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C – statistical analysis
D – data interpretation
E – manuscript preparation
F – literature search

Performance analysis of a reservoir in arid region Case study: Babar reservoir, Aurès region, Algeria

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Abstract

Long term and mid-term reservoir operation involves derivation of rule curves for optimal management of the available resource. The present work deals with reservoir operation in the Aurès arid region. As an example, Babar reservoir is selected to apply the proposed approach which estimates all the water balance terms, especially those which are random as water inflows. For each demand scenario a reservoir operation optimization model using Explicit Stochastic Dynamic Programming (ESDP) is performed, to derive optimal rule curves based on historical operating records (Jan 2002–Dec 2013) and using "Reservoir" R package®. Subsequently, risk analysis is conducted for these different demand scenarios rules by the RRV (reliability, resilience, vulnerability) metrics. Results show the advantage of using the "Reservoir" R package for a rapid and an easy analysis of the performance criteria jointly with the optimization algorithm to Re-operate Reservoir operation.

Key words: *arid region, Babar reservoir, Explicit Stochastic Dynamic Programming (ESDP), optimization, performance, reservoir, risk, RRV (reliability, resilience, vulnerability)*

INTRODUCTION

Climatic characteristics between the northern and southern borders in the region of Aurès differ considerably, the temperature is much higher in the South than in the North [BUSSON 1900]. Spatial distribution of rainfall follows two parameters, hypsometric distribution of the relief and northeast/southwest directions [MEHARZI 2010].

Despite the contribution of mountainous areas, most of rivers inflows of arid regions are very scarce [MEBARKI 2004; SCHMANDT *et al.* 2013]. Accordingly, water resources must be managed sustainably in order to meet increasing demand and climate change. Reservoirs in Algeria are operated by the Algerian Agency of Dams and Transfers (Fr. Agence Nationale des Barrages et Transferts – ANBT) considering rule curves established during dam design study, which can disregard for present circumstances of climate and both social and economic conditions, and lack of a clearly defined objective function [HOWARD 1999].

Reservoir operation modelling can provide beneficial information to stakeholders to improve operational water management [LIN, RUTTEN 2016]. Both optimization and simulation techniques are widely used for deriving operating rule curves [RANI, MOREIRA 2010]. As the problem is often dynamic and since uncertainty is an essential characteristic of water resources systems, Dynamic Stochastic Optimizations are the most popular approaches used for reservoir operation [LEE, LABADIE 2007; LOUCKS *et al.* 1981; NANDALAL, BOGARDI 2007; STEDINGER *et al.* 1984; 2013]. However, these optimization techniques suffer from "curse of dimensionality" which causes a heavy computational burden [PAN *et al.* 2015].

Operation of reservoir system defined as rule curves is often evaluated using the most used statistical measures of reliability, resilience and vulnerability (RRV) first formulated by HASHIMOTO *et al.* [1982]. Also, changes in relative sustainability of such systems can be measured using these indicators [LOUCKS 1997; SIMONOVIC, ARUNKUMAR 2016].

Many studies have been conducted to asses reservoir performance including water demand variation.

SOLEIMANI *et al.* [2016] evaluated operation rules corresponding to four different optimization scenarios which include water demand uncertainty using Stochastic Dynamic Programming (SDP) technique. MOGHADDASI *et al.* [2010] demonstrated benefits of using variable demands for long-term reservoir operation to help manage water resources system in Zayandeh-rud River basin in Iran.

For the same reservoir system, ZAHRAIE and HOSSEINI [2009] used genetic algorithm (GA) optimization model for reservoir operation, both classic and fuzzy regression analysis to estimate the parameters of the operation policies based on four performance criteria of reliability, resiliency, total vulnerability, and maximum monthly vulnerability showed that asymmetric fuzzy coefficients, used for the regression equation, have the best long-term performance in meeting variable demands.

Under highly uncertain conditions such climate and increasing demand, existing reservoirs must be re-operated (RR) and adjusted to eventual new climate, socio-economic and environmental conditions. A new R® package named "Reservoir" [TURNER, GALELLI 2016] is designed for a rapid and easy reservoir operation analysis. The package comprises tools for both performance analysis and release policy optimization using SDP. Different increased demand as 20, 40, 60, 80 and 100% of the mean monthly inflows scenarios are analysed and compared with historical releases. Correspondent derived rule curves are evaluated using performance measures available in the same package (reliability, resilience and vulnerability indices).

STUDY AREA

Babar reservoir (Fig. 1) was built on El Arab River in South-East of Khenchela district, especially for meeting agricultural and domestic water needs with an actual capacity of 38 hm^3.

Principal characteristics of Babar reservoir:

- construction year 1989
- impoundment year 1995
- initial capacity 41 hm^3
- last capacity (2004) 38 hm^3
- mean annual flow 19.50 hm^3
- normal water level 940.00 m
- destination irrigation, water supply

METHODS

EXPLICIT SDP FORMULATION

The well known Explicit Stochastic Dynamic Programming – ESDP [VEDULA, MUJUMDAR 2005] (Fig. 2) is applied to optimize operating rules for Foum El Kherza reservoir.

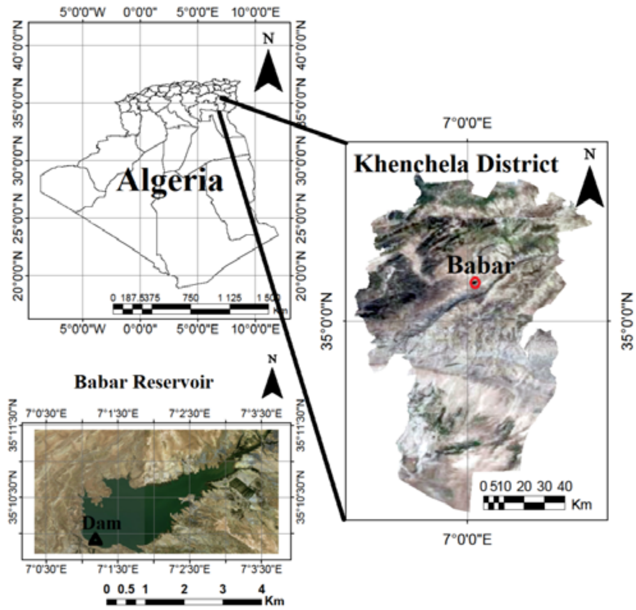

Fig. 1. Babar reservoir; source: own elaboration

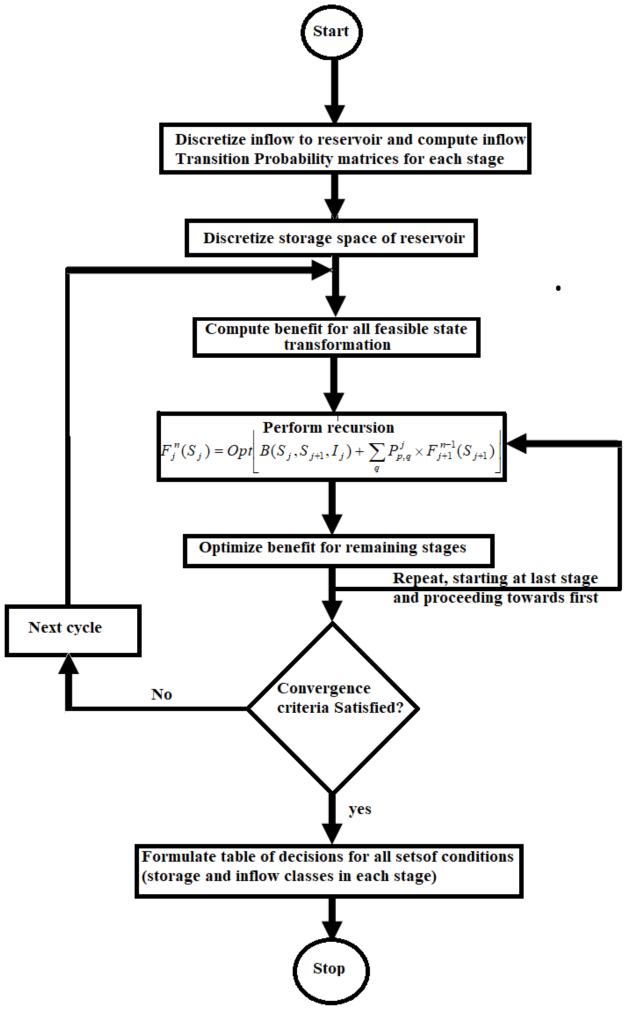

Fig. 2. Stochastic Dynamic Programming Flow Chart after NANDALAL, BOGARDI [2007]

Bellman recursive equation in this case is:

$$f_j^n(S_j) = \min_{R_j}[\{B(S_j, S_{j+1}, I_j)\} + \sum_q P_{p,q}^j f_{j+1}^{n-1}(S_{j+1})] \quad (1)$$

Where: $B(S_j, S_{j+1}, I_j)$ = cost or contribution of the decision (release) R_j given state S_j at the initial stage; $f_{j+1}^{n-1}(S_{j+1})$ = accumulated suboptimal cost (or contribution) by optimal operation of the reservoir over the last n–1 stages; I_j = inflow during period j; $P^j_{p,q}$ = transition probability of inflows; S_j= system state at stage j; $S_{j+1} = t(S_j, R_j)$ = system state transformation equation; R_j = decision (release) taken at stage j; $p^j_{p,q} = p[I_{j+1} = q | I_j = p]$. Transition probability that inflow to the reservoir at month j+1 falls in state q given at month j the streamflow to the reservoir was in state p.

