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Assessment of hydropower potential in small karst catchments: the case of the Rocche Plateau, Central Italy

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Abstract. Estimation of flow duration characteristics is key in assessing hydropower potential in natural catchments. However, such analysis is not usually straightforward, especially in ungauged sites and/or in complex catchment areas. In this study we evaluate the feasibility of revamping of a small hydroelectric power plant, located in a karst plateau in central Italy, by assessing the hydropower potential of its feeding surface and subsurface stream network. A thorough analysis of runoff processes occurring in the examined area is carried out in order to corroborate regionalization studies based on measured specific flows in neighboring homogeneous basins. The results show an appreciable availability of water resources to be exploited for hydropower purposes.

1 Introduction

The assessment of flow regime in natural streams is essential for a proper management of water resources. Flow duration curves have proven to be useful for e.g. water supply and hydropower design studies, where it is important to define the variability of flows in natural catchments. The most reliable means for the determination of a flow duration curve is to use actual stream flow data measured at the point of interest. However, regionalization techniques from a gauged to an ungauged location are more often applied in practice, although with a certain degree of uncertainty, since flow records are not always available.

This paper analyzes, by means of a case study in Central Italy, the importance of performing detailed analyses of runoff generation and propagation processes as a support to the results of regionalization techniques for a comprehensive assessment of the hydrologic regime and hydropower potential in complex catchments.

2 Study area overview

The Stiffe spring flows out from a fracture in the limestone mass near the homonymous village of Stiffe, L'Aquila (Italy). This water, originating from several waterfalls, reaches

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the downstream valley, where, after being channeled, it is used for industrial purposes. This spring deserves a particular mention in relation to the peculiar orography and geology of the upstream catchment of the Rocche Plateau, which, as shown by Perrone [1], would have become a lake of about 10 km^2 if water had not breached through the fractures in the limestone layers, creating a characteristic sinkhole system in the valley. Indeed, the endorheic Rocche Plateau is a closed drainage basin, with no direct outflow to external water bodies, which converges to a sinkholes area in Saline Camp that connects it, through a karst system with a 600 m drop, to the Stiffe spring (Figure 1).

3 Previous surveys and studies for the determination of the mean annual flow

In this section we report the results of existing studies and surveys, with the first ones dated back to the late XIX century, aimed at the determination of the mean annual flow for the Rocche Plateau catchment.

3.1 First flow measurements in Stiffe spring (1898-1899)

The first isolated flow measurements recorded in Stiffe spring took place at the end of the XIX century, as follows: June, 2 1898: Q_{St}=122 l/s; August, 28 1898: Q_{St}=80 l/s; November, 18 1898: Q_{St}=227 l/s; August, 19 1899: Q_{St}=68 l/s.

3.2 Surveys and studies conducted by the Mezzogiorno Development Fund (1983)

In a study conducted in the early 1980s, the Mezzogiorno Development Fund [2] estimated the following annual flows in Stiffe spring: maximum flow $Q_{St,max}$=900 l/s, minimum flow $Q_{St,min}$=10 l/s and mean flow Q_{St}=200 l/s.

Differential flow measurements indicated that the runoff generated in the sinkholes area of the Plateau contributed to about 70% of the flow registered in Stiffe spring. The remaining part was considered to be attributable to the widely diffused conduits dug out into the limestone rock mass, with one of the main entrance in the Pozzo Caldaio sinkhole.

