STORAGE-YIELD CURVES WITH INFLOWS FROM A DIVERSION CHANNEL

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ABSTRACT

Probabilistic analytical methods for building storage-yield curves provide reliable preliminary design condition for new reservoirs and assessment of performances of existing ones. In this framework, the evaluation of storage-yield curves of reservoirs when additional inflows from a diversion channel are available is the subject of this paper. To achieve this result the same deficit analysis of inflows is performed on the reservoir and on the volumes trasferred by the channel, according to methods respectively suggested by *Rasulo and Rossi* (1980) and by *Claps et al.* (1996). Both carryover and seasonal capacities are considered, respectively based on the deficits of annual and the dry-season runoff volumes. The procedure was applied to an existing water resources system in Basilicata (Italy).

KEYWORDS

Reservoirs, diversion channels, storage-yield curve, probabilistic methods.

INTRODUCTION

In situations of preliminary water resources planning many economic, social and environmental issues play a major role in conditioning the design of reservoir systems. In these cases, despite the existence of refined modeling techniques for the design of reservoir storage, there is still need for design tools that are simple enough to generate confidence in the decision makers, as well as effective enough to produce realistic and reliable storage-yield design curves.

A class of design procedures presenting these characteristics is that of probabilistic analytical methods, based on the evaluation of the runoff deficit for a given probability of exceedance upon different critical periods. This class of methods is best suited for the design of a single reservoir, even though configurations with a few reservoirs in series can also be handled with minor additional efforts. Main references for these methods are *Alexander* (1962), *Gould* (1964) and *Rasulo and Rossi* (1980). The present paper is based essentially on the deficit analysis theory as presented by the latter authors, which will be briefly resumed in the following.

Deficit analysis is best suited for semi-arid environments, where annual flows are practically independent and where the annual flow distribution can be well fitted by a Box-Cox transformed Normal.

The main contribution provided here concerns a technique to supplement the above-mentioned design procedure with the possibility to account for extra-basin inflows added without additional storage.

The use of diversion channels to supplement 'natural' inflows in existing dams is receiving increasing attention in the last years, particularly in semi-arid climates, to face the augmenting water volumes required to boost the agronomic and industrial development in those areas. This additional input helps in improving the operation of sometimes redundant reservoirs while ensuring relatively low environmental impact in terms of subtraction of water and sediments from the river.

The configuration considered is made up of a small dam put on a different river (e.g. a tributary) that diverts water volumes into the main dam by means of a channel. The lack of storage capability on the tributary makes the additional input entirely dependent on the river regime and allows one to include this inflow to the main dam with no concern about kind of operating rules on the secondary dam.

Probabilistic estimation of volumes conveyed by a diversion channel has been the subject of a paper by *Claps et al.* (1996), which will also be shortly resumed below. Application of this approach will allow one to introduce the additional inflows to the main dam in the same probabilistic terms used by Rasulo and Rossi and to apply coherently their method.

THE PROBABILISTIC ANALYTICAL METHOD BY RASULO AND ROSSI (1980)

The analytical approach in storage design is based on the derivation of the probability distribution of storage capacity that, when the target draft is smaller than the mean inflow (partial regulation) is equal to the maximum accumulated deficit of the inflow partial sums (see *McMahon and Mein*, *1986*). The design problem is then essentially constituted by the derivation of the stochastic model of the runoff process. The family of random variables to handle in order to build carryover storage-yield curves, according to *Rasulo and Rossi* (1980), is $D_{k,F}$, as the mean annual runoff over *k* consecutive years with non-exceedance probability F.

Once these variables are determined, the carryover storage volume required to cover deficits up to a frequency F for the annual yield *E* is:

$$V_{c,F} = max|_K \,[kE - k\, D_{k,F}\,] \qquad (1)$$

The period k varies from 1 and K, the latter being a number of the order of 10. This requirement is needed to ensure that the autocorrelation implied in the overlapping sequence of mean runoff in k years remains insignificant. Limitations on K usually do not practically affect the design, unless one gets very close to the full regulation region of the storage-yield curve.