The state transformation equation based on the principle of continuity is as follows:

$$S(t+1) = S(t) + I(t) - E(t) - R(t) \quad (2)$$

Where: $S(t)$ = system state during period t; $I(t)$ = inflow to the reservoir during period t; $R(t)$ = release from reservoir during period t; $S(t+1)$ = system state during period t after decision $R(t)$; $E(t)$ = evaporation from the reservoir during period t.

SYSTEM PERFORMANCE

HASHIMOTO *et al.* [1982] presented three statistical indices to analyse water systems performance: reliability, resilience, and vulnerability. From the output supply time series of the reservoir operation X_t, two binary indices are defined:

Z_t describes if a system is in satisfactory (1) or unsatisfactory state (0) according to a criterion C defined as the demand to be met within a period T.

W_t to capture transition from unsatisfactory to satisfactory state (1) or inversely (0).

The probability that the system state lies in the set of satisfactory states is the system reliability (C_R) and it is given by:

$$C_R = \frac{\sum_{t=1}^{T} Z_t}{T} \quad (3)$$

The most important reliability indexes are time reliability, volume reliability and annual reliability. As a measuring tool for assessing damage vulnerability (C_v) is given by:

$$C_v = \max\{\sum_{t\in} C - X_t\} \quad (4)$$

Resilience (C_{RS}) describes how quickly a system recovers from failure [KARAMOUZ *et al.* 2010].

$$C_{RS} = \frac{\sum_{t=1}^{T-1} W_t}{T - \sum_{t=1}^{T} Z_t} \quad (5)$$

MONTHLY INFLOWS AND EVAPORATION LOSSES

Monthly river inflows to Babar reservoir (2002–2013) are plotted in Figure 3 where we can observe the flood of August 2002 with a volume of 35.23 hm^3 which has led to an important spilled volume. The boxplot in the same figure summarizes the principal characteristics of the time series and shows that are highly skewed to the right and for most of months,the interquartile range is below a volume of 2 hm^3.

Evaporation losses from Babar reservoir (Fig. 4) are substantial because of aridity of the region and cannot be neglected. A maximum value of 0.77 hm^3 was observed in July 2005 with a monthly mean of 0.29 hm^3.

RESULTS AND DISCUSSION

Stochastic Dynamic Programming "sdp_supply" function in "Reservoir" R package optimises release decisions tominimise the sum of penalty costs B incurred in long-term operationof the reservoir. This function is used for deriving rule curves for Babar reservoir considering net monthly inflows time series (– E) for different demand targets respectively, 20, 40, 60, 80 and 100% of the mean monthly inflows I. Objective function as defined by TURNER, GALELLI [2016] is calculated as:

$$B = \left(\frac{Demand_{Target} - Release}{Demand_{Target}}\right)^{Exponent} \quad (6)$$

Where default exponentvalue is 2.

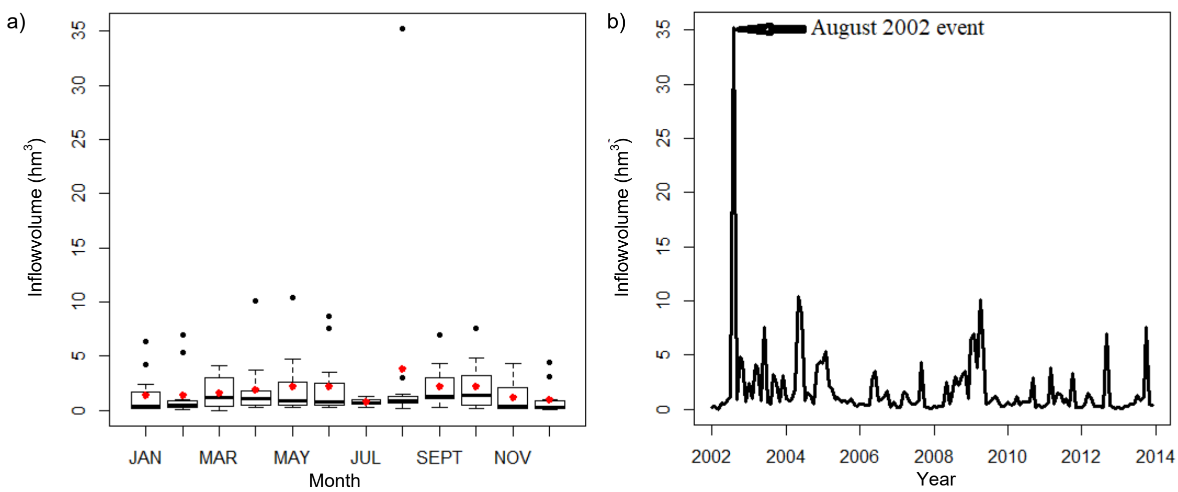

Fig. 3. Monthly inflows to Babar reservoir (2002–2014); a) boxplot, b) time series; source: own elaboration

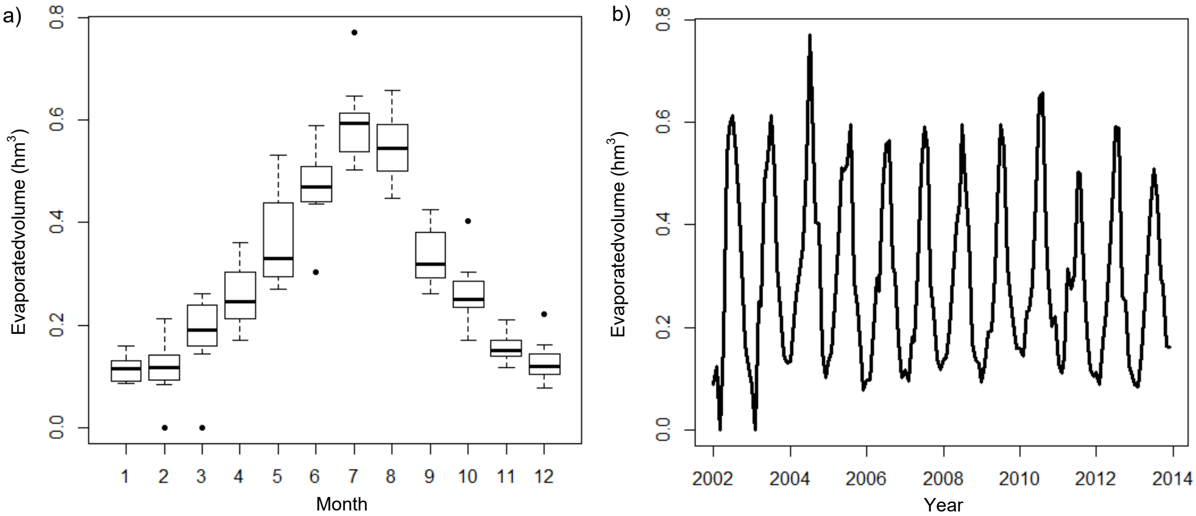

Fig. 4. Evaporation losses from Babar reservoir (2002–2014): a) box plot, b) time series; source: own elaboration

Equation (6) returns a look-up table ofreleases based on monthly inflows discretized according to bounding quantile and considered as a first order Markov chain process, reservoir capacity and demand target that would be available to the current inflow and time of year are also discretized.

The “RRV” function in “Reservoir” package computes reservoir performance indices as defined above using the output of the “SDP function”, allowingperformance analysis under variable demands schemes.

Outputs of above functions are the optimal rule as release decisions; the Bellman cost function; the optimized release, corresponding storage and spill time series.

Based on storage time series, results show that historical storages are greater than those correspondent to 40% of mean monthly flows (Fig. 5). This result indicates that the reservoir is still unexploited for more than 13 years since its impoundment. This storage leads to a very important spilled water volume without using it effectively.

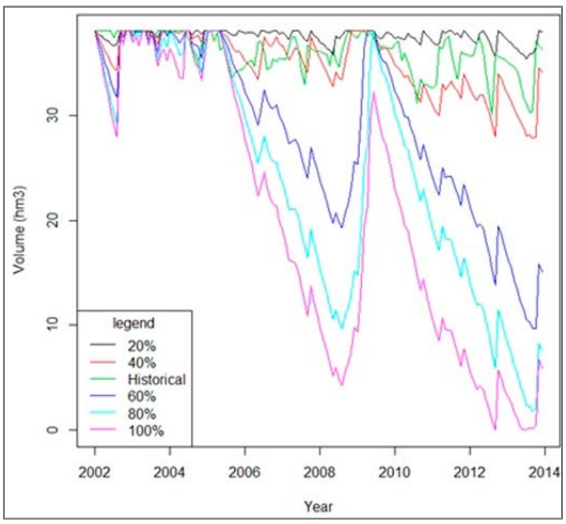

Fig. 5. Storages at Babar reservoir with different demand scenarios; source: own study

For more detailed analysis of the reservoir operation, RRV measures for the different demand-mean of monthly inflows ratios, figure 6 shows that below a demand of 60% the system remains above 85% reliable.

Figure 7 indicates that Babar reservoir system has low resilience in spite of its little vulnerability index.

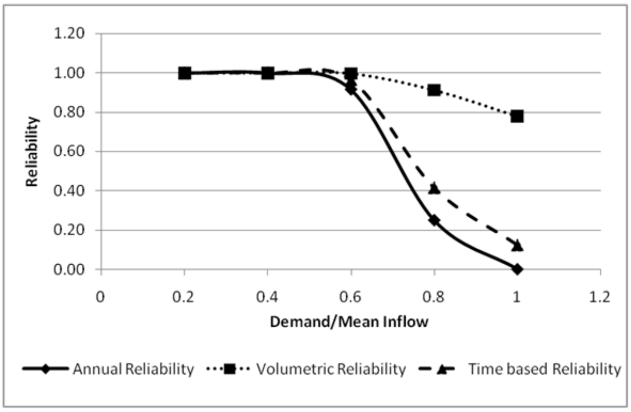

Fig. 6. Reliability indices for Babar reservoir; own study

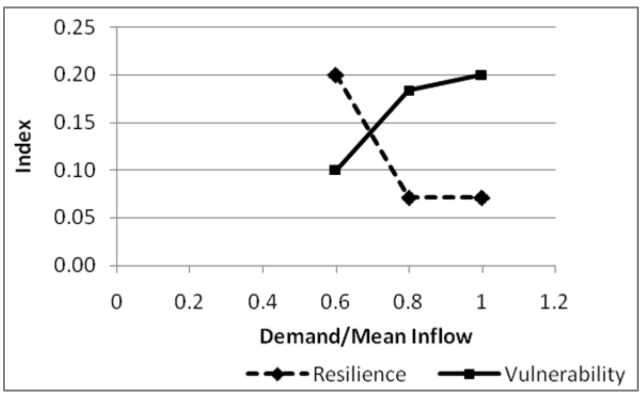

Fig. 7. Babar system resilience and vulnerability; source: own study

CONCLUSIONS

Reservoirs have to be best operated to achieve maximum benefits from them. Operators are expected to maintain these pre-fixed water levels. Estimated *RRV* indices for Babar Reservoir with demands below 60% of mean monthly inflows reveal that correspondent rule curves can be adopted by the Algerian Agency of Dams and Transfers (ANBT) and may be useful to support decision-making for more sustainable water use. From above analysis, we can deduce that stochastic optimization for different scenarios of demand can improve reservoir operation without losing its reliability. Simple and fast analysis of reservoir operation should be undertaken for many reservoirs in the region. This will in turn enable us to improve and modify system operations to make their performance better within a short time.

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Analiza działania zbiornika w regionie o suchym klimacie na przykładzie zbiornika Babar w regionie Aurès w Algierii

STRESZCZENIE

Długo- i średnioterminowe działanie zbiornika obejmuje ustalenie reguł operacyjnych do optymalnego zarządzania dostępnymi zasobami. Przedstawiona praca dotyczy działania zbiornika w regionie Aurès znajdującym się na obszarze suchego klimatu. Jako przykład wybrano zbiornik Babar celem zastosowania proponowanego podejścia, w którym ustala się wszystkie warunki bilansowania wody, w tym czynniki losowe, np. dopływ wody. Dla każdego scenariusza zapotrzebowania na wodę opracowano dla zbiornika model optymalizacyjny z zastosowaniem stochastycznego programowania dynamicznego (ESDP), bazującego na historycznych zapisach operacyjnych z okresu styczeń 2002–grudzień 2013 i na pakiecie „Reservoir" programu statystycznego R. Następnie przeprowadzono analizę ryzyka dla różnych scenariuszy za pomocą miar RRV (wiarygodność, odporność, podatność). Wyniki wskazują na korzyści płynące z użycia pakietu „Reservoir" do szybkiej i łatwej analizy kryteriów operacyjnych w powiązaniu z algorytmem optymalizacyjnym.

Słowa kluczowe: *Babar, działanie, optymalizacja, RRV (wiarygodność, odporność, podatność), ryzyko, stochastyczne programowanie dynamiczne (ESDP), zbiornik*