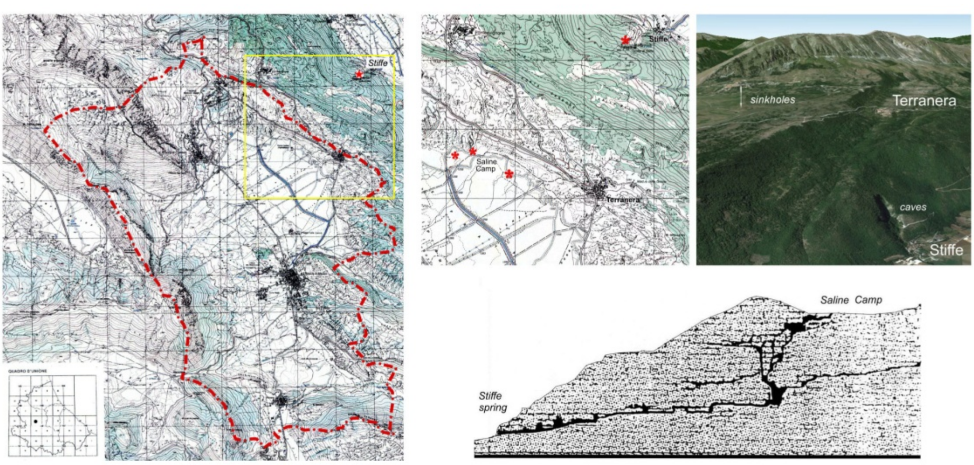

Fig. 1. Overview of the Rocche Plateau and the karst system in Saline Camp.

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3.3 Regionalization study led by ENEL and University of L'Aquila (1987)

The study [3] was focused on the identification of potential locations for hydropower generation in mountain areas of regional basins between Aso and Trigno Rivers. After a preliminary phase, only few sites were considered for further detailed geological, hydrogeological and hydraulic investigations, with the aim of assessing their hydropower potential. For Stiffe, which was one of these selected locations, the mean annual producible power was estimated by means of "artificial" flow duration curves. The procedure consisted in the reconstruction of the mean annual isohyets and in the assessment of annual flow based on runoff coefficients calculated from water balances studies performed in regional stream gauge stations (river basins located between Chienti and Trigno Rivers). Long-term time series of mean annual flow measured in 61 gauged stations and geomorphologic features of the related drainage areas (extension, mean altitude, effective drainage area) were the main input data. A power-law relationship of specific flow to drainage area was found by means of the method of least squares, as follows:

$$q = a \cdot A^{-b} = 42.5 \cdot A^{-0.26} \tag{1}$$

where q is the specific flow [l/s km^2] and A the drainage area.

Based on the geological characteristics of the endorheic Rocche basin, it was possible to consider about 50% of the total drainage area (A=52 km^2) as non-contributing to the flow of Stiffe spring. Therefore, with an effective area of about 30 km^2, the calculated specific flow was q=17.5 l/s km^2 and then the mean flow expected at the sinkholes and, consequently, at Stiffe spring was estimated to be Q_{sink}=526 l/s and Q_{St}=750 l/s, respectively (assuming that about 70% of the flow observed in Stiffe may be attributable to the flow entering the upstream sinkholes, according to [2]).

3.4 Regionalization study for ENEL-VALOREN EU Project (1992)

In this project [4], given the peculiarity of the area, the number of stream gauge stations used for the regionalization of the specific flow was restricted to 6 sites (Table 1) located in the neighboring Aterno, Tasso and Sagittario river basins, which were considered to be part of the same homogeneous hydrological region. With this limited dataset, the regional relationship obtained for the specific flow was the following:

$$q = a \cdot A^{-b} = 27.15 \cdot A^{-0.2291} \tag{2}$$

Adopting the exponent of the function as an homogeneity index, Eq. (2) could be referred to the average specific flow expected in the nearest stations of Treponti, L'Aquila and Molina (Table 1), as shown in Eq. (3):

$$q = 26.77 \cdot A^{-0.2291} \textit{ (Treponti)};\ q = 36.77 \cdot A^{-0.2291} \textit{ (L'Aquila)};\ q = 21.72 \cdot A^{-0.2291} \textit{ (Molina)} \tag{3}$$

Table 1. Mean annual specific flows measured in the stations of the Aterno River basin.

River	*Station*	*Drainage area [km^2]*	*Specific flow [l/s km^2]*	*Permeable part [%]*
Aterno	Treponti	114	9.04	34
Aterno	L'Aquila	531	7.31	46
Aterno	Molina	1303	4.20	60
Tasso	Scanno	80	8.62	97
Sagittario	Villalago	108	12.54	89
Sagittario	Capo Canale	599	11.60	93

In this case, assuming for the scale factor the minimum value (21.72) between the three calculated in Eq. (3), the specific mean annual flow for the Rocche basin was estimated to be q=10 l/s km^2, i.e. an expected mean annual flow at the sinkholes Q_{sink}=300 l/s and at Stiffe spring Q_{St}=420 l/s.

4 Analysis of runoff processes occurring in the Rocche Plateau

Analysis of runoff processes occurring in the examined basin is carried out herein in order to corroborate the results shown in the previous section (and specifically, the relationship existing between Q_{sink} and Q_{St}) in order to use recent flow measurements to derive a flow duration curve for the study area.

Depending on actual data availability and accuracy requirements of the results, the runoff processes can be modeled at different levels of detail, from practical formulas to complex representations of runoff generation and propagation in the catchment.

4.1 Estimation of runoff using Iszkowski formula

In the literature many formulas exist for relating the expected streamflow to the pluviometric regime of the tributary catchment. An example is the simple Iszkowski formula [5] which relates the streamflow Q to the mean annual rainfall depth h:

$$Q = \lambda \cdot m \cdot h \cdot A = \psi \cdot h \cdot A \tag{4}$$

where λ and m can be expressed by a coefficient of proportionality, i.e. the runoff coefficient ψ, as a function of the ratio of impervious drainage area A_{imp} to the total drainage area A, as follows:

$$\psi = 0.315 \cdot \left(\frac{A_{imp}}{A} \right)^{0.393} \tag{5}$$

Considering the rain gauge station of Rocca di Mezzo, with a registered mean annual rainfall of about 1000 mm, the application of Eq. (4) and (5) for the Rocche Plateau catchment led to an estimated annual flow Q_{sink}=389 l/s.

4.2 Estimation of runoff using SCS-CN method

With the aim of calculating a probable high-frequency runoff in the study area, the SCS-CN method [6] was used for estimating an expected low return period flow of about 1.5÷2 years. The SCS-CN model combines infiltration losses with surface storage by Eq. (6):

$$Q_p = \frac{(P - I_a)^2}{P - I_a + S} \tag{6}$$

where Q_p [mm] is the accumulated runoff, P [mm] is the rainfall depth of given return period, I_a [mm] is the initial abstraction, which includes surface storage, interception and infiltration prior to runoff (if $P<I_a$, $Q_p=0$), and S [mm] is the potential maximum retention, given by:

$$S = 254 \cdot \left(\frac{100}{CN} - 1 \right) \tag{7}$$

where the Curve Number, CN [dimensionless, ranging from 0 to 100], is derived from data reflecting land cover, hydrologic soil group and antecedent soil moisture condition (AMC).

Therefore, when $P>I_a$, the runoff generated by a rainfall event of given return period (1.5÷2 years, in this case) can be estimated as:

$$Q = \frac{Q_p \cdot A}{t_c} \tag{8}$$

where t_c is the time of concentration of the basin.

4.2.1 CN parameter estimation

Area-weighted *CN* for the examined catchment was calculated using a GIS procedure described in Leopardi and Scorzini [7]. This consists in combining information from the regional land cover map and the hydrologic soil group map, which is produced by assigning a particular hydrologic soil group (A, B, C or D) depending on the soil's minimum infiltration rate. Subsequently, to create a CN map, the hydrologic soil group field from the soil theme and the land use field from the land cover theme are selected for intersection. This operation generates a new polygon shapefile indicating the merged soil hydrologic group and land cover themes. Appropriate *CN* values according to [6] are assigned to each polygon of this new map under the hypothesis of average moisture condition (AMC II).

Data extracted with this procedure were then used to compute the area-weighted *CN* for the Rocche catchment, CN=67. Therefore, by substituting this value in Eq. (7), we obtained S=125.1 mm and an initial abstraction $I_a=0.2\ S$=25 mm, calculated according to the USDA expression [6].

4.2.2 Estimation of time of concentration

Several definitions and methods to compute the time of concentration are in use in the literature. According to [8], it can be defined as the time taken by a water drop to move itself, within an hydraulic path, from the most distant point in the basin until the outlet point. In other words, it can be expressed as a travel time, including surface t_s and channel flow t_{ch}:

$$t_c = t_s + t_{ch} \tag{9}$$

The estimation of t_s is usually affected by large uncertainties related to the complex storage phenomena occurring in natural catchments. Nevertheless, the so-called "velocity method" can be a hydraulically sound way for determining the time of concentration [9]. This method assumes that this parameter can be expressed as the sum of travel times for reach segments along the hydraulically most distant flow path (with segment lengths L_i and average flow velocities V_i):

$$t_c = \sum_i \frac{L_i}{V_i} \tag{10}$$

During field surveys in the study area on February-April 2016, we identified along the main reach in Saline Camp some characteristic cross-sections which were used for flow velocity measurements. Figure 2 shows the localization of the cross-sections and the identification of the different reach segments, with measured average minimum and maximum flow velocities. Based on data of Figure 2, we estimated, by means of Eq. (10), a time of concentration t_c for the examined area ranging from 3.3 to 3.4 hours.

In addition, different practical formulas developed by other authors were applied to the case study for comparison purposes. These included Giandotti [10] and Kirpich [11] formulas (Eq. 11 and 12), which were found coherent with our experimental result:

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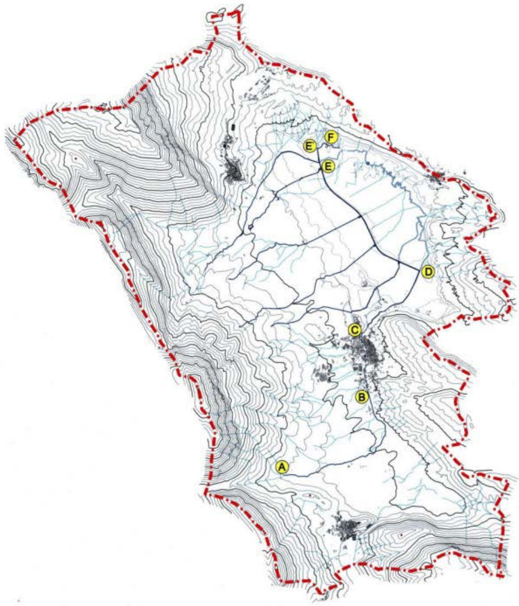

Reach	L_i [m]	Δq [m]	i_i [m/m]	V_{min} [m/s]	V_{max} [m/s]
A - B	3.129	65,5	0,0209	3,0	3,5
B-C	1.142	5,5	0,0048	2,5	3,0
C-D	1.664	13,0	0,0078	2,0	2,5
D-E	2.859	2,0	0,0007	0,2	0,2
E-E'	265	1,0	0,0038	0,5	0,7
E'-F	410	4,5	0,0110	2,0	2,5

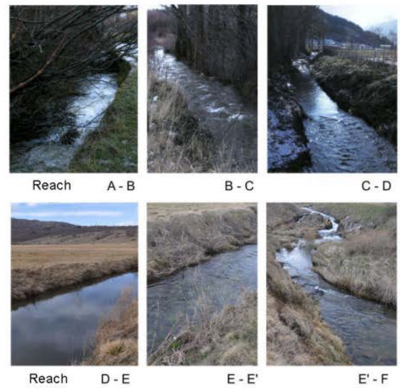

Fig. 2. Identification of the reach segments used for flow velocity measurement in Saline Camp.

$$t_c = \frac{4\sqrt{A} + 1.5L}{0.8\sqrt{H_0}} = 3.9 \; hours \tag{11}$$

$$t_c = 0.000325 \cdot L^{0.77} \cdot s^{-0.385} = 3.5 \; hours \tag{12}$$

with L=total length of the main channel, H_0=difference between the mean basin elevation and the outlet elevation and s=mean slope.

4.2.3 Expected flow determination

The expected flow in Saline Camp sinkholes area was then determined by means of Eq. (8) using the parameters defined above and an accumulated runoff P of about 27÷29 mm calculated for a 1.5÷2 years return period rainfall event with a duration equal to the time of concentration of the basin. The resulting Q_{sink} ranged around 340÷360 l/s.

4.3 Recent in situ flow measurements in the Rocche Plateau and Stiffe spring

The results shown in the previous section were integrated with a streamflow measurement campaign (February-April 2016) in the Rocche Plateau and specifically in Saline Camp sinkholes area and in the spring in Stiffe cave.

First, we checked the actual functioning of the sinkholes system, since during the 1960s land reclamation and drainage works were carried out to solve the problem of frequent water stagnation phenomena occurring in the Plateau. Consequently, all the minor streams flowing in the Plateau towards Pozzo Caldaio sinkhole (now fed only by some remaining minor streams) were drained into a main channel which ended in Saline Camp. Here, during our surveys, five sinkholes were found to be active.

In addition, stream flow measurements were performed on February 23, March 15 and April 6 2016 in the three control cross-sections shown in Figure 4, on Rio Gamberale (XS1), Rio Caporitorto (XS2) and upstream from the sinkholes area (XS3). Cross-sections

1 and 2 were identified by two broad crested weirs (Figure 3), whose discharge rating curve was given by:

$$Q_{1,2} = 0.385 \cdot L_w \cdot h \cdot \sqrt{2g \cdot h} \tag{13}$$

where 0.385 is the weir coefficient, L_w is the weir length and h is the head above weir crest. Section 3 was located upstream from sinkhole 1 (Figure 3) in Saline Camp, at the end of a straight 120 m long reach segment. Here, we installed a trapezoidal Cipolletti weir, whose discharge rating curve was expressed by Eq. (14):

$$Q_3 = Q_{sink} = 0.415 \cdot L_w \cdot h \cdot \sqrt{2g \cdot h} \tag{14}$$

Average flows measured in the three control sections during the different field surveys are reported in Table 2.

During these surveys we also performed parallel flow measurements by means of an electronic hydrometer located on a weir in the Stiffe cave, in order to validate the aforementioned relationship found by the Mezzogiorno Development Fund [2] between the flow observed in Stiffe spring and in Saline Camp. Spring discharges registered in Stiffe Q_{St} (averaged over a 5-days period for each survey) are shown in Table 2, together with the related flows observed in Saline Camp, Q_{sink}. The calculated ratio Q_{sink}/Q_{St} confirmed the results obtained by the Mezzogiorno Development Fund [2], i.e. water flowing to the sinkholes area in the Rocche Plateau contributes to about 60÷70% of the flow discharging out from Stiffe spring.

Table 2. Recent field flow measurements in the Rocche Plateau: in the sinkholes area of Saline Camp and Stiffe spring.

Survey	*Measured flow [l/s]*				Q_{sink}/Q_{St}
	Q_1	Q_2	$Q_3 = Q_{sink}$	Q_{St}	
Feb, 23 2016	250	138	400	639	0.63
Mar, 15 2016	290	156	460	724	0.63
Apr, 6 2016	144	82	234	335	0.70

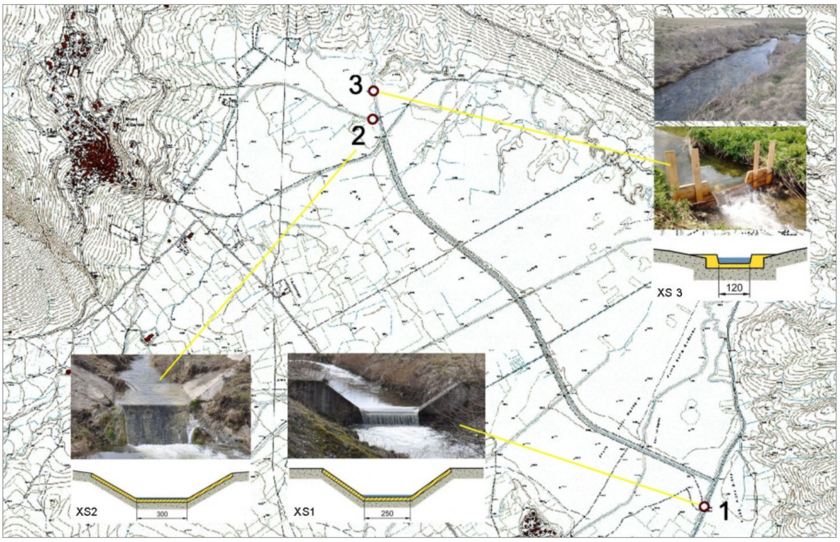

Fig. 3. Localization of the control sections used for flow measurement in Saline Camp.

5 Assessment of hydropower potential and conclusions

In order to estimate the availability of water usable for electricity generation, i.e. to assess the hydropower potential of the study area, it was essential to derive a flow duration curve for Stiffe spring. This could be easily accomplished by using flow records at the gauge station in Stiffe cave. However, such time series was limited to the periods 1995,1999, 2003÷2008 and 2014÷2015; in addition, the years 2003, 2006, 2007 and 2014 were excluded due the large amount of missing data, resulting in an available 6-years long time series.

It is clear that a flow duration curve based on a short record would be an unreliable tool for decision making. Nevertheless, in this case we could take advantage, for validation purposes, of the results obtained from the analysis of runoff processes and from the verified relationship existing between the flow generated in the Rocche Plateau and the discharge flowing out from Stiffe spring. Therefore, we used the available flow records to obtain information on flow characteristics in the examined location. Figure 4a reports the flow records for the different years, together with that of the mean hydrological year.

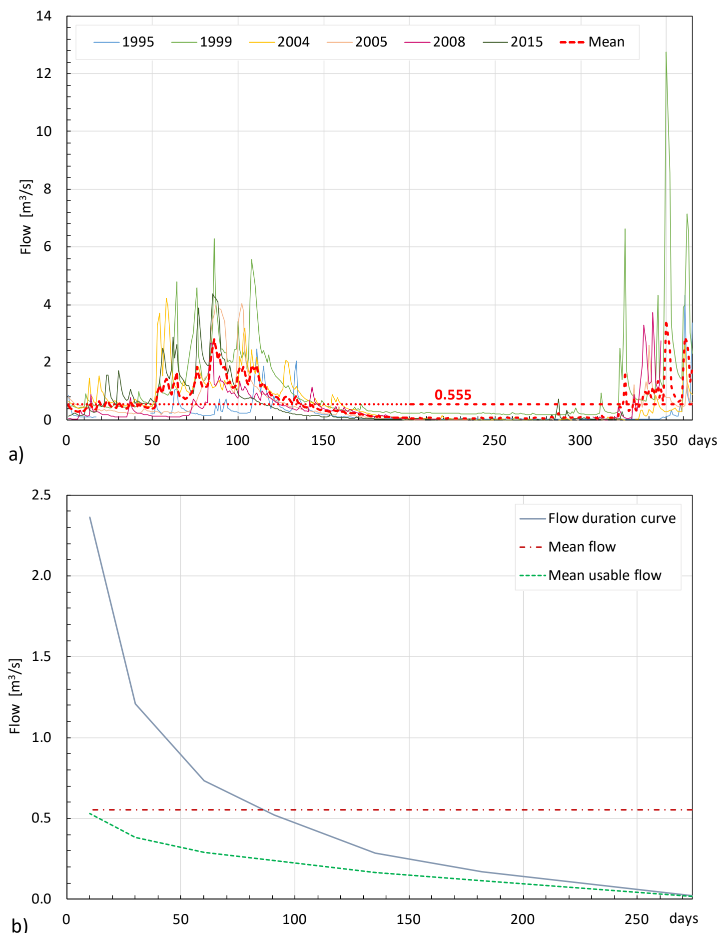

Fig. 4. a) Flow time series measured in Stiffe spring; b) Flow duration curve and mean usable flow curve derived from flow measurements in Stiffe spring.

Despite the limited sample and the instable flow pattern, it was possible to recognize a well defined hydrological regime, characterized by significant flow values in spring (March, April) and fall (November, December) and a mean annual flow for the mean hydrological year equal to Q_{St}=555 l/s.

In conclusion, by comparing this value to the calculated runoff expected in the sinkholes area of Saline Camp, Q_{sink}=340÷390 l/s (depending on the selected approach) and by verifying the ratio $Q_{sink} / Q_{St} \approx 0.7$, it was possible to prove the reliability of the result obtained by using the short flow time series recorded in Stiffe.

Therefore, based on these data, the flow duration curve and mean usable flow duration curve shown in Figure 4b were finally determined and used as fundamental input data for the design of the hydroelectric power plant in Stiffe.

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