Journal of Hydrology 527 (2015) 794–808

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

A catchment as a simple dynamical system: Characterization by the streamflow component approach

Simon Rusjan *, Matjaž Mikoš

University of Ljubljana, Faculty of Civil and Geodetic Engineering, Chair of Hydrology and Hydraulic Engineering, Jamova 2, SI-1000 Ljubljana, Slovenia

ARTICLE INFO

Article history:
Received 18 November 2014
Received in revised form 22 May 2015
Accepted 25 May 2015
Available online 1 June 2015
This manuscript was handled by Konstantine P. Georgakakos, Editor-in-Chief, with the assistance of Alon Rimmer, Associate Editor

Keywords:
Streamflow recession
Catchment storage
Bypassing flow
Discharge sensitivity function
Streamwater electrical conductivity
Hydrograph separation

SUMMARY

The simple dynamical system approach was implemented to analyze, explain and simulate streamflow fluxes in diverse seasonal hydrological conditions within the forested Padež stream catchment in SW Slovenia. The catchment is characterized by the flushing, torrential hydrological response conditioned by the flysch geological settings of a low hydraulic conductivity. Consequently, the streamflow formation is not controlled solely by the deeper subsurface catchment storage but is also strongly influenced by the rainfall–runoff that bypasses the deeper subsurface part of the total catchment storage. Therefore, fast component of the streamflow is identified using two-component hydrograph separation; the component recession behavior is described by a separate sensitivity function and used in a simple model to simulate the streamflow. According to the simulation results, the Padež stream catchment behaves primarily like a deeper subsurface storage-dependent system during most of the hydrological conditions. When rainfall intensities increase (rainfall intensities close to 10 mm/h or higher), triggering of the secondary streamflow formation mechanism described by separate, bypassing flow sensitivity function becomes evident and causes fast hydrograph formation with steeply rising and falling limbs. To be able to implement the modeling concept for streamflow predictions, the rainfall losses, most likely associated with interception losses not covered under the potential evapotranspiration calculation, would have to be more thoroughly analyzed through rainfall interception measurements. Our study shows the possible way that two hydrological concepts, the streamflow recession analysis and the two-component hydrograph separation based on relatively easily measurable tracers, such as electrical conductivity, could be combined for analyzing streamflow fluxes.

1. Introduction

Catchments are spatial landscape elements that control water fluxes through a variety of topographic, physical and geological properties. At the most basic level, a catchment's function might be defined as the collection, storage and release of water (Black, 1996). The final result of the water flow convergence from a catchment is relatively easily observable as a stream discharge. However, knowing the hydrological outcome of the catchment response to the atmospheric inputs gives us only a blurred and unclear picture of the hydrological processes that result in a stream hydrograph change (Rinaldo et al., 2011). Consequently, the analysis and modeling of the catchment hydrological processes is complicated because of several factors. The volume of water stored within a catchment and its partitioning among the groundwater, soil moisture, snowpack, vegetation, surface and stream water are some of the variables that are frequently included as parameters in hydrological models used to characterize the state of the hydrologic system. The aforementioned model parameters, from a catchment spatial perspective, are spatially heterogeneous and difficult to measure; furthermore, the optimal model structure may change with the scale at which the models are applied (Kirchner, 2006).

Traditionally, hydrological models have been developed around the central assumption that the functional behavior of hydrological systems can be predicted from the physical properties of the system combined with the governing flow equations and the initial and boundary conditions (Teuling et al., 2010). Based on many hydrological modeling efforts (e.g., Mendoza et al., 2003; Schulz et al., 2006; Clark et al., 2009; McMillan et al., 2011), it became evident that it is extremely difficult to determine system properties at the selected scale in advance by manipulating numerous model parameters to achieve a satisfactory correspondence between the observed and simulated fluxes. A step toward inferring the mechanistic model structure from the time-series data was taken

* Corresponding author. Tel.: +386 1 425 33 24; fax: +386 1 25 19 897.
E-mail address: simon.rusjan@fgg.uni-lj.si (S. Rusjan).

http://dx.doi.org/10.1016/j.jhydrol.2015.05.050
0022-1694/

through the introduction of data-based mechanistic (DBM) transfer function models (Young, 1993, 2003; Lees, 2000) as a "top-down" approach to hydrological modeling. As suggested by Sivapalan et al. (2003), a downward approach should play a more prominent role in dominant process identification and model development, whereby time series characteristics would be used to derive model structures rather than be used solely for the optimization of parameters for an "a priori" given model structure.

The conceptualization of streamflow generation processes and their integration into rainfall–runoff models remains one of the major research challenges in catchment hydrology (Vache and McDonnell, 2006; Birkel et al., 2011a; Kavetski et al., 2011; McMillan et al., 2012). Kirchner (2009) demonstrated how streamflow time series can be used to construct a storage–discharge relationship that can be applied to simulate a full range of streamflow conditions when combined with precipitation and evapotranspiration measurements. The model structure was conceptualized on the system properties, which were directly inferred from observed changes during streamflow recession. Other recent research studies (Harman et al., 2009; Teuling et al., 2010; Shaw and Riha, 2012; Xu et al., 2012) have increased confidence in the belief that streamflow recession does not necessarily solely reflect aquifer characteristics but instead provides a broader measure of the system-wide storage–discharge or geomorphological characteristics within the catchment. This further implies that more information, in addition to the information provided by more traditional hydraulic aquifer theory approaches, can be extracted from the streamflow recession (Birkel et al., 2011b; Hrachowitz et al., 2011).

Field studies in catchment hydrology continue to characterize and catalogue the enormous heterogeneity of rainfall–runoff processes through complex hydrological pathways in an increasing number of catchments, in different hydroclimatic regimes and at different scales (McDonnell et al., 2007). Identification of the water pathway gives an insight into the magnitude and timing of solute fluxes from different hydrological reservoirs in the landscape and is, therefore, essential for the understanding of the variations of the stream water chemistry (Beven, 2010; McDonnell et al., 2010).

This study is an attempt to implement the "catchment as a simple dynamical system", a concept presented by Kirchner (2009), in a mesoscale catchment in Slovenia and combine it with basic in-stream solute concentration dynamics to be able to describe the catchment response to rainfall. The hydrological characteristics of the studied catchment somewhat differ from the catchment subsurface storage vs. the discharge framework proposed by Kirchner (2009) where an assumption has been made that there is a single form of a storage–discharge function valid for a particular catchment. In terms of climate, our study catchment has Mediterranean climatic characteristics. The catchment's hydrological response can be characterized as fast and flushing due to flysch layers of low permeability. Its hydrograph characteristics and streamwater chemistry suggest that the catchment response changes during high-intensity rainfall events (Rusjan et al., 2008). Furthermore, this could be an indication that the stream discharge might not be controlled solely by the deeper underground part of the total catchment storage but is also strongly influenced by the rainfall–runoff that bypasses the deeper subsurface catchment storage mechanism and, therefore, enters the stream chemically relatively unchanged. Similar hydrogeological behavior has been reported by McGuire and McDonnell (2010), Penna et al. (2011) and Hrachowitz et al. (2013).

The two presumed streamflow components respond to rainfall–runoff inputs in a different manner; therefore, the sensitivity of the discharge to changes in the storage (the so-called discharge sensitivity function) was analyzed for each component of the streamflow. The sensitivity functions were jointly used to simulate streamflow hydrographs. Our study, thus, represents an attempt of merging the discharge recession analysis with the two-component hydrograph separation to better describe the hydrological functioning and behavior of the studied catchment. The main objectives of the paper are as follows: (1) to evaluate and extract the hydrological information retained in streamflow recession curves; (2) to study the dynamics of a fast streamwater component that was identified using the electrical conductivity of rainwater and streamwater as a tracer; and (3) to combine the concept of the simple two-component hydrograph separation with the catchment behavior as a simple dynamical system.

2. Catchment and data description

The Padež stream catchment is situated in the Southwestern part of Slovenia (Fig. 1); it is a mesoscale catchment of 42.1 km^2. The Padež stream is a tributary of the Reka River, one of the widest known sinking streams of the Classic Karst area in Slovenia (Brilly et al., 2002). The Padež catchment reaches deeply into the hilly area of Brkini in the south (altitude up to 811 m a.s.l.), while the outflow to the Reka River is at 368 m a.s.l. The Brkini hilly area, and the Padež catchment, consist of Eocene flysch (mainly marl and sandstone layers) underlain by deep cretaceous carbonate bedrock that also surrounds the wider area of the Brkini flysch pool. From a hydrogeological point of view, the Padež catchment has a uniform structure characterized by low permeability of the erodible flysch layers and a consequently well-developed, dense and highly incised stream channel network with a drainage density of 1.94 km/km^2. The lowest parts of the main valleys (the Padež and Suhorka stream valleys) are covered by up to 4 m thick alluvial deposits. The hydraulic conductivity of flysch is low (in the range 10^{-6} m/s to 10^{-5} m/s), the hillslopes are steep (average slope derived from the digital elevation model amounts to 33%), and the average slope of the Padež stream channel is almost 3%.

In terms of climate, the Brkini hilly area is a transitional area between the Mediterranean and continental climates with a mean annual temperature of 9.6 °C. The mean annual precipitation is 1440 mm. The prevailing movement of the wet air masses is in the southwest–northeast direction. The majority of the precipitation falls during the October–March period with periodical snowfall on the highest parts of the Brkini hills, which does not have substantial influence on the catchment hydrology. The long-term mean annual discharge of the Padež stream amounts to 0.097 mm/h. The hydrologic response of the catchment is very fast, which is reflected in the flushing, almost torrential regime of the Padež stream. During most of the year, water is present only in the Padež stream and its major tributary, the Suhorka stream, with the other smaller streams in the catchment being intermittent. Spatially, the soils in the study area are uniform. According to the WRB 2006 soil classification, they are classified as Haplic Cambisol (Humic, Hyperdystric, Endoskeletic).

The Padež stream catchment is minimally disturbed by human activity. It has already been used as a drinking water supply, and as such, it is also foreseen as an additional source of drinking water for the water-deficient area of the Slovenian coastal region (Kryžanowski et al., 2010). According to the CORINE 2006 land cover data, 82% of the catchment is covered by forest (79% by broad-leaved forest), and 18% of the catchment comprises complex cultivation patterns (mainly meadows with significant areas of natural vegetation) that are all in the state of successive afforestation. The lower parts of the catchment are almost completely covered by deciduous forest.

The monitoring system at the Padež catchment, which was established in 2005, is shown in Fig. 1. Precipitation data were obtained from 6 Onset RG2-M tipping bucket rain gauges located within the Padež catchment; the meteorological data were