The storage $V_{c,F}$ refers to a generic sequence of years that presents initially full reservoir, and this affects with some underestimation the curve in the region of the full regulation. The probabilistic method discussed also relies on the assumption of uncorrelated annual runoff series, which is often realistic, particularly when considering runoff data aggregated over the water-year. Anyhow, even in presence of autocorrelation it is possible to adjust the probability distribution so that the reproduction of the observed minima is ensured (*McMahon and Mein*, *1986, p. 337*).

Using the Box-Cox Normal distribution to fit $D_{k,F}$ allows on to derive analytically of the distribution of the k-dependent stochastic process D_k, because the sum (or the average) of k normal variables is still normally-distributed, so that parameters of the transformed variable $(D_k)^\lambda$ can be derived from these of D $(=D_1)$ using the relations:

$$m(D_K^{\ \lambda}) = m(D^\lambda) \qquad s(D_K^{\ \lambda}) = s(D^\lambda)\ /\ \sqrt{K} \qquad (2)$$

with m and s as the mean and the standard deviation, respectively.

In a subsequent work (*Rasulo and Rossi*, 1984) the additional storage required to cover within-year deficits with the same probability of failure was determined with reference to the probability distribution of the deficit in the dry season. This part of the storage-yield curve is significant for low and medium regulations, and is decisive for reservoirs in semi-arid regions.

In the Mediterranean climate there is only one wet and one dry seasons, clearly separated. This means that in the carryover storage-yield curve it is possible to take into account the average deficit of the dry season preceding the critical period. This deficit is nothing but the quantity

$$V^* = E_S - m(d) \qquad (3)$$

where E_S is the yield in the dry season and $m(d)$ is the mean seasonal runoff. In this way, $E_S - m(d)$ is representative of the deficit of a generic dry season.

The deficit of the critical dry seasons is, on the other hand, given by the relation

$$V_{S,F} = max|_S \,[E_s - d_{s,F}] \qquad (4)$$

where $d_{s,F}$ is the minimum runoff with non-exceedance probability F in s consecutive months out of the S months of the dry season, with $d_{S,F} = d_F$.

Given that the irrigation yield is not constant in the dry season, the length S of the critical season essentially depends on the within year diagram of the draft. It is to say, however, that volumes required for irrigation share about the same pattern in a given climatic region, so that the deficit season is the same in large areas.

The probability distribution of the seasonal runoff was found by *Rasulo and Rossi* (1984) and by *Claps et al.* (1998) substantially coinciding with that of the annual runoff, which is a cube-root normal, at least in the regions of Southern Italy. In short, the global storage-yield curve, accounting for both the seasonal and the carryover storage is determined as

$$V_F = max[V_{c,F} + V^*,\ \ V_{S,F}\,] \qquad (5)$$

THE DIVERSION CHANNEL DESIGN METHOD BY CLAPS ET AL. (1996)

Traditional methods to select the optimal maximum discharge of a diversion channel are based on the use of flow duration curves, that involve a deterministic approach to the design task. In an effort to overcome the deterministic connotation in this approach, *Claps et al.* (1996) suggested a specific methodology for the selection of the design discharge in such channels, based on the estimation of volumes transferred annually with assigned non-exceedance probability.

The problem was defined in terms of the process of the annual volumes (or average annual discharge) Q_{rd} transferred with a 'diversion ratio' r_d , which is the ratio between the channel design discharge *Dq* and the river average discharge *q.*

The analysis made by *Claps et al.* (1996) led to the estimation of the quantile $q_{rd,F}=Q_{rd,F} / q$, for given diversion ratio r_d and non-exceedance probability F, considering the time series of 11 different rivers in southern Italy, with coefficient of variation *Cv* of the daily data ranging between 1.1 and 6. The outcome was that at the annual scale the variable q_{rd} is Gaussian, regardless of the values of r_d and of the river considered.

Therefore, to obtain $q_{rd,F}$ from r_d it was sufficient to estimate relations between mean and variance of the distributions of q_{rd} and r_d itself. The relations found were shown to depend uniquely on the coefficient of variation of the daily data, as reported in the following formulas:

$$m[q_{r_d}] = (2C_V)^{-1/2} + 1/3\,(1-0.1C_V)\,ln\,r_d \qquad (6)$$

$$s\,[q_{r_d}] = 0.10 + 0.09\,ln\,r_d$$

After minor simplifications, the relation obtained between $q_{rd,F}$ and r_d was

$$q_{r_d,F} = (2C_V)^{-1/2} + 1/3\,(1-0.1C_V)\,ln\,r_d + 0.1\,u_F\,[1 + ln\,r_d] \qquad (7)$$

with u_F as the normal reduced variate.

Best performances of this procedure are obtained in semi-arid situations, in which coefficients of variation of daily flows are significantly greater than 1. The reason is that for lower *Cv* the mean of q_{rd} approaches 1 for r_d slightly greater than 1, whereas relation (7) is not upper-bounded.

Evaluation of *Cv* from hydro-geological features is also possible by using the strong correlation between *Cv* and the BFI (*Lvovitch* 1972), the latter being correlated to the hydro-geological structure of the basin.

STORAGE-YIELD CURVES WITH DIVERTED INFLOWS

Storage-yield curves for a single reservoir can be quite easily determined with the analytical methods even in some cases of natural or man-made modifications, when these alterations are systematic, *i.e.* do not depend on operating rules or so. In this regard, it is intuitive how to deal with the case of reduction of natural runoff for springflow tapping, which is a typical case of permanent reduction of the natural inflows. Different structural man-made alteration of the natural runoff, due to partitioning of the basin with a dam or a diversion, can involve some control on the water actually available at the main dam. In this case, each operating option increases the degrees of freedom in the determination of the main dam storage-yield curve.

Inflow volumes coming from the diversion channel are subject to virtually no regulations, so that on a given period of k years and with probability F the diverted volumes can be just summed up to the natural inflows $D_{k,F}$.
The necessary hypothesis to sum up values in different sections is that annual and seasonal minima occur with the same probability. Given the time scales of interest, this hypothesis is certainly met for water resources systems with basins that lie in the same climatic region (i.e. having the same number and the same position of maxima and minima of runoff within the year).
Therefore, given the r_d for the channel at hand, values of $D_{k,F}$ to be put into relation (1) are obtained through the sum $D_{k,F} = D'_{k,F} + Q_{k,F}$ where $D'_{k,F}$ is the quantile of the natural inflow and $Q_{k,F}$ is the corresponding mean of the annual volumes transferred in k years with probability F. Being Q_F a Normal variate, $Q_{k,F}$ can be derived through relations (2).
Evaluation of the seasonal runoff transferred by the channel requires an additional discussion, since the procedure by *Claps et al.*(1996) is only concerned with diversion of annual volumes. By a practical viewpoint the evaluation of the seasonal runoff quantiles transferred by the diversion channel is not particularly difficult, given that to obtain good performances of the diversion the ratio r_d will not be so small to cut a significant part of the runoff in the dry season.
In the case study described below, with reference to the Basento river section at Trivigno, the following statistics for the annual and the dry season data were found:

	Mean(m^3/s)	*Cv*
Year	3.92	2.81
Dry season	1.12	3.05

In short, the $q_{rd,F}$ curves are about the same for the global and the dry-season process, because *Cv* is the same, but the diversion ratio increases in summer by a factor of 3.5, as the ratio between the two means. Looking at the curves in Fig. 1, built for the section mentioned earlier, one can immediately realize that this increase in r_d will lead to $m[q_{rd}]$ practically equal to 1.

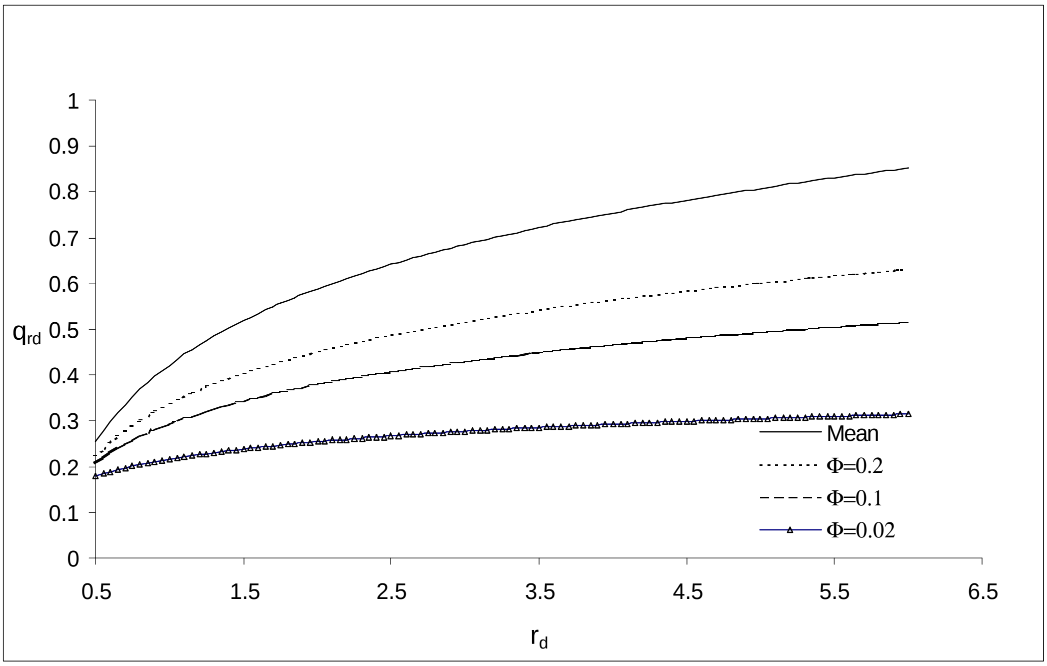

Fig.1. Curves of q_{rd} vs. r_d for the Basento river at Trivigno with different non-exceedance probabilities.

Moreover, unlike annual volumes, reducing the non-exceedance probability (i.e. going toward drier years) allows one to divert a greater amount of the seasonal runoff. Therefore, at least in the Mediterranean climates, in which the differences of the annual and the dry-season mean are considerable while the coefficient of variation does not change correspondingly, on can conclude that the amount of water diverted in the dry season is the whole d_F when F is less than 0.5.

APPLICATION

The derivation of a storage-yield curve with diverted inflows has been obtained for a water resources system in Basilicata (Italy) that consists of two connected dams (Acerenza and Genzano dams) with very small upstream basins. The dams are located in the Bradano Basin and they are about to be served by a diversion channel, that will convey a maximum of 10 m^3/s from the Basento River at Trivigno (r_d=2.5).

In this evaluation step operation of reservoirs will not be considered, and the dams will be treated as a single reservoir, with storage as the sum of the two capacities. Consequently, quantiles of the natural inflows are the sum of those estimated for the two basins. The data required for computation of the storage-yield curve, that will be provided for constant yield throughout the year, are reported in Table 1, and are extracted from a regional water resources assessment study (*Claps et al.*, 1998).

