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THE HYDROLOGICAL CHARACTERISTICS OF THE VAJONT VALLEY

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ABSTRACT

In this paper a study on the hydrology of Vajont creek, in northern Italy, is presented. The Vajont creek is dramatically known because of the disaster which occurred in 1963, when, before the dam located on the creek between the towns Erto and Casso started its operation, a huge landslide detached from the Toc mountain, falling in the reservoir during the filling stage. Consequently, a water wave overtopped the dam. Although the dam is still there, the damage caused by the wave was so high that this disaster is remembered as one the most dramatic in a very long time.

As just a little has been said about the hydrology of the water resources system planned at the time of the dam design, the volume of water, which could have been used if the system were realized, is here estimated by use of a storage-yield curve theory and it is compared to the amount of water that can really be nowadays exploited, that has been in turn estimated by a hydrological model proposed in 1996.

INTRODUCTION

The history of the Vajont dam dates back to years '20s and it is dramatically known because of disaster occurred on October 9th, 1963, at 10:39 pm, which caused nearly 2000 deaths and derangement of entire towns as Longarone, Erto and Casso.

Actually, waters flowing through the Vajont creek had been used for centuries well before the dam construction. Official documents are found since the 14th century. But it was in 1948 that a modern plan was developed to integrate Vajont water resources with those flowing in Piave river and in Boite as well as Maè and Val Gallina creeks. In 1957, this plan was called "Grande Vajont", literally in English: big Vajont. The plan was mainly aimed to hydropower purpose and it included the design of the now well famous dam, with a height of 266 m and a effective storage of 175 Mcm. The entire water supply scheme was supposed to exploit once an a half times the amount of water withdrawn by the plants of the entire upper Piave valley.

Unfortunately, due to the dramatic event, the scheme has never been completed and operated.

Also for that, the history of Vajont dam has been very widely discussed with respect to causes, responsibility, legal conflicts, etc., related to the disaster, but a very little has been told about the hydrological potential which has not been used because of the impossibility of exploiting water stored in the reservoir.

In this paper, a hydrological analysis was carried out to evaluate the amount of water which could have been used in presence of an active reservoir behind the Vajont dam.

In particular, in order to understand what has been really lost in terms of water supply, annual runoff yields were estimated based on the theory of storage-yield curve, and then, as a comparison, the amount of water which can be used nowadays was analyzed by a stochastic method proposed by (Claps *et alii*, 1996).

Hydrological data used for this study ware daily, monthly, and annual flow recorded on the Vajont creek at Erto Caldaia and at Erto Bindi, two different hydrometric stations very close each other, which operated in different periods. Incidentally, it may be useful to know that the average mean annual flow provided by both the recorded data series, is about 2.15 m^3s^{-1}.

THE STORAGE-YIELD CURVE. THEORY

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 (McMahon & 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 (Rasulo & Rossi, 1980), is $D_{k,\Phi}$as the mean annual runoff over k consecutive years with non-exceedance probability Φ.

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

$$V_{C,\varphi} = max_k\left[kE - kD_{K,\varphi}\right] \qquad (1)$$

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 $V_{C,\Phi}$ 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 & Mein, 1986).

Using the Box-Cox Normal distribution to fit $D_{k,\Phi}$ allows on to derive analytically 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 $(D_k)^{\mu}$ can be derived from these of D (=D1) using the relations:

$$\mu\left(D_K^{\lambda}\right) = \mu\left(D^{\lambda}\right) \quad \sigma\left(D_K^{\lambda}\right) = \sigma\left(D^{\lambda}\right)/\sqrt{K} \qquad (2)$$

with μ and σ as the mean and the standard deviation, respectively.

In a subsequent work (Rasulo & 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

$$V^{*} = E_s - \mu(d) \qquad (3)$$

where E_S is the yield in the dry season and μ(d) is the mean seasonal runoff. In this way,the precedent equation 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

$$V_{S,\Phi} = max_S\left[E_S - d_{S,\Phi}\right] \qquad (4)$$

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

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 (Rasulo & Rossi, 1984; Claps *et alii,* 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 capacity, is determined as

$$V_{\Phi} = max\left[V_{C,\Phi} + V^{*}, V_{S,\Phi}\right] \qquad (5)$$

THE STORAGE-YIELD CURVE FOR THE VAJONT WATER SUPPLY SCHEME

The flow records registered from 1926 through 1951 on the Vajont creek, before the construction of the dam, were used for estimation purpose.

The goodness of fit of the cube-root normal distribution to the annual runoff series is shown in Fig. 1 the normal cumulative probability distribution of $D^{1/3}$ is fitted to data in a normal plot.

Following the procedure descripted in the section above, the global storage-yield curve for the examined scheme was derived.

The carryover storage volume required to cover deficits up to a frequency Φ for the annual yield E was first derived, and the curves obtained by the use of Eq.1 were consequently calculated. They are shown in Fig. 2 for k varying from 1 through 10. In the figure, both E and V are measured in millions of cubic meters.

In order to estimate the deficit of the critical dry seasons it was assumed as dry the period from May to October. Three different water uses ware considered. In particular, one case was referred to agricultural purposes, for which water demand is entirely concentrated in the dry season; another one was considered for civil purpose, where the water consumption is taken as homogenously distributed within the year, and the

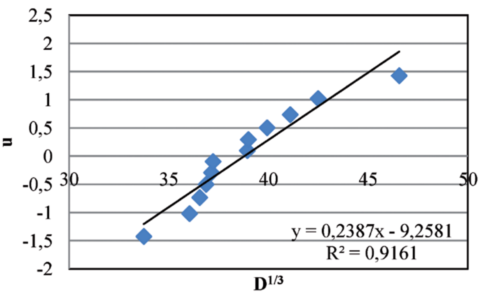

Fig . 1 - Cube – i9root normal distribution of annual runoff

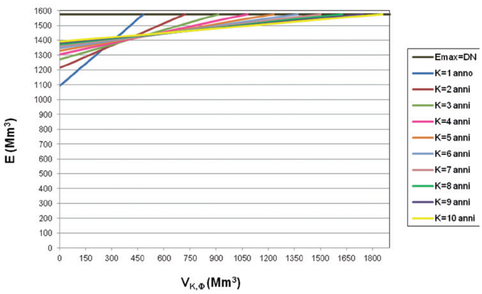

Fig. 2 - Annual Curve E-$V_{k,\Phi}$

third was assumed as a mixing of the first two by assuming a fifty-fifty partition between them.

The relation E-$V_{s,\Phi}$ is shown in Fig. 3 and whereas the global storage-yield curve, as given by equation (5) is shown in Fig. 4.

As a result we could conclude that, according to our estimation, given that the effective storage volume in the Vajont reservoir would have been of 175 Mm^3,

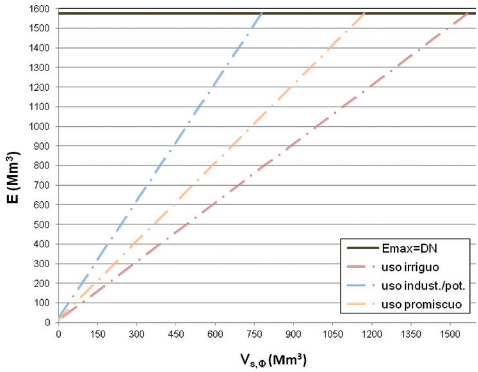

Fig. 3 - Dry Seasons Curve E-$V_{S,\Phi}$

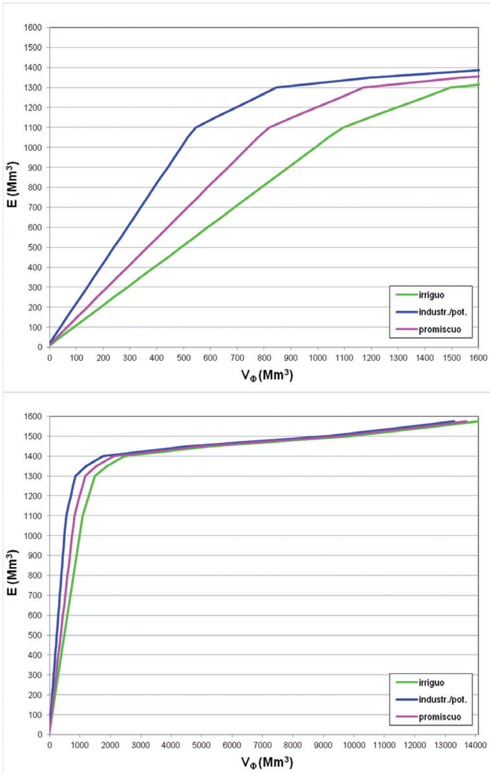

Fig. 4 - Totally STORAGE-YIELD Curve E-V_{Φ}

the annual regulated yield would have varied from 160 Mm^3 for agricultural water supply to 320 Mcm for a civil water use.

It is noteworthy to mention that this result deals with flows of Vajont creek only, while in the so called “grande Vajont” plan, the reservoir was supposed to collect runoff from the Piave river and from the Boite, Maè and Val Gallina creeks, so increasing significantly the amount of water to use.

THE DIVERSION CHANNEL DESIGN METHOD BY CLAPS *ET ALII* (1996)

As the Vajont dam reservoir has never been used for water storage purposes, it is interesting to evaluate the annual yield which can be achieved by simple water withdrawal at its site.

To this aim, let us consider that 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, they 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 (Claps *et alii*, 1996).

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

The analysis made led to the estimation of the quantile $q_{rd,\Phi}=Q_{rd,\Phi}/q$ for given diversion ratio rd and non-exceedance probability Φ, considering the time series of 11 different rivers in southern Italy, with coefficient of variation C_v of the daily data ranging between 1.1 and 6. The outcome was that at the annual scale the variable qrd is Gaussian, regardless of the values of rd and of the river considered.

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

$$\mu[q_{rd}] = (2C_V)(2C_V)^{1/2} + 1/3\,(1-0.1C_v)\ln r_d$$
$$\sigma[q_{rd}] = 0.10 + 0.9\ln r_d \qquad (6)$$

After minor simplifications, the relation obtained between $q_{rd,\Phi}$ and rd was

$$q_{rd,\varphi} = (2C_V)^{1/2} + 1/3\,(1-0.1C_v)\ln r_d + 0.1\,u_\varphi[1+ln r_d]$$

with u_Φ as the normal reduced variate.

It is acknowledged that 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 C_v the mean of qrd approaches 1 for rd slightly greater than 1, whereas relation (7) is not upper-bounded. Nevertheless, this procedure has been applied to the Vajont case in order to provide a first approximation result.

In order to estimate equation (7) parameters for the case here considered, daily flow data recorded on the Vajont at Erto Caldaia in the periods 1941-1946 and 1948-1953 and at Erto Bindi between 1954 and 1958 were used.

Mean, standard deviation and coefficient of variation of available series are reported in Tab. 1.

With regard to return periods T= 5 and 10 years, and consequently to Φ=1/T equal to 0.20 and 0.10 respectively, qrd values have been calculated for rd ranging from 0.5 to 5. They are summarized in Tab. 2.

The relations qrd-rd are also plotted in Fig. 5 and 6 for the Erto Caldaia and Erto Bindi stations, respectively.

As an overall comment, we could point out that if the maximum derivable discharge is of the order of the mean annual flow, that is about 2.15 m^3s^{-1}, an annual volume of about 60% of the annual runoff could be used. Whereas, this last percentage increases to about 70% if the design discharge is doubled. On the other hand, no further significant advantage is achieved even if the maximum derivable discharge is consistently increased. Therefore, in absence of water storage in the reservoir, the amount of water which can be used is nearly 40-50 million of cubic meters, much less than 350 Mm^3, which would have been exploited by the use of the reservoir in case of withdrawal for civil purposes.

CONCLUSIONS

In this paper a study on the hydrology of Vajont creek is presented. In particular, attention was given to estimate the amount of water which has not been used because of the fact that the reservoir ended its operation after the well known disaster occurred in 1963.

This has been done by using a storage-yield curve

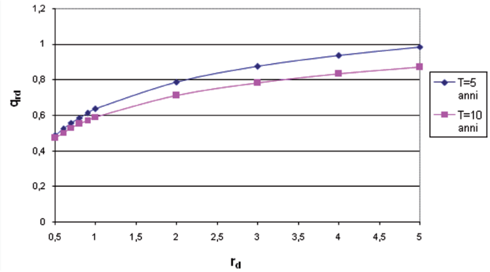

Fig. 5 - Curves of qrd vs. rd for the Vajont river at Erto Caldaia with different non exceedance probabilities

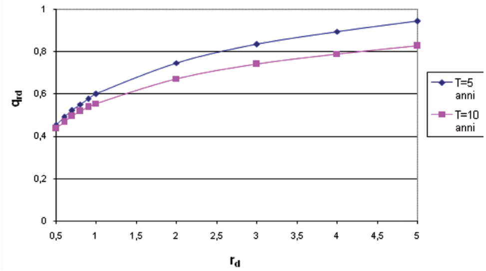

Fig .6 - Curves of qrd vs. rd for the Vajont river at Erto Bindi with different non exceedance probabilities

VAJONT at ERTO CALDAIA Periods 1941-1946 and 1948-1953			VAJONT at ERTO BINDI Period 1954-1958			VAJONT at ERTO CALDAIA & ERTO BINDI Periods 1941-1946 and 1948-1958		
$\mu(Q)$	$\sigma(Q)$	CV (Q)	μ (Q)	σ (Q)	CV (Q)	μ (Q)	$\sigma(Q)$	CV (Q)
2,13	2,05	0,97	2,17	2,33	1,07	2,14	2,14	1,00

Tab. 1 - Statistical parameters of daily flow data series

	r_d	0,5	0,6	0,7	0,8	0,9	1	2	3	4	5
q_{rd}	Erto Caldaia T=10 anni	0,48	0,52	0,56	0,59	0,61	0,63	0,79	0,87	0,94	0,98
	Erto Caldaia T=5anni	0,47	0,50	0,53	0,55	0,57	0,59	0,71	0,78	0,83	0,87
	Erto Bindi T=10 anni	0,45	0,49	0,52	0,55	0,58	0,60	0,75	0,83	0,89	0,94
	Erto Bindi T=5 anni	0,44	0,47	0,49	0,52	0,54	0,55	0,67	0,74	0,79	0,83
	Erto Bindi & Erto Caldaia T=10 anni	0,47	0,51	0,55	0,58	0,60	0,62	0,77	0,86	0,92	0,97
	Erto Bindi & Erto Caldaia T=5 anni	0,46	0,49	0,52	0,54	0,56	0,58	0,70	0,77	0,82	0,86

Tab. 2 - qrd-rd values as estimated from equation (7) by daily flow data recorded at Erto Caldaia and Erto Bindi

theory, which allowed us to estimate in a range between 160 and 320 Mm^3 the amount of water usable after reservoir regulation, in the very conservative case of a water supply scheme including the Vajont creek only, and excluding the other creeks which should have been connected to the reservoir.

The study was also devoted to estimate the annual amount of water that nowadays can actually be withdrawn. To this aim, a method proposed by Claps *et alii* (1996) was used. As a result, we demonstrated that, in this case, no more than about 60 Mm^3 can be exploited.

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