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ANALYSIS OF LONG-TERM (1878-2004) MEAN ANNUAL DISCHARGES OF THE KARST SPRING FONTAINE DE VAUCLUSE (FRANCE)

ANALIZA DOLGOČASOVNEGA (1878-2004) POVPREČNEGA LETNEGA PRETOKA KRAŠKEGA IZVIRA FONTAINE DE VAUCLUSE (FRANCIJA)

Ognjen BONACCI[1]

Abstract UDC 556.36(44)

Ognjen Bonacci: Analysis of long-term (1878-2004) mean annual discharges of the karst spring Fontaine de Vaucluse (France)

Statistical analyses have been carried out on a long-term (1878-2004) series of mean annual discharges of the famous karst spring Fontaine de Vaucluse (France) and the mean annual rainfall in its catchment. The Fontaine de Vaucluse is a typical ascending karst spring situated in the south-eastern region of France. The spring has an average discharge of 23.3 m^3/s. The average annual rainfall is 1096 mm. Its catchment area covers 1130 km^2. Using the rescaled adjusted partial sums (RAPS) method the existence of next five statistically significant different sub-series was established: 1) 1878-1910: 2) 1911-1941; 3) 1942-1959: 4) 1960-1964; 5) 1965-2004. The different spring discharge characteristics during this long period (1878-2004) can be caused by natural climatic variations, by anthropogenic influences, and possibly by climate changes. At this moment it should be stressed that objective and scientifically based reasons for different hydrological behaviour in five time sub-periods could not be found.

Keywords: karst hydrology, mean annual discharges, annual catchment rainfall, karst spring, Fontaine de Vaucluse, France.

Izvleček UDK 556.36(44)

Ognjen Bonacci: Analiza dolgočasovnega (1878-2004) povprečnega letnega pretoka kraškega izvira Fontaine de Vaucluse (Francija)

V prispevku predstavim statistično analizo časovne vrste povprečnega letnega pretoka in letnih padavin v zaledju slavnega izvira Fontaine de Vaucluse v Franciji. Fontaine de Vaucluse je tipični kraški izvir pri katerem voda priteka iz velike globine. Nahaja se v jugovzhodni Franciji. Povprečni pretok izvira je 23,4 m^3/s. Povprečna količina letnih padavin v zaledju, ki meri 1130 km^2, je 1096 mm. Z uporabo metode umerjenih delnih vsot (RAPS) smo določili pet statistično pomembnih različnih podobdobij: 1) 1878-1910: 2) 1911-1941; 3) 1942-1959: 4) 1960-1964; 5) 1965-2004. Vzrokov za različne pretoke preko celotnega obdobja (1878-2004) je lahko več; npr. klimatske spremembe in antropogeni vplivi. V tem trenutku moramo poudariti, da objektivne znanstvene razlage za različne hidrološke značilnosti v petih podobdobjih še ne poznamo.

Ključne besede: hidrologija krasa, povprečni letni pretok, količina letnih padavin, kraških izvir, Fontaine de Vaucluse, Francija.

INTRODUCTION

The Fontaine de Vaucluse represents one of the most famous and most important karst springs on the Earth. It is located in the south-eastern karst region of France (Figure 1), about 30 km eastward of the town of Avignon. It represents the only flow exit from the 1500 m thick karst aquifer of Lower Cretaceous limestone (Blavoux *et al.*, 1992b). The karst system of the Fontaine de Vaucluse is characterised by an approximately 800 m unsaturated zone. Emblanch *et al.*, (1998) and Emblanch *et al.*, (2003) stressed important role of this zone for the transformation of rainfall into runoff. The Fontaine de Vaucluse karst spring catchment area is estimated to be 1130

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km^2 (Cognard-Plancq *et al.*, 2006a; 2006b). The average catchment altitude is 870 m a. s. l. The average annual air temperature of the catchment is 9,6 °C.

Fig. 1: Location map of karst spring Fontaine de Vaucluse.

The Fontaine de Vaucluse is typical ascending karst spring (Michelot & Mudry 1985; Blavoux *et al.*, 1991/1992; 1992a). Its limestone channel ranges in diameter from 8 to 30 m (Mudry & Puig, 1991). The lowest depth reached by diver was -308 m below the gauging station datum of 84.45 m a. s. l. This depth is still not at the bottom of the ascending karst channel.

The maximum water level measured at the gauging station was 24.10 m above the datum, the minimum was a few centimetres below the datum. The rate of the maximum discharge of the spring has never been precisely measured, but it is estimated that it cannot exceed 100 m^3/s (Blavoux *et al.,* 1991/1992; 1992a). Cognard-Plancq *et al.* (2006b) state that maximum spring discharge varies between 100 and 120 m^3/s. This surmise identifies a karst spring with limited discharge capacity (Bonacci 2001). The historical minimum discharge is 3.7 m^3/s (Blavoux *et al.,* 1991/1992).

Every karst aquifer has complex hydrodynamic behaviour. The Fontaine de Vaucluse karst system responses to rainfall quite rapid in comparison with the large recharge area. The peak of hydrograph occurred 24 to 72 hours after the rainfall events. The spring water level and discharge recessions are slow, which can be explained by the existence of a large storage capacity of the aquifer (Cognard-Plancq 2006b).

The primary objective of the investigation was to define sub-periods with different hydrological behaviour of the Fontaine de Vaucluse karst spring during 127 years period (1878-2004), analysing time series of mean annual spring discharges. It should be the first step in explanation of this extremely important and interesting phenomenon.

ANALYSIS OF CATCHMENT ANNUAL RAINFALL TIME SERIES

The climate in the catchment is Mediterranean. Rainfall distribution over the year as well as over the large spring catchment is irregular. Intensive and significant rainfall events occurred during autumn and spring, while summer and winter are generally dry. Interannual fluctuations of rainfall on the catchment are very high.

In order to define an historical homogeneous catchment rainfall database Cognard-Plancq *et al.,* (2006b) used six rainfall gauging stations. The mean elevation of these stations is 445 m a. s. l., while the mean elevation of the spring catchment is 870 m a. s. l. Transformation of the measured monthly rainfall to the altitude of 870 m a. s. l. was made. The average annual catchment rainfall in the 1878-2004 period is 1096 mm, while the minimum and maximum observed values were 641 mm (1953) and 1740 mm (1977) respectively.

Data series with linear trend line of the annual rainfall on the Fontaine de Vaucluse catchment for the period 1878-2004 are presented in Figure 2. The increasing trend of the catchment rainfall of 1.045 mm per year is not statistically significant but should not be neglected in further analyses.

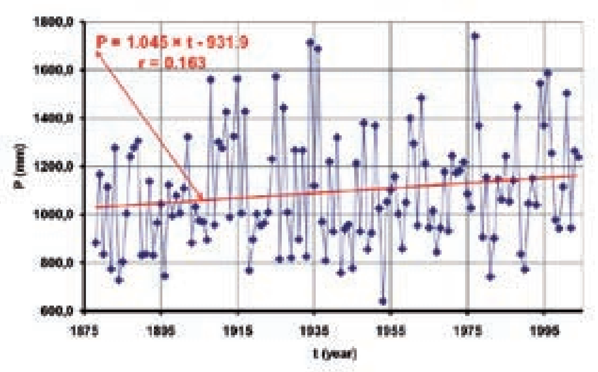

Fig. 2: Time data series of annual rainfall P at the Fontaine de Vaucluse catchment with trend line for the period 1878-2004.

ANALISIS OF MEAN ANNUAL DISCHARGES TIME SERIES

Data series with linear trend line of the mean annual spring discharges Q for the period 1878-2004 are presented in Figure 3. The decreasing trend of the mean annual discharges of 0.0468 m^3/s per year is not statistically significant. The average annual catchment discharge in the 1878-2004 period was 23.3 m^3/s, while the minimum and maximum observed values were 7.61 m^3/s (1990) and 53.4 m^3/s (1915) respectively.

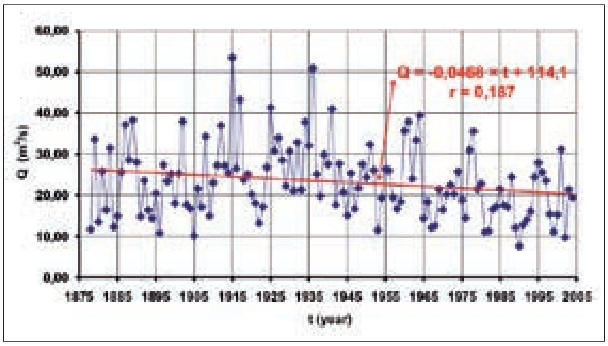

Fig. 3: Time data series of mean annual discharges Q at the Fontaine de Vaucluse karst spring with trend line for the period 1878-2004.

It should be stressed that annual catchment rainfall during the same period has an increasing trend. In Figure 4 linear regression between the mean annual the Fontaine de Vaucluse discharges Q and the Fontaine de Vaucluse catchment annual rainfall P is shown. The linear correlation coefficient is only 0.713, which is relatively low. A special problem is that the regression line cut abscissa line at 222 mm of annual rainfall P, which is relatively low value. Explanation of so unusual rainfall-runoff relationship can be found in fact that accuracy of discharges and rainfalls are not very high, and maybe the value of catchment area of 1130 km^2 is not precisely defined.

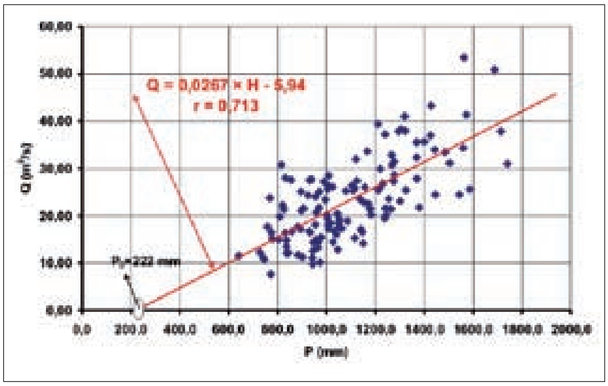

Fig. 4: Linear regression between the mean annual the Fontaine de Vaucluse discharges Q and annual the Fontaine de Vaucluse catchment rainfall P.

It should be stressed that determination of exact catchment area in karst is one of the greatest and very often unsolved problems. This may be the case with the catchment of the Fontaine de Vaucluse spring. The weak relationship between runoff and rainfall means that some others factors (probably: air temperature, groundwater level, interannual rainfall distribution, changes of catchment area during the time, preceding soil wetness, anthropological influences, climate change etc) have influence on it.

A time series analysis can detect and quantify trends and fluctuations in records. In this paper the Rescaled Adjusted Partial Sums (RAPS) method (Garbrecht & Fernandez 1994) was used for this purpose. A visualisation approach based on the RAPS overcomes small systematic changes in records and variability of the data values themselves. The RAPS visualisation highlights trends, shifts, data clustering, irregular fluctuations, and periodicities in the record (Garbrecht & Fernandez 1994). It should be stressed that the RAPS method is not without shortcomings. The values of RAPS are defined by equation:

$$RAPS_k = \sum_{t=1}^{k} \frac{Y_t - \overline{Y}}{S_Y}$$

where $\overline{Y}$ is sample mean; is standard deviation; n is number of values in the time series; (k=1, 2…,n) is counter limit of the current summation. The plot of the RAPS versus time is the visualisation of the trends and fluctuations of Y_t.

Time data series of Rescaled Adjusted Partial Sums (RAPS) for mean annual spring discharges in the period 1878-2004 are given in Figure 5. Therefore, the total data

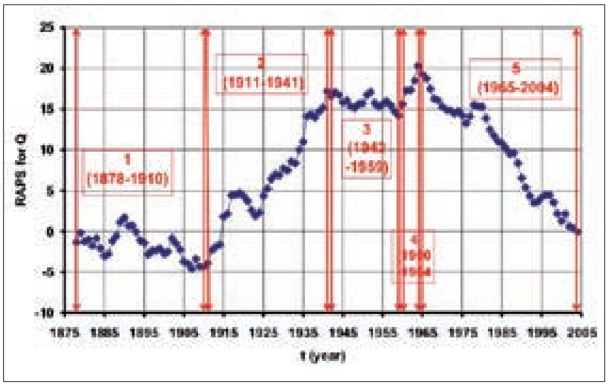

Fig. 5: Time data series of the Rescaled Adjusted Partial Sums (RAPS) for mean annual discharges Q for the period 1878-2004 with designated next five sub-periods: 1) 1878-1910; 2) 1911-1941; 3) 1942-1959; 4) 1960-1964; 5) 1965-2004.

series was divided into next five subsets: 1) 1878-1910; 2) 1911-1941; 3) 1942-1959; 4) 1960-1964; 5) 1965-2004. Cognard-Plancq *et al.,* (2006a; 2006b) defined the same five stationary sub-periods using different methodology.

Five time data sub-series of the Fontaine de Vaucluse karst spring mean annual discharges Q with trend lines for five defined sub-periods are shown in Figure 6. In order to investigate statistically significant differences between the averages of five time sub-series for Q and P the t-test was used. The neighbouring averages of discharges for all five sub-series are statistically significant at the 5 % and even more 1 %. At the same time the neighbouring sub-series averages of the catchment rainfall are not statistically significant.

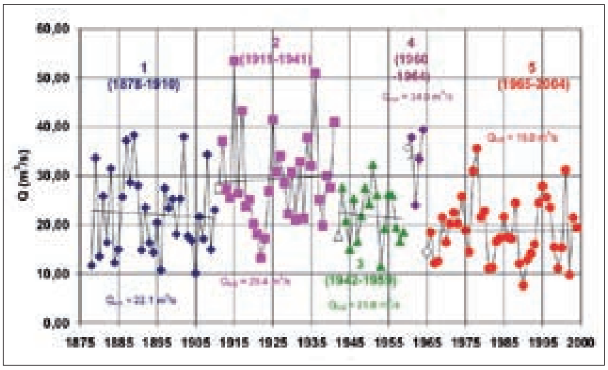

Fig. 6: Five time data sub-series of the Fontaine de Vaucluse karst spring mean annual discharges Q with trend line for five defined sub-periods.

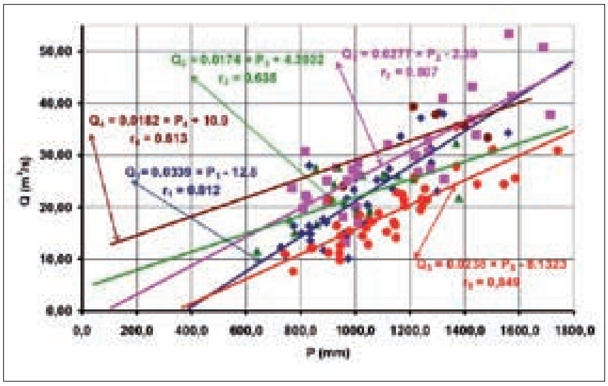

Fig. 7: Linear regressions between mean annual discharges Q and annual catchment rainfall P defined for five different sub-periods.

Figure 7 shows five linear regressions between mean annual discharges Q and annual catchment rainfall P defined for five different sub-periods. It can be seen that linear correlation coefficients for all sub-series, except for third (1942-1959) and fourth (1960-1964) ones are higher than the linear correlation coefficient for whole time series.

CONCLUSION

The rescaled adjusted partial sums (RAPS) method established existence of next five statistical, and hydrological significant different time sub-series: 1) 1878-1910: 2) 1911-1941; 3) 1942-1959: 4) 1960-1964; 5) 1965-2004. Variations in the Fontaine de Vaucluse karst spring hydrological regime during relatively short period of 127 years are very strong and cannot be neglected. Anthropogenic impacts are probably the main cause of such behaviour of the mean annual spring discharges time series analysed, but the natural pattern of drought and wet years is also possible. Land-use changes and overexploitation of surface water and groundwater at the spring catchment on hydrological regime of the Fontaine de Vaucluse spring certainly exists. Their exact quantification during analysed period is extremely questionable due to missing of many parameters. Strict division of natural and anthropogenic influences on the hydrological regime is hardly possible.

The significant changes of spring discharge characteristics during 127 years long period (1878-2004) can be caused by natural climatic variations, by anthropogenic influences, and possibly by climate changes. It is extremely hard, but at the same time extremely practically and theoretically important, to find correct and scientifically based explanation of this phenomenon.

Cognard-Plancq *et al.,* (2006a) consider that rainfall-runoff data have shown the large impact of climatologic variations on the hydrogeological system. They conclude that the underground storage zone is an important influence on karst spring outflow, which depends on rainfall amount over 2 or 3 previous years. Investigations made in this paper do not confirm this statement.

Correct answers on many questions dealing with changes in hydrological-hydrogeological regime of the Fontaine de Vaucluse karst spring cannot be done using only annual data. Some processes can be explained measuring and analysing climatologic, hydrologic, hydrogeological and geochemical interactions in shorter as well as larger time increments. The problem is that most of parameters required for these analyses were not monitored in the past.

More accurate and precise delineation and definition of the Fontaine de Vaucluse spring catchment should be done. It is possible that its catchment area changes as a function of groundwater level. This means that groundwater level measurements in deep piezometers should be organized across the catchment. The second task which should be considered in further analyses is detailed analysis of influence of rainfall distribution during the year on the spring runoff. This can have very strong influence on the relationship between rainfall and runoff, especially in karst areas.

It can be stated that main dilemmas about variations of mean annual discharges of the Fontaine de Vaucluse karst spring during 127 years long period have not been solved. They should be explained using number of different procedures and climatic as well as other indicators, and performing further detailed measurements and analyses. The paper presents the need for interdisciplinary analyses incorporating several approaches and techniques. For the sustainable development and the protection of such valuable water resource it is very important to establish prerequisites for the definition of a causes and consequences of its hydrological changes.

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