Table 1. Parameters needed for building storage-yield curves. $Q_{rd,F}$ for Trivigno is derived from Figure 1 using q_{rd} corresponding to r_d=2.5 on the curve for F=0.2.

section	Area (km^2)	m(D) (*mm*)	m(d) (*mm*)	$s(D^{1/3})$ ($mm^{1/3}$)	$s(d^{1/3})$ ($mm^{1/3}$)	m(D) 10^6 m^3	m(d) 10^6 m^3	m(d) 10^6 m^3	$Q_{rd,0.2}$ 10^6 m^3
Genzano	36.5	102.8	10.3	1.060	0.714	3.8	0.4	0.4	
Acerenza	156.2	184.3	23.6	1.060	0.714	28.8	3.7	3.7	
Trivigno	405	305.2	48.3	1.012	0.751	123.6	19.6	19.6	60.9

Figure 2 reports the storage-yield curves of the twin dams with and without the diverted inflows, and shows that the system is well designed to be efficient with the additional inflows, that allow the dams to reach a significant level of regulation.

CONCLUSIONS

Two probabilistic methods, one for the derivation of the storage-yield relation and the other for the estimation of volumes transferred from a diversion channel were connected in this paper, in order to provide storage-yield curves with extra-basin inputs. Based on the hydrological regime of rivers in semi-arid environments, it is also indicated that quantiles of the seasonal runoff slightly less than the mean can be considered as entirely transferable for all practical purposes. This allows one to build storage-yield curves in a quick and reliable way for in these cases, leaving more room for economic, social and environmental issues, as well as for a very accurate probabilistic analysis of annul and seasonal runoff.

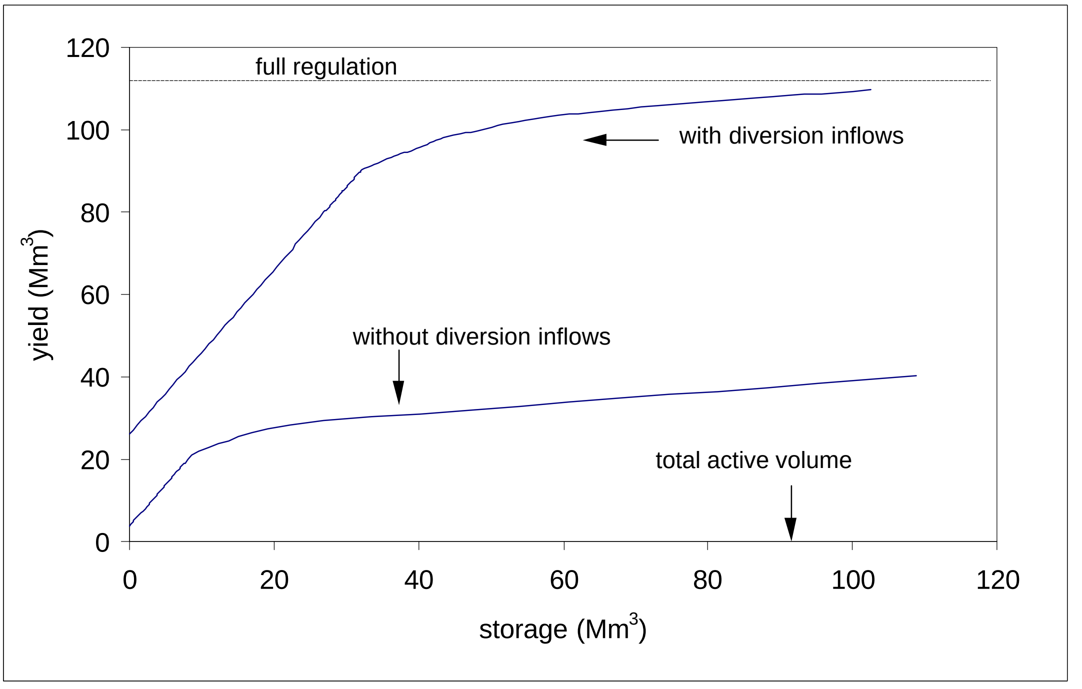

Fig.2. Storage-yield curves with and without diverted inflows, with uniform yield, F=0.2 and dry season within May and October (incuded).

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