XXXVIII
IAH Congress

Groundwater Quality Sustainability
Krakow, 12–17 September 2010

Extended Abstracts

Editors:
Andrzej Zuber
Jarosław Kania
Ewa Kmiecik

University
of Silesia
Press 2010

abstract id: **401**

topic: **1**
Groundwater quality sustainability

1.1
Evaluation and management of groundwater — sustainable exploitation

title:

Automatic baseflow separation

author(s): **Radek Vlnas**
Czech Hydrometeorological Institute, Czech Republic, `vlnas@chmi.cz`

keywords: automatic baseflow separation, hydrograph recession, recursive digital filtering

INTRODUCTION

Monthly baseflow values in majority of hydrogeological zones are reported yearly by the CHMI in accordance with the Water Framework Directive (WFD). Information on low flow characteristics provides threshold values for different water-based activities and is required for such water resource management issues as water supply, irrigation, and water quality and quantity estimates. An understanding of the outflow process from groundwater is essential in studies of water budgets and catchment response. The knowledge about baseflow fluctuation is also useful for calibration of hydrological models since baseflow is usually one of the runoff components being simulated and its fluctuation considerably determines the correspondence of measured and calculated stream flow. But, the quality of low flow data is often a limiting factor when analysing hydrograph recessions. Accuracy and frequency of the low flow measurements determine and restrict the process that can be studied. Contemporary development in recession analysis tends to work out automatic and objective methods, which eliminate some of the subjective elements of recession analysis. Use of fixed parameters, some of which might be derived from stream flow records, ensures repeatable and consistent results.

PUBLISHED FILTERS

Baseflow as defined by Hall (1968) is the portion of flow that comes from groundwater or other delayed sources. The gradual depletion of discharge during periods with little or no precipitation makes up the drainage or recession rate. The Boussinesq equation (Boussinesq, 1877) assuming the groundwater storage behavior as a liner reservoir has the form

$$S = kQ \qquad (1)$$

where Q is the discharge, and k a recession constant. In accordance with the Hall's definition Q can be henceforth viewed as baseflow within the presented equations. The equation for the recession curve first derived independently around the 1904 by Maillet (1905) and Horton (1933) can be expressed by

$$Q_t = Q_0 \exp(-t/k) \qquad (2)$$

where Q_t is the discharge at time t, Q_0 the initial discharge. Assuming the constant time step the term $\exp(-t/k)$ can be replaced by a and for consecutive time steps we get the simplified form

$$Q_i = a\, Q_{i-1} \qquad (3)$$

Where i is the time step number. Such an equation can easily be processed on a computer. Werner and Sundquist (1951) showed that eq (2) is the linear solution of the one-dimensional general differential equation governing transient flow in confined aquifers. Wittenberg and Sivapalan emphasized that parameter a fitted to different discharge ranges of the recession curves in actual rivers does not remain a constant but increases systematically with the decrease of stream flow (Chapman, 1963; Wittenberg, 1994; Wittenberg, 1994; Wittenberg and Sivapalan, 1999), which is a strong indication of nonlinearity. Therefore, they introduced the nonlinear relationship in the form

$$S = kQ^b \qquad (4)$$

The skewed distribution of the exponent *b* is mostly peaking between 0.3 and 0.4 with the mean value of b ≈ 0.5. Furthermore, Wittenberg proposed replacing the eq 3 in case of shallow aquifer and developed the form:

$$Q_i = \frac{Q_{i-1}(1+(1-b)Q_{i-1})}{ab^{\frac{1}{b-1}}} \tag{5}$$

However, the formulas introduced above may describe only the decreasing part of the stream flow records after the crest when flow diminishes and no precipitation or consecutive infiltration occur and thus no ground water supply may be induced. The question arises then how to assess the baseflow during the periods when the storage has been supplied, too.

