

Exploring Geological and Topographical Controls on Low Flows with Hydrogeological Models

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Abstract

This study investigates how catchment properties influence low-flow dynamics. With 496 synthetic models composed of a bedrock and an alluvial aquifer, we systematically assess the impact of the hydraulic conductivity of both lithologies, of the hillslope and of the river slope on catchment dynamics. The physically based hydrogeological simulator HydroGeoSphere is employed, which allows obtaining a range of low-flow indicators. The hydraulic conductivity of the bedrock K_{bedrock} , a proxy for transmissivity, is the only catchment property exerting an overall control on low flows and explains 60% of the variance of Q95/Q50. The difference in dynamics of catchments with same K_{bedrock} depends on hillslope gradients and the alluvial aquifer properties. The buffering capacity of the bedrock is mainly related to K_{bedrock} and the hillslope gradient. We thus propose the dimensionless *bedrock productivity index* (BPI) that combines these characteristics with the mean net precipitation. For bedrock only models, the BPI explains 82% of the variance of the ratio of Q95 to mean net precipitation. The alluvial aquifer can significantly influence low flows when the bedrock productivity is limited. Although our synthetic catchment setup is simple, it is far more complex than the available analytical approaches or conceptual hydrological models. The direct application of the results to existing catchments requires nevertheless careful consideration of the local geological topographic and climatic conditions. This study provides quantitative insight into the complex interrelations between geology, topography and low-flow dynamics and challenges previous studies which neglect or oversimplify geological characteristics in the assessment of low flows.

Introduction

In the context of climate change, it is essential to identify regions vulnerable to dry spells. The probability of water scarcity to occur depends on meteorological factors and the ability of the catchment to store and release water in the absence of precipitation. Catchment storage and discharge processes are governed by physiographic characteristics (Smakhtnin 2001). The diversity of geology, topography, soil, and land use is largely superior to precipitation discrepancies at typical water management scales (Van Loon and Laaha 2015). Identifying key catchment properties controlling streamflow and groundwater dynamics during dry seasons is thus a precondition for assessing the vulnerability of water resources. The discharge at the outlet often reflects the combined surface and subsurface dynamics and is thus of great utility to assess the low-flow behavior of a catchment.

Hydrogeological case studies have established a link between geology and low-flows. Tague and Grant (2004) identify, for instance, the dominant control of a young volcanic geological unit on the flow regime of the studied region in Oregon, this geological formation having an exceptionally high permeability. Pfister et al. (2017) show that bedrock permeability significantly influences the ratio between average summer and winter run-off of 16 investigated catchments in Luxembourg. For a selection of Swiss catchments, Naef et al. 2015 associate higher low flows with slowly draining porous bedrock and low streamflow during dry periods for catchments dominated by Moraine deposits. Käser and Hunkeler (2016) have shown that alluvial aquifers, even if they represent only a small portion of the catchment surface, can contribute significantly to the catchment outflow especially during low-flow periods. Alluvial aquifers can thus also be relevant for total catchment groundwater storage. Carlier et al. (2018) statistically analyzed 22 catchments of the Swiss Plateau and Prealpes to establish relationships between streamflow indicators and various geological and hydrogeological properties of the bedrock and Quaternary deposits, along with meteