Chemical streamflow analysis as a support for hydrograph filtering in small size watersheds: the Ciciriello experimental catchment (Cilento, Vallo di Diano and Alburni European and Global Geopark)

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Abstract: - The aim of the present study is to understand the relative role of runoff generation processes for the T. Ciciriello experimental catchment, a 3km$^2$ watershed located in the Cilento, Vallo di Diano and Alburni European and Global Geopark (Southern Italy). Rainfall, streamflow data and electrical conductivity are available, at the daily scale, for about one year. Two different hydrograph filtering techniques have been applied to quantitatively derive the baseflow pattern, the first being a constraint for the second one. Discharge and electrical conductivity (EC) data have been preliminary used to operate an EC mass balance filtering (ECF). ECF gained results are then used to operate the calibration phase of a more straightforward hydrograph filtering technique, a recursive digital filter (RDF), for which application only streamflow data are needed. Different value for the RDF BFI$_{\text{max}}$ parameter have been found, dependently on the considered objective function. The results, confirming the potential for the T. Ciciriello to be an experimental catchment, would further allow the possibility to extend the analysis at different space-time scale in similar hydro-geomorphological basins.

Key-Words: - hydrograph filtering, baseflow separation, electrical conductivity, recursive digital filter, Cilento

1 Introduction

The baseflow represents the slow streamflow component and it is generally related to groundwater storages, in that its main features are also related to geological catchment properties [1, 2, 3, 4]. Understanding the baseflow process is useful in many different water related issues, such as for the assessment of water quality and low-flow conditions, as support to the sustainable local development. But continuous measurements of base flow and related processes are actually unavailable, thus, hydrograph filtering approaches come to overcome this deficiency, to provide a quantitative assessment of such streamflow component.

Hydrograph separation has been defined in the past as “one of the most desperate analysis techniques in use in hydrology” [5]. Indeed the procedures available to this purpose are still, to a large extent, arbitrary, but provide a repeatable methodology to derive objective measures or indexes related to a particular streamflow source. Several approaches are reported in the scientific literature providing hydrograph filtering methods. These can be grouped into analytical, empirical and mass balance methods.

Analytical methods are based on the fundamental theories of groundwater storages, assuming frequently ideal conditions that may not always be true [6]. Empirical approaches have found considerable success: they are mainly based on a modelling framework, for which calibration is needed, based on field measurements or simply based on the user experience. Among these a large number of recursive digital filters, based on the assumption that the baseflow is the smooth frequency component of total hydrograph, have been proposed in the past literature [7, 8, 9, 10].

The mass balance methods are instead based on the assumption that baseflow has different chemical characteristics compared with surface runoff, because of the different residence times and flow paths of these two sources. The mass balance filtering method is considered to be an objective approach because it is based on basin-specific physical processes and relevant monitoring activities. Among different applications, a wide use has been gained from the electrical conductivity [11, 12, 13, 14].
Since the 2012, a research program on the relation between geodiversity and ecosystem functioning in the headwaters of the Cilento, Vallo Diano and Alburni National Park has been started. The program, currently granted by the European & Global Geopark, promotes the monitoring activities carried out in the reference catchments significant for the geodiversity of the terrigenous landscapes, in the perspective of a progressive extension of the research to the similar catchments in the Geopark and in other protected areas of the southern Italy.

Within this program, a 3 km$^2$, the T. Ciciriello catchment, tributary of the Bussento river (Fig. 1), has been instrumented in order to collect a data archive relevant to understand the hydro-geomorphological behavior of the terrigenous, forested catchments, located in the Geopark [15].

2 The Ciciriello experimental catchment

2.1 Hydrogeological outline of the Cilento, Vallo Diano and Alburni - European Geopark

From an hydro-geomorphological point-of-view, the Cilento and Vallo di Diano GeoPark consists of carbonate, terrigenous and alluvial aquifers [16]. Terrigenous aquifers, although have a great local interest in ecological issues and traditional agriculture and forestry maintenance, have had minor attention by scientific community.

2.2 The experimental watershed hydrogeological properties

The experimental catchment is an exclusively terrigenous bedrock outcropping watershed [15]: at the base, a marly-clayey formation passes upward, in unconformity, to a south-western dipping sandstone sequence. Along the left valley side, inter-bedded to the sandstone strata, an up to 10 m-thick lenticular marly bed outcrops (Fig. 2). The bedrock is covered by thick regosols on the upper ridges, regolith on the noses and spurs and gravelly slope deposits at the toe of the open slopes. The stream bed is incised in alluvial, coarse deposits and partly on bedrock. In the headwaters, colluvial hollows are located in the bottom of the zero order basins. Permanent springs from bedrock aquifers and seasonal outflows from colluvial swallets increase progressively downstream the stream discharge.

Fig.1 - Hydrogeological scheme of the Cilento and Vallo Diano European GeoPark (mod. by [16]).

The aim of the present study is then to understand the relative role of runoff generation processes in the above mentioned catchment, with a particular look at the baseflow process and to test the validity of the parsimonious monitoring campaign in providing insights about the hydro-geomorphological behavior of small size catchments, which prediction is of particular challenge.

Fig.2 - Schematic geological map and monitoring stations of the T. Ciciriello catchment in the Bussento river basin (Cilento Geopark).
2.3 Data collection

During 2012-2013, a number of monitoring stations were located along the drainage network of the T. Ciciriello watershed. The main station has been located at the outlet of the catchment (420 m asl) and the sub-stations along the main channel, at significant river sections (Fig. 2).

In addition, secondary stations were located just upstream the main tributary junctions and downstream the perennial bedrock springs and temporary seasonal through flow outlets from the zero order basins. Location and timing of the monitoring activity has been based on detailed, multi-temporal hydro-geomorphological survey and mapping, oriented by the “variable source areas” concept [5] and the “hydro-geomorphic paradigm” [17].

Since December 2012, water depth (D), discharge (Q) and electrical conductivity (EC) were measured, daily, at main station and, weekly, at the sub-stations. The Swoffer 3000 current meter (Swoffer Inc., USA) has been used for discharge measurements whereas the HI9828 multi-parametric probe (Hanna Instruments Inc., Romania) has been used for EC measurements. During selected storm events, 10-minute D and EC data have moreover been recorded at the main station by using the data logger DL/N70-Multi (STS Inc., Switzerland). Rainfall data, at 10-minute time resolution, for the Sanza rain gauge have been provided by courtesy of the Civil Protection Service of the Campania Region.

3 Hydrograph filtering

Hydrograph separation procedures provide a repeatable methodology to derive objective measures or indexes related to a particular streamflow source, the slow and the fast components. As previously mentioned, several approaches are reported in the scientific literature providing hydrograph filtering methods. In the following two different methods, belonging to the mentioned groups, are applied for the Ciciriello experimental catchment data, one providing important information for the calibration of the second approach and showing the relevant impact of the monitoring campaign in understanding the runoff production mechanisms in a small size catchment.

3.1 Mass balance filtering

The mass balance method is based on the assumption that baseflow has different chemical characteristics compared with surface runoff due to the different flow paths of these two types of flows. As a consequence, total streamflow hydrograph can be separated into different components on the base of the single component concentrations. The electrical conductivity EC, as proxy of the Total Dissolved Solids mass balance is one of the most widely used technique. The baseflow component has generally greater EC value compared to the surface runoff conductivity and for this reason EC can be used as a natural tracers of the streamflow component. This behavior is particularly evident in Fig. 3, where the measured EC approaches the largest values during the low flow period. According to this assumption, it is possible to consider the following equation system:

\[
\begin{align*}
q_{tot}(t) &= q_s(t) + q_b(t) \\
q_{tot}(t) \cdot EC_{tot}(t) &= q_s(t) \cdot EC_s(t) + q_b(t) \cdot EC_b(t) \\
q_{tot}(t) &= q_s(t) + q_b(t) \\
q_{tot}(t) \cdot EC_{tot}(t) &= q_s(t) \cdot EC_s(t) + q_b(t) \cdot EC_b(t)
\end{align*}
\]

where

- \( q_{tot} \): measured total streamflow (l/s);
- \( q_s \): surface streamflow component (l/s);
- \( q_b \): baseflow streamflow component (l/s);
- \( EC_{tot} \): measured streamflow EC (\( \mu \)S/cm);
- \( EC_s \): surface component EC (\( \mu \)S/cm);
- \( EC_b \): baseflow component EC (\( \mu \)S/cm);

Parameters \( EC_s \) and \( EC_b \) have been directly measured in groundwater and surface runoff, respectively during the monitoring campaigns pre- and post-heavy rainfall events. In this application \( EC_s \) and \( EC_b \) where respectively set as TDS proxy values 40 and 170 mg/l. The consequent hydrograph separation is illustrated in the following Fig. 4.

The baseflow component, according to the variable mixing component assumption, represents, on a
daily time interval, about the 100% of measured streamflow during the low flow conditions and the 5-10% during the peak flow conditions. Considered as the ratio between the baseflow volume and the total streamflow volume, the T. Ciciriello watershed BFI is about 12.7%, consistently with the catchment geological features.

Fig. 4 – Electrical conductivity mass balance filtering (ECF) for baseflow separation at T. Ciciriello watershed main station.

The mass balance filtering method is considered to be an objective approach because it is based on basin-specific physical processes and relevant monitoring. For this reason it can be used as a constraint for different baseflow filtering techniques, such as the recursive digital filters, which performances are largely dependent on some watershed-specific parameters, needing a calibration.

3.2 Digital filter

Digital filtering techniques assume that baseflow has a longer wavelength response than quickflow and that baseflow can be extracted from total flow by the application of a low-pass filter. Among filtering techniques, the Eckhardt’s filter is used in this study, because it has been shown that a number of one-parameter filters, reported in the specific literature, are all special cases of the two-parameter filter he has proposed [9].

If the total streamflow y(t) at each time step can be decomposed into:

\[ y(t) = b(t) + f(t) \]  

where \( b(t) \) and \( f(t) \) would be the slow and fast streamflow component, at each time step, then the slow baseflow component can be considered as:

\[ b(t) = Ab(t-1) + By(t) \]  

subject to the restriction \( b(t) \leq y(t) \). Assuming a linear relation between outflow from the aquifer and its storage, parameters \( A \) and \( B \) in Equation (3) can be expressed as functions of the recession constant \( a \), and a second parameter, called the BFI \(_{\text{max}}\), the following expressions indeed hold:

\[
\begin{align*}
B &= \frac{(1-a) \cdot \text{BFI}_{\text{max}}}{1 - a \cdot \text{BFI}_{\text{max}}} \\
A &= \left( \frac{1 - \text{BFI}_{\text{max}}}{1 - a \cdot \text{BFI}_{\text{max}}} \right) a 
\end{align*}
\]  

and the filter is then expressed as:

\[ b(t) = \frac{(1 - \text{BFI}_{\text{max}})ab(t-1) + (1 - a)\text{BFI}_{\text{max}}y(t)}{1 - a\text{BFI}_{\text{max}}} \]  

subject to the restriction \( b(t) \leq y(t) \). While parameter \( a \) can be estimated by a recession analysis, there is no objective way to define \( \text{BFI}_{\text{max}} \). Eckhardt [9] introduced pre-defined parameters depending on geological and hydrogeological catchment properties: \( \text{BFI}_{\text{max}} = 0.80 \) for perennial streams with porous aquifers; \( \text{BFI}_{\text{max}} = 0.50 \) for ephemeral streams with porous aquifers; \( \text{BFI}_{\text{max}} = 0.25 \) for perennial streams with hard rock aquifers. The author also suggested that these pre-defined values can cause tendentious approximations in the BFI calculation, and that the coupled use of different methods, such as tracers experiment, could be useful to optimize the parameter settings.

The aim of the current study is to use the EC mass balance filtering results as constraint for \( \text{BFI}_{\text{max}} \) parameter assessment, with reference to the T. Ciciriello watershed experimental data.

As a first step, a recession analysis has been performed to set a value for the \( a \) parameter. Four recession events have been selected along the one year measurements.

For each recession event, two different declining slopes have been identified, likely corresponding to the fast and slow streamflow components (Fig. 5). An exponential decay function has been used for fitting the hydrograph recession limb data:

\[ Q(t) = Q_0 e^{-\alpha t} \]  

where \( Q(t) \) is the flow rate during the recession period (l/s), \( Q_0 \) is the flow rate at the beginning of recession (l/s), and \( \alpha \) is the recession rate constant (units of 1/day). However, since the RDF method considers only one recession constant parameter, an
average recession constant has been calculated as the average of the fast and slow flow rate parameter [14]. The value for $a$ has been consequently set on 0.35, corresponding to a delay of about 3 days.

$$y = -0.1628x + 6725.9$$
$$R^2 = 0.9755$$

$$y = -0.07x + 2894.8$$
$$R^2 = 0.989$$

Fig.5 – Recession analysis for the 24/01/2013-04/02/2013 event at T. Ciciriello watershed main station. Logarithm of discharge is indicated.

To calibrate the value to be set for the $BFI_{\text{max}}$ parameter, the EC mass balance filtering results have been considered as a constraint [18].

As a first assumption, a value of $BFI_{\text{max}} = 0.250$, as suggested by the literature, has been considered. The baseflow separation, in this case, is associated to a RMSE (calculated with reference to the ECF baseflow time series) of about 73.45 l/s and the long term BFI is equal to 0.252, significantly larger than the ECF BFI value.

Two different conditions have been then consider as an optimization of the $BFI_{\text{max}}$ parameter. As a first condition, the $BFI_{\text{max}}$ has been calibrate to have a BFI value equal to the one estimated for the ECF method. $BFI_{\text{max}}$ has resulted in a value of about 0.125 and the consequent RMSE is of about 28.47 l/s.

Tab. 1 – $BFI_{\text{max}}$ parameter calibration, RMSE and BFI assessment.

<table>
<thead>
<tr>
<th>$BFI_{\text{max}}$</th>
<th>RMSE (l/s)</th>
<th>BFI</th>
</tr>
</thead>
<tbody>
<tr>
<td>min sum dev</td>
<td>0.200</td>
<td>54.08</td>
</tr>
<tr>
<td>same BFI EC</td>
<td>0.125</td>
<td>28.47</td>
</tr>
<tr>
<td>literature</td>
<td>0.25</td>
<td>73.45</td>
</tr>
</tbody>
</table>

As a second condition, the index $\pi$, the mean percentage by which estimated baseflow deviates from minimum annual streamflow, introduced by Furey and Gupta [19], has been minimized. $BFI_{\text{max}}$ has resulted in a value of about 0.200 and the consequent RMSE is of about 54.08 l/s with a long term BFI of about 0.202. Optimization conditions and corresponding results are illustrated in Tab. 1.

The baseflow separation is moreover illustrated in Fig. 6, for different values of $BFI_{\text{max}}$ parameters. As evident, large $BFI_{\text{max}}$ would lead to larger baseflow volumes.

Fig.6 – Baseflow separation by recursive digital filtering (RDF) at T. Ciciriello watershed main station (impact of different $BFI_{\text{max}}$ parameter).

Fig.7 and Fig. 8, further graphically compare the application of the ECF and RDF method, to separate baseflow time series from measured streamflow data at the T. Ciciriello watershed. Fig. 7 illustrates the RDF separation performed for $BFI_{\text{max}}$ equal to 0.125. In this case optimal BFI value and minimum error index have been found, but the RDF pattern seems to be significantly different from the ECF one, clearly also during the low flow conditions, when the baseflow component is supposed to be the main flow component.

Fig.7 – ECF and RDF methods comparison for baseflow separation at T. Ciciriello watershed main station ($BFI_{\text{max}} = 0.125$).

Fig. 8 illustrates the RDF separation performed for $BFI_{\text{max}}$ equal to 0.250. In this case the BFI value is significantly larger than the ECF BFI and error
index is maximum, but the RDF pattern seems to better resemble the ECF one, clearly also during the low flow conditions.

As a final results, a sensitivity analysis has been performed to understand the weight of each of the two RDF parameters. A grid for \( a \), ranging from 0.2 to 0.8 (a delay of 5 to 1 day) and for \( \text{BFI}_{\text{max}} \), from 0.125 to 0.250, has been set, and for each couple of the filter parameters a synthetic index, the long term BFI, has been computed (Tab. 2). It appears rather clearly that the RDF filter, for this particular experimental catchment, is affected by the \( \text{BFI}_{\text{max}} \) settings at a larger extent.

Tab. 2 – Recursive digital filter sensitivity to model parameters.

<table>
<thead>
<tr>
<th>( a )</th>
<th>( \text{BFI}_{\text{max}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.125</td>
<td>0.150 0.200 0.250</td>
</tr>
<tr>
<td>0.2</td>
<td>0.127 0.152 0.202 0.202</td>
</tr>
<tr>
<td>0.4</td>
<td>0.127 0.152 0.202 0.252</td>
</tr>
<tr>
<td>0.6</td>
<td>0.128 0.153 0.203 0.253</td>
</tr>
<tr>
<td>0.8</td>
<td>0.131 0.156 0.205 0.254</td>
</tr>
</tbody>
</table>

4 Conclusion

The baseflow represents the slow streamflow component and the understanding of the generating process and mechanism is useful in many different water related issues. The present study has reported about a number of analysis performed for the T. Ciciriello experimental catchment, to understand the relative role of the different runoff generation processes, with a particular look at the baseflow process at the hydro-geomorphological behavior of small size, headwater catchments. Assessment of behavior for these catchments and prediction of their hydrological response for changing land use or climate is moreover of particular challenge and interest.

The investigations carried out in the Ciciriello T. Experimental Catchment provide new insights about hydrological response of the drainage basins fed by terrigenous aquifers, which although have a great local interest in ecological issues and traditional agriculture and forestry maintenance, have received minor attention by scientific community. Discharge and electrical conductivity data, monitored at the catchment outlet, for about one year at the daily scale, have been used to provide a preliminary quantification of the baseflow pattern, by the application of a ECF mass balance filtering algorithm. Assuming that the mass balance filtering method is an objective approach, because based on basin-specific physical processes and relevant monitoring, gained results have been used as a constraint for the application of a recursive digital hydrograph filter. The applied Eckhardt RDF would represent a more straightforward application, since only total streamflow data are necessary, but a calibration of the filter parameters is need, which has been indeed achieved using the information provided by the ECF. With reference for the \( \text{BFI}_{\text{max}} \) parameter, it has been found that an absolute optimal value cannot be found: the pre-defined value of about 0.25 provides a baseflow pattern particularly similar to the ECF pattern, especially during the low flow period, whereas minimal value of about 0.125 is needed if the filtering technique is applied with the aim to derive a global index such as the BFI.

References:


