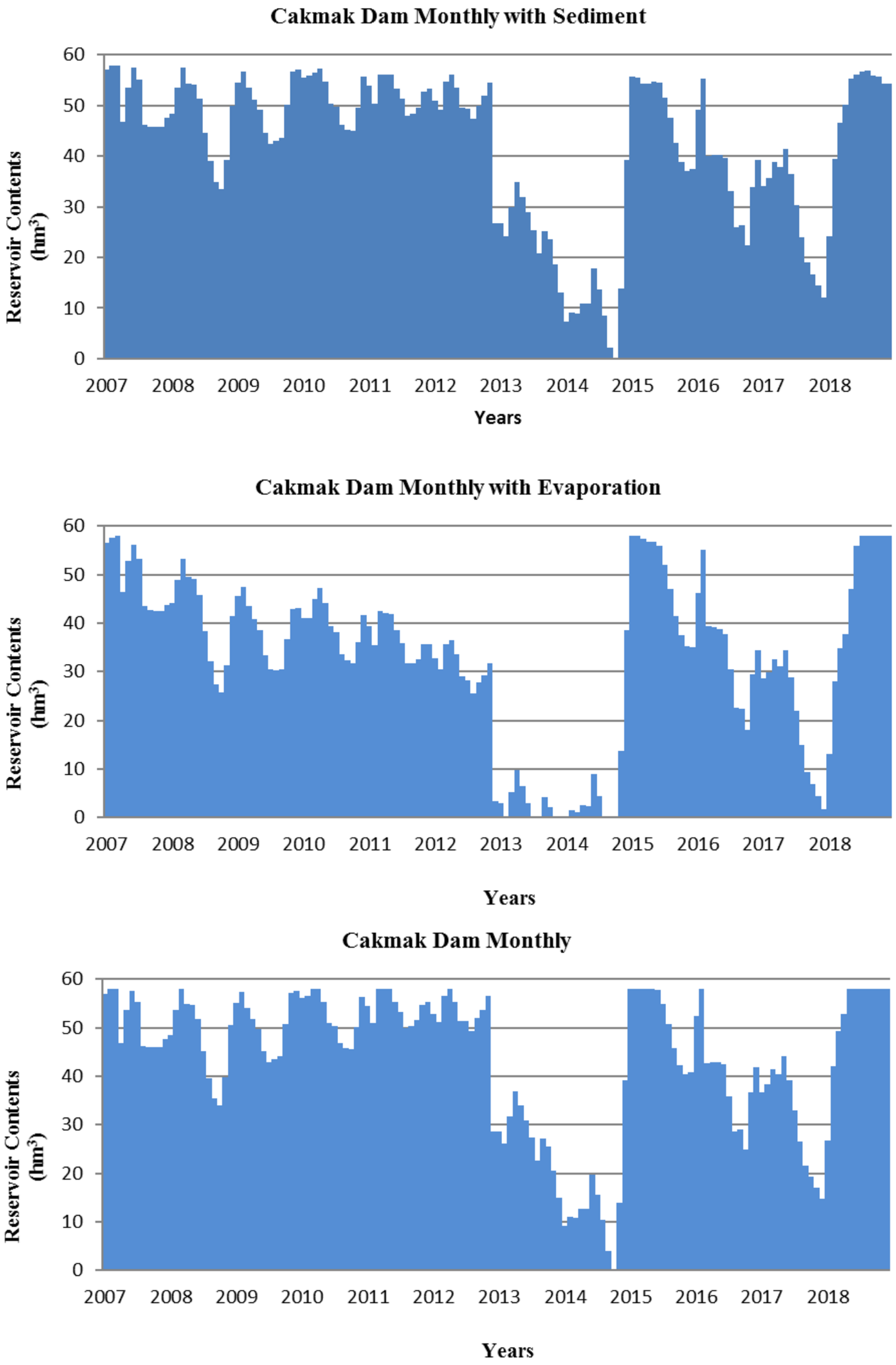

Fig. 16 The Time Series Plots of the Cakmak Reservoir Contents with Evaporation and Sedimentation

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Data Availability Some data, models or code used during the study are available from the corresponding author on request.

Declarations

Ethical Approval The authors declare that the work reported is original and has not been submitted for publication elsewhere. All mention of third party works have been duly acknowledged and referenced.

Consent to Participate All the authors agreed with the content of the article and all gave explicit consent to submit the work for publication.

Consent to Publish All the authors obtained consent from the responsible authorities at their respective institutions thus paving the way for the work to be submitted.

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