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Evaluation of aquifer parameters at regional scale by spectral analysis of discharge time series

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Introduction
Low flow hydrology

- River stream is the result of several complex processes operating at basin scale.
- The river catchment can be conceptualized as a series of interlinked compartments, which are characterized by their individual response time to a rainfall event.
- Each compartment generates a flow component, such as the **direct runoff**, the **interflow** and the **baseflow.**
- **Baseflow**, typically generating from groundwater, is the slower portion of stream flow and plays a key role in studying the hydrological droughts.
- Since baseflow is related to storage properties and subsurface hydraulics, it can be used to infer aquifer properties at a regional scale.

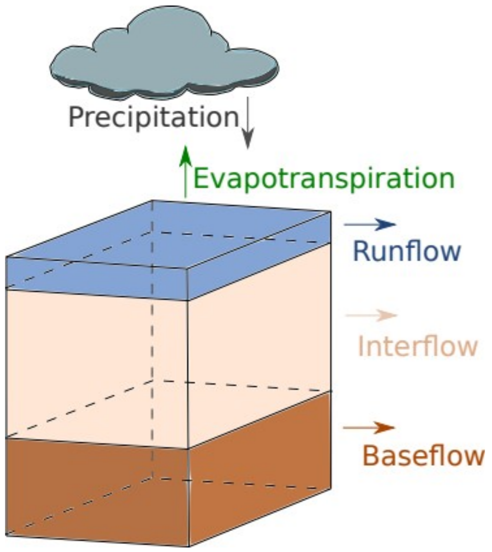


Figure 1: Different flow compartments acting in a catchment system

Introduction
Baseflow characteristic time

- In many catchment or large-scale hydrologic models, the groundwater dynamics are typically described by a linear reservoir model, which depends on the state of the reservoir and a parameter, named recession coefficient ɑ or characteristic time tc. The groundwater discharge Q is therefore given by:

$$Q(t) = Q_0 \exp(-\alpha t) = Q_0 \exp\left(-\frac{t}{t_c}\right)$$

- The characteristic time can be considered as the time needed until an aquifer reacts to a certain perturbation. So far, the characteristic time has been estimated by analyzing the slope of the recession (discharge) curve. The most used methods are the *Correlation method* and the *Matching Strip Method* [1]

- *Correlation Method*

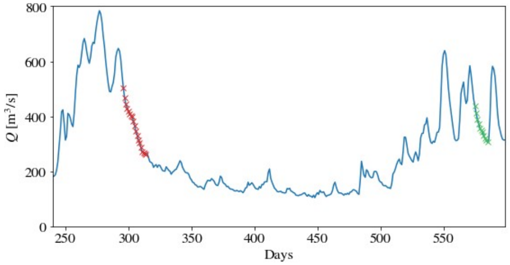


Figure 2: Identification of the recession periods

$$Q_{i-N_d} > Q_{i-N_d+1} > \cdots > Q_{i-1} > Q_i$$

$N_d = 0.83A^{0.2}$ minimum duration of the recession [2] where A is the area of the catchments

By analyzing the recession period data, the parameter K is given by:

$$K = \exp(-\alpha) = \text{mean}\left[\frac{Q_i}{Q_{i-1}}\right]$$

Therefore, the characteristic time can is given by the relationship:

$$t_c = -\frac{1}{\ln K}$$

Aim of this work

Aquifer characterization by means of Spectral Analysis

- However, as the correlation method assumes that the recharge is zero within the basin, it may lead to inaccurate estimate when such a hypothesis is not fulfilled in reality.

- Here, we proposes to infer the characteristic time by using a stochastic approach based on spectral analysis [3,4]. The catchment aquifer can be viewed as a filter, which modifies an input signal (e.g., rainfall or recharge) into an output signal (e.g., the baseflow or the hydraulic head).

Input

Recharge r(t)
Spectrum Srr(ω)

Filter

Aquifer

$$TF(\omega; t_c) = \frac{S_{qq}}{S_{rr}}$$

Output

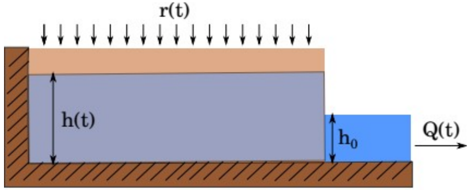
Baseflow q(t)
Spectrum Sqq(ω)

- Since the transfer function TF(ω;tc), namely the ratio between the spectrum of baseflow and the spectrum of recharge, is dependent on the aquifer characteristics, it can be used to infer the aquifer parameters, such as the characteristic time tc.

Analytical solutions for the Transfer Function

Two simplified models are considered:

- ***Linear Reservoir***
(lumped linear reservoir system, neglects spatial variation of water level and assumes that the averaged thickness of the saturated zone is a function of time)



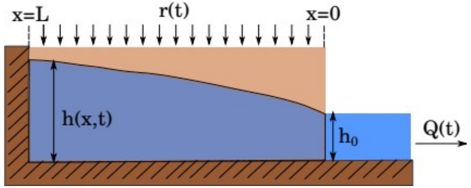
$$S\frac{dh(t)}{dt} + a[h(t) - h_0] = r(t)$$

a [T^{-1}] discharge constant
S [L^3 L^{-3}] specific yield

Transfer function [4]

$$\frac{S_{qq}}{S_{rr}} = \frac{1}{1 + t_c^2\omega^2}$$

- ***Dupuit Aquifer***
(one-dimensional system, flow lines are horizontal and parallel, and the hydraulic gradient is equal to the slope of the water table)



$$S\frac{\partial h(x,t)}{\partial t} - T\frac{\partial^2 h(x,t)}{\partial x^2} = r(t)$$

$$h(x=0,t) = h_0 \qquad \left.\frac{\partial h(x,t)}{\partial x}\right|_{x=L} = 0$$

T [L^2T^{-1}] Transmissivity
L [L] hillslope length

Transfer function [4]

$$\frac{S_{qq}}{S_{rr}} = \frac{1}{3t_c\omega}\left|\tanh\left(\sqrt{3i|\omega|t_c}\right)\right|^2$$

Characteristic time with Spectral Analysis
Baseflow filters

The baseflow can be filtered by using different methods:

- Graphical method
  (***UKHI*** [5])
  The local minima are identified and the baseflow hydrograph is given by linear interpolation of local minima
- Recursive digital filters
  (***Lyne&Hollick*** [1], ***Chapman*** [6], ***Eckhardt*** [7])
  Based on signal theories, the baseflow is identified as the low frequency component of discharge series
- Physically based filter
  (***Furey&Gupta*** [8])
  A digital filter whose parameters are based on discharge and rain data analysis

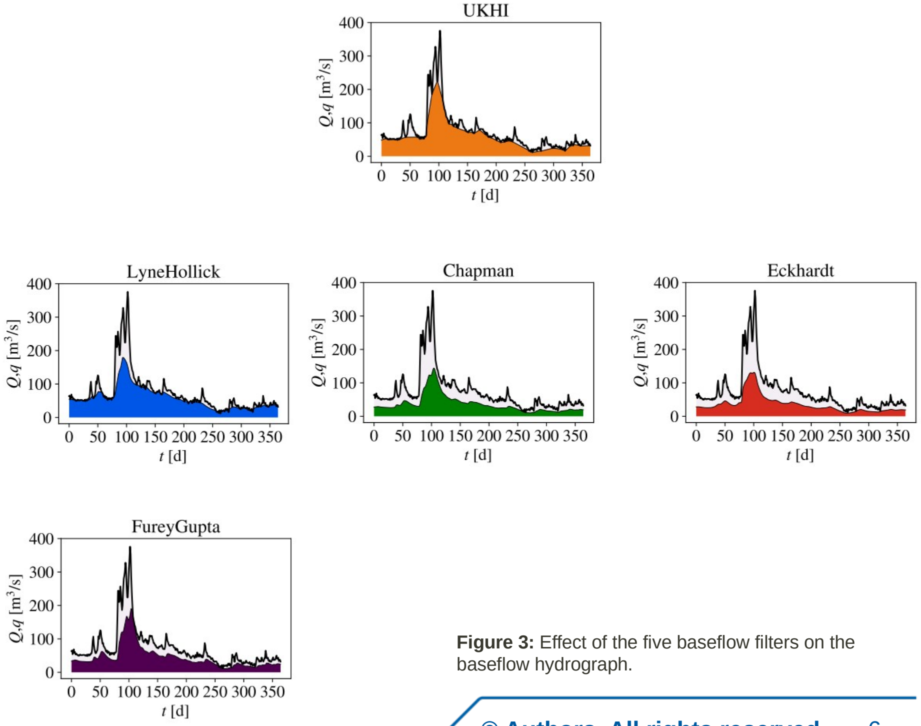


Figure 3: Effect of the five baseflow filters on the baseflow hydrograph.

Case Study
Main River

The Main is a river in the south-western Germany.

The gauging station is at Steinbach, where the catchment has an area of 17,888 km²

The discharge time series contains 19054 daily measurement from 11/1/1964 to 31/12/2017

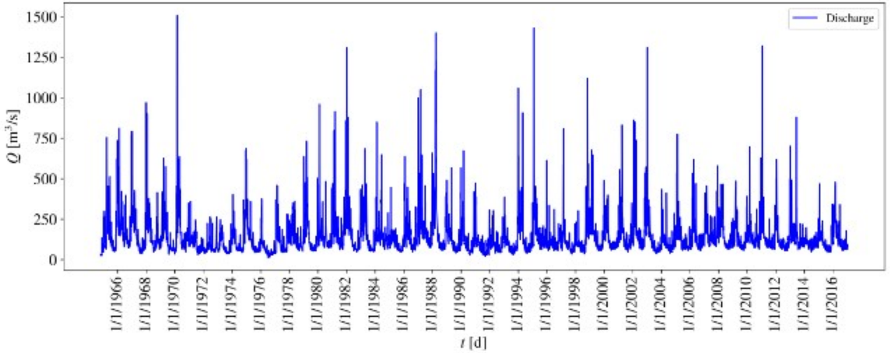


Figure 4: Discharge at Steinbach, data are given by Gewässerkundlicher Dienst Bayern

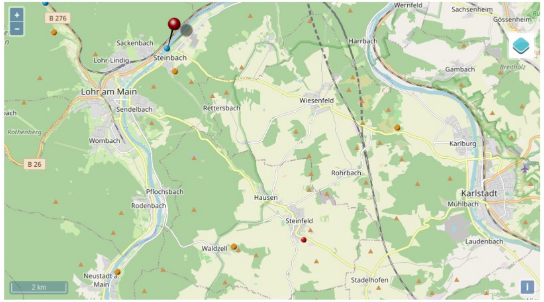


Figure 5: Steinbach station, from Gewässerkundlicher Dienst Bayern

Figure 6: Main catchment at Steinbach

Baseflow filters
Moments Analysis

The moments of baseflow are compared with the moments of recharge, which is evaluated through the model mHM [9, 10]

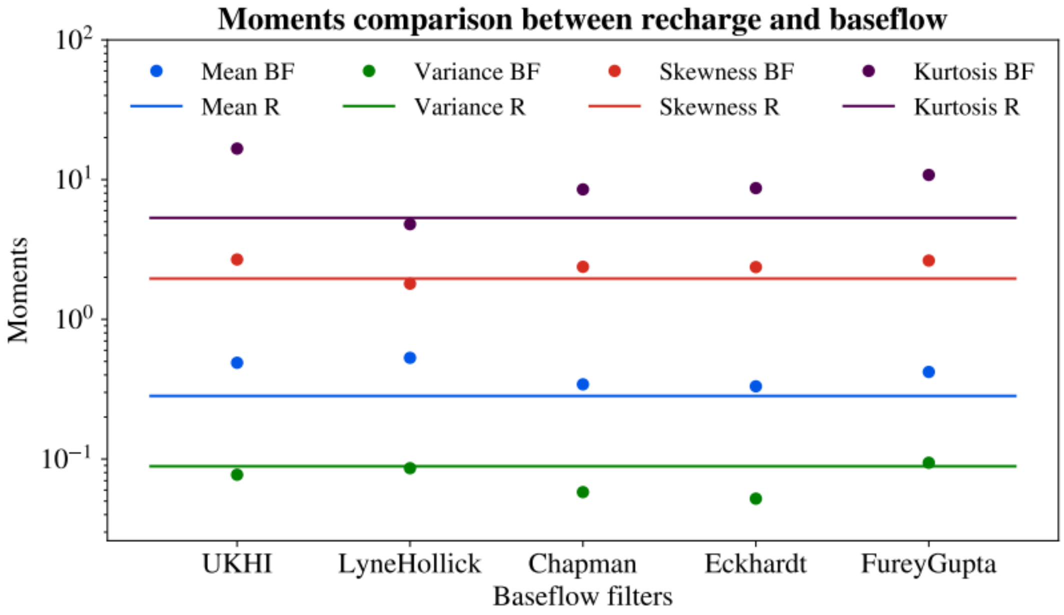


Figure 7: Comparison between the moments of the recharge and the moments of five baseflow filters.

The comparison between recharge and baseflow moments should obey these relationship:

- Mean baseflow and mean recharge should be equal due to mass conservation
- The variance of baseflow should be smaller that the variance of recharge (baseflow fluctuations are smoothed by aquifer filter)

The most consistent filters are **Chapman** and **Eckhardt**.

Baseflow filters
Spectral analysis

The spectra of the recharge and the baseflows are calculated through the Welch algorithm.

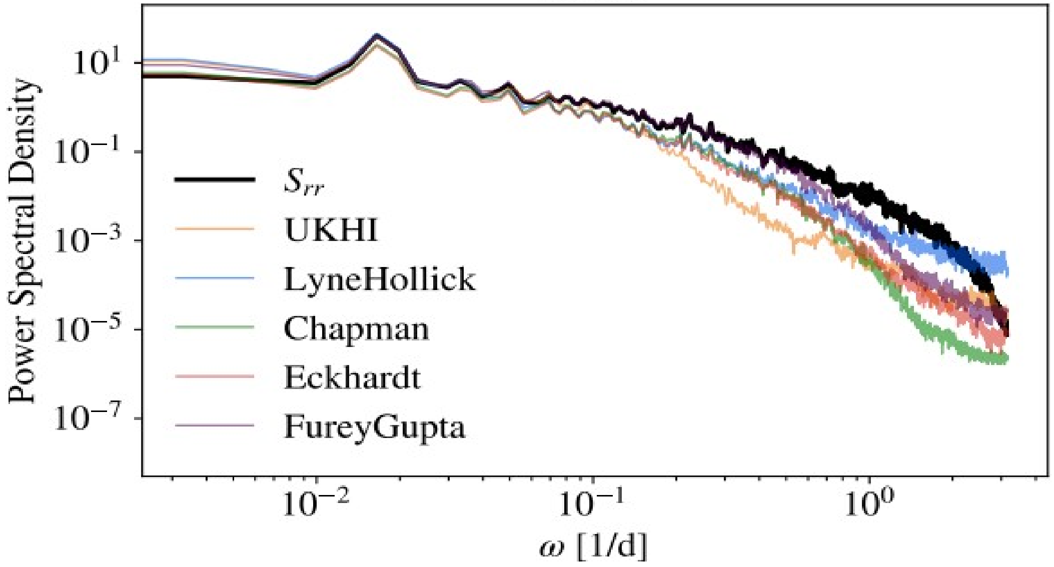


Figure 8: Spectra of the recharge and the five baseflow filters.

- For small frequencies, the spectrum of recharge and discharge coincides.
- After a certain frequency, the spectrum of baseflow bends as an effect of the aquifer filter.
- This frequency correspond to the characteristic time.
- The TF is calculated by the ratio between the spectrum of baseflow and recharge, than it is fitted with the analytical functions at slide 5

Spectral analysis
Characteristic Time

The characteristic time is plotted vs the Coefficient of Determination R^2, calculated between the fitted and the measured spectra. The values are compared with the t_c^{Res}, namely the characteristic time evaluated by analysis of the recession curve (see slide 3).

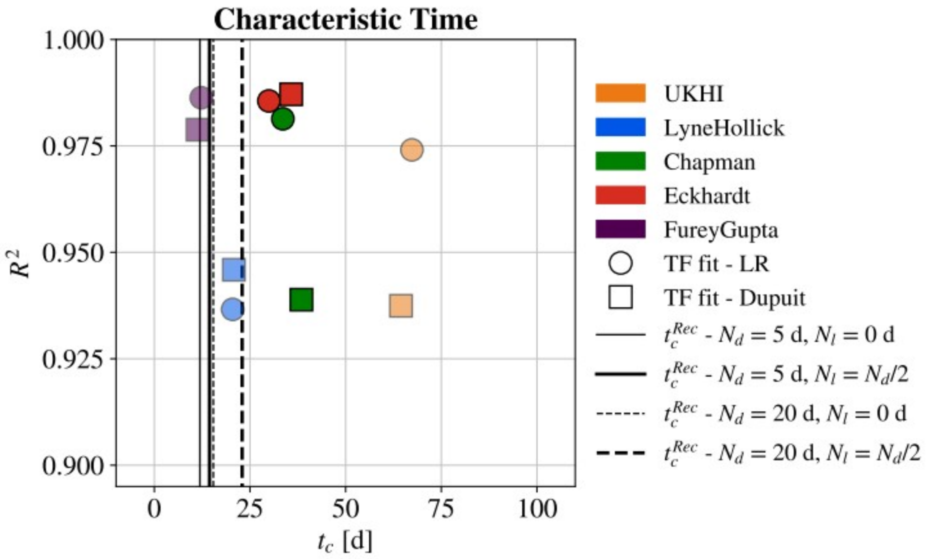


Figure 9: The characteristic time vs the coefficient of determination between measured and fitted spectrum. The recession time is calculated for N_d as the minimum number of recession days and for N_l indicating how many days after the discharge peak the recession analysis start.

- The filters with the most consistent moments (see slide 8) are highlighted in a saturated color (Chapman and Eckhardt).
- The characteristic time for Eckhardt and Chapman yields to larger recession time than the characteristic time from recession curve.
- The t_c^{Rec} approaches the tc by spectral analysis when increasing the duration of recession period N_d.

Conclusion

- This work is aimed at inferring the characteristic time of natural aquifers at a regional scale by means of a spectral approach.
- Compared with other methodologies based on the analysis of recession curve, the spectral analysis leads to a larger characteristic time.
- The linear reservoir model might be a good approximation of baseflow.
- Among the analyzed baseflow filters, both Chapman and Eckhardt yield to the better estimation for characteristic time. Both Chapman and Eckhardt baseflows have moments consistent with the moments of recharge and have the higher Coefficient of Determination with the analytical spectra.

References

[1] Nathan, R. J., & McMahon, T. A. (1990). Evaluation of automated techniques for base flow and recession analyses. Water resources research, 26(7), 1465-1473.

[2] Linsley Jr, R. K., Kohler, M. A., & Paulhus, J. L. (1975). Hydrology for engineers.

[3] Gelhar, L. W. (1974). Stochastic analysis of phreatic aquifers. Water Resources Research, 10(3), 539-545.

[4] Molénat, J., Davy, P., Gascuel-Odoux, C., & Durand, P. (1999). Study of three subsurface hydrologic systems based on spectral and cross-spectral analysis of time series. Journal of Hydrology, 222(1-4), 152-164.

[5] Piggott, A. R., Moin, S., & Southam, C. (2005). A revised approach to the UKIH method for the calculation of baseflow/Une approche améliorée de la méthode de l'UKIH pour le calcul de l'écoulement de base. Hydrological Sciences Journal, 50(5).

[6] Chapman, T. G. (1991). Comment on “Evaluation of automated techniques for base flow and recession analyses” by RJ Nathan and TA McMahon. Water Resources Research, 27(7), 1783-1784.

[7] Eckhardt, K. (2005). How to construct recursive digital filters for baseflow separation. Hydrological Processes: An International Journal, 19(2), 507-515.

[8] Furey, P. R., & Gupta, V. K. (2001). A physically based filter for separating base flow from streamflow time series. Water Resources Research, 37(11), 2709-2722.

[9] Samaniego, L., Kumar, R., & Attinger, S. (2010). Multiscale parameter regionalization of a grid□based hydrologic model at the mesoscale. Water Resources Research, 46(5).

[10] Kumar, R., Samaniego, L., & Attinger, S. (2013). Implications of distributed hydrologic model parameterization on water fluxes at multiple scales and locations. Water Resources Research, 49(1), 360-379.