Lyne and Hollick (1979) appear to have been the first to suggest the use of a digital filter. Recursive digital filters, which are routine tools in signal analysis and processing, are used to remove the high-frequency quickflow signal to derive the low-frequency baseflow signal.

$$y_i = f_i + b_i \tag{6}$$

where *y* denotes total stream flow, *f* direct runoff and *b* baseflow. For the b_i holds

$$b_i = ab_{i-1} + \frac{1-a}{2}(y_i + y_{i-1}) \tag{7}$$

subject to $b_i \le y_i$, where *a* is the filter parameter.

The Lyne-Hollick algorithm has been used by Nathan and McMahon (1990) and Arnold and Allen (1999), for instance. Nathan and McMahon have noticed that using the filtering technique (Equation 7) the base flow recession curve does not follow the exponential decay function associated with storage depletion (Equation 1). Moreover, Chapman (1991) pointed out that this algorithm implies constant baseflow values without recession during periods with no direct runoff and provided the improved algorithm where *a* got the hydrological meaning of the recession constant, i.e. with no direct runoff observed the baseflow gradually decreases being multiplied by constant *a*. Chapman and Maxwell (1996) further simplified the equation:

$$b_i = \frac{a}{2-a} b_{i-1} + \frac{1-a}{2-a} y_i \tag{8}$$

Nevertheless, according to the author's observation, the main weakness of the filtering technique remained: the filter provides baseflow values with BFI value equal to 0.5, which is obviously physically incorrect. BFI is often used to express the rate of baseflow to total stream flow and may vary between 0.2 in poorly fractured crystalline rocks to 0.8 in sedimentary Cretaceous aquifers. So, what the filter actually provides is just variable baseflow dynamics handled by parameter *a*, but using a range of *a* the long term baseflow mean remains constant.

Eventually, Eckhardt (2005) developed the filter algorithm constructed under the assumption that the outflow from an aquifer is linearly proportional to its storage:

$$b_i = \frac{(1-\mathrm{BFI}_{\mathrm{max}})ab_{i-1} + (1-a)\mathrm{BFI}_{\mathrm{max}}y_i}{1-a\mathrm{BFI}_{\mathrm{max}}} \tag{9}$$

where *a* denotes filter parameter and $\mathrm{BFI}_{\mathrm{max}}$ maximum baseflow index.

METHOD TESTING

Eckhardt's filter among some others has been tested on a set of 170 gauging stations in the period 1971–2003 in daily time step.

The filter parameter a can be expressed using the recession constant k in (2). Therefore, it can be objectively derived by recession analysis during dry-weather periods. For this purpose, the *recess* program inspired by Rutledge (1998) has been developed. The data processing applies the *matching strip method*, which involves ranking multiple recession curves derived from the hydrograph in order of decreasing maximum discharge (Toebes, Strang, 1964). Each recession curve is superimposed and adjusted horizontally to produce an overlapping sequence. The master recession curve is interpreted as the mean to this sequence, and the recession constant k can be derived from its slope (Equation 2).

The program uses the following parameters fixed for all the series: the recession is considered to start 10th day after the peak flow and should last at least 20 days. The length of the recession period is limited to 300 days. The visual inspection of stream flow hydrographs and its respective recession periods derived by *recess* program has revealed that even the periods of evident recession might be split or unidentified by the program. This is caused by occasional day to day swing in hydrographs because the program strictly identifies only the decreasing flow series as a recession. Therefore, it can be recommended smoothing the stream flow records before the recession analysis is to be performed. The 11 days moving minimum followed by 30 days mean has been used in our analysis. Such an approach may induce slightly less steep course of stream flow during recession periods with only negligible effect on the recession constant k and enables the program to identify the periods of flow generally considered as a recession.

The filter parameter BFI_{max} is the maximum rate of baseflow to total stream flow. According to our experience BFI_{max} can be derived by manual calibration with a values already known. The most appropriate BFI_{max} is usually the parameter value that naturally accomplishes the condition $b_k \leq y_k$ and derived baseflow should closely trace the course of stream flow during the low flow periods. The comparison of BFI_{max} values derived by manual calibration mentioned above with hydrogeological maps reveals the very good fit with basin lithology giving the BFI_{max} value higher in sandstone basin aquifers and lower in low permeable aquifers in crystalline rocks.

The baseflow separation using the Eckhardt's formula is partly objective: parameter a can be objectively derived by the recession analysis and BFI_{max} can be optimized to meet the condition that baseflow should not exceed total stream flow. On the other hand, the *kliner-kněžek* method, which has been used to derive baseflow in the CHMI so far, is rather subjective (Kliner, Kněžek, 1974). It depends a lot on a subjective decision on how to relate piezometer heads measured in a borehole with the stream flow records. The method is highly sensitive to the selection of a representative borehole or spring, respectively. The fact that the method incorporates the information on groundwater storage is unquestionably beneficial. However, the appropriate borehole or spring is often difficult to meet. An example of baseflow separation driven by Eckhardt's formula compared with the *kliner-kněžek* separation is given in Fig. 1. The nearest suitable borehole in this particular case is located in the Teplá basin in the alluvium of the Lomnický brook, which is adjacent to the basin of the gauge 1750 Trpisty but northward oriented. The yearly maximum of piezometric head is constant within the whole period. Even in the year of countrywide heavy flooding like in 2002 the piezometric head does not exceed the maximum achieved in other years. It means that no matter how intensive groundwater recharge and consecutive groundwater level rise is the maximum baseflow separated by the *kliner-kněžek* method is also giving constant values over the years. It is evident from the figure that despite the occasional better-than-average groundwater conditions of the basin the borehole represents only the very local processes depending on an actual stream discharge.

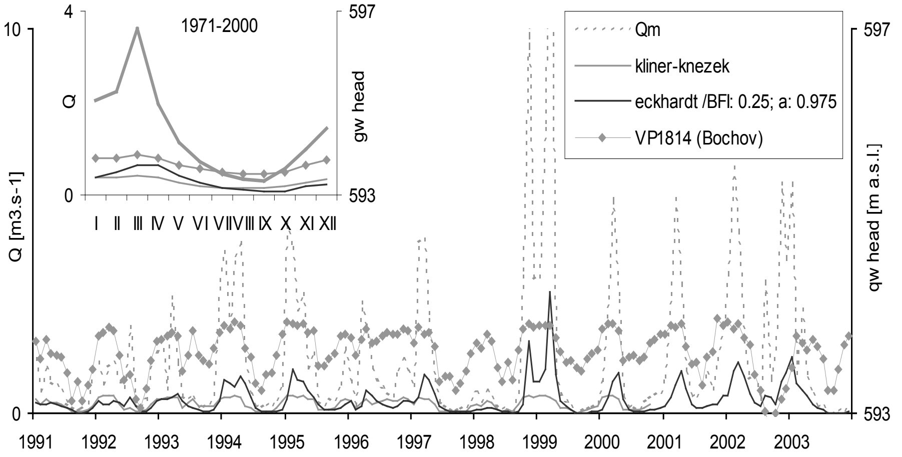

Figure 1. Comparison of mean monthly baseflow values for the gauge 1750 Trpisty (Úterský p.) obtained with the *kliner-kněžek* method and digital filtering using Eckhardt's formula. VP 1814 is the borehole used in *kliner-kněžek* separation. Qm is total monthly stream flow. The small figure shows mean monthly values for the 1971–2000 period that is used as normal for ground water regime assessment in CHMI.

RESULTS

The Eckhardt's method of baseflow separation has been tested on a set of 170 gauging stations in the period 1971–2003. 30 gauges out of the whole set have been compared with the results obtained with the *kliner-kněžek* separation. The baseflow separated using both methods differs at particular stations. The monthly baseflow mostly varies up to 20% (often to 10%) relatively to total discharge. Much higher differences have been registered in the stations where corresponding borehole or spring measurement is inadequate for a range of reasons. It might be supposed that the Eckhardt's filter can be recommended for the routine baseflow assessment in the CHMI.

ACKNOWLEDGEMENT

The analysis was supported by a grant of the Czech Ministry of Environment
(VaV SP/2e1/153/07).

REFERENCES

Arnold J.G., Allen P.M., 1999: *Validation of automated methods for estimating baseflow and groundwater recharge from stream flow records.* Journal of the American Water Resources Association, vol. 35, no. 2, pp. 411–424.

Boughton W.C., 1993: *A hydrograph–based model for estimating the water yield of ungauged basins.* Hydrology and Water Resources Symposium, Institution of Engineers Australia, Newcastle, pp. 317–324.

Boussinesq J., 1877: *Essai sur la théorie des eaux courantes.* Mémoires présentés par divers savants à l'Académie des Sciences. Paris 23 (1), 660 p.

Chapman T.G., 1963: *Effects of ground-water storage and flow on the water balance.* Water Resources, Use and Management. Melbourne University Press, Canberra, pp. 290–301.

Chapman T.G., 1991: *Comment on 'Evaluation of automated techniques for base flow and recession analyses' by R.J.* Nathan and T.A. McMahon. Water Resources Research, vol. 27, pp. 1783–1784.

Chapman T.G., 1999: *A comparison of algorithms for stream flow recession and baseflow separation.* Hydrological Processes 13, pp. 701–714.

Chapman T.G., Maxwell A.I., 1996: *Baseflow separation—comparison of numerical methods with tracer experiments.* Hydrological and Water Resources Symposium, Institution of Engineers Australia, Newcastle. Hobart, pp. 539–545.

Hall F.R., 1968: *Base-flow recessions - A review.* Water Resources Research, 4(5), pp. 973–983.

Eckhardt K., 2005: *How to construct recursive digital filters for baseflow separation.* Hydrological Processes 19, pp. 507–515.

Horton R. E., 1933: *The role of infiltration in the hydrological cycle.* Trans. Am. Geophys. Union 14, pp. 446–460.

Kliner K., Kněžek M., 1974: *Metoda separace podzemního odtoku při využití pozorování hladiny podzemní vody (A method of baseflow separation using groundwater level observation).* Vodohospodársky časopis SAV, vol. 22, no. 5, Bratislava.

Lyne V.D., Hollick M., 1979: *Stochastic time-variable rainfall runoff modeling.* Hydrology and Water Resources Symposium, Institution of Engineers Australia, Perth, pp. 89–92.

Maillet E., 1905: *Essais d'Hydraulique Souterraine et Fluviale.* Hermann, Paris, 218 p.

Nathan R.J., McMahon T.A., 1990a: *Evaluation of automated techniques for base flow and recession analyses.* Water Resources Research. 1990a, vol. 26, no. 7, pp. 1465–1473.

Nathan R.J., McMahon T.A., 1990b: *Practical aspects of low-flow frequency analysis.* Water Resources Research, vol. 26, pp. 2135–2141.

Rutledge A.T., 2007: *RECESS: A computer program for analysis of streamflow recession [online].* USGS, http://water.usgs.gov/ogw/recess/.

Rutledge A.T., 1998: *Computer programs for describing the recession of ground-water discharge and for estimating mean ground-water recharge and discharge from stream flow records.* USGS WRIR. 98–4148.

Tallaksen L.M., 1995: *A review of baseflow recession analysis.* Journal of Hydrology 165, pp. 349–370.

Werner P. W., Sundquist K. J., 1951: *On the ground water recession curve for large watersheds.* General Assembly Brussels, International Assoc. Scientific Hydrology v. 2, pp. 202–212

Wittenberg H., 1994: *Nonlinear analysis of flow recession curves.* IAHS Publ. 221, pp. 61–67.

Wittenberg H., 1999: *Baseflow recession and recharge as nonlinear storage processes.* Hydrological Processes 13, pp. 715–726.

Wittenberg H., Sivapalan M., 1999: *Watershed groundwater balance estimation using recession analysis and baseflow separation.* Journal of Hydrology 219, pp. 20–33.

International Association of Hydrogeologists

AGH University of Science and Technology

2-vol. set + CD
ISSN 0208-6336
ISBN 978-83-226-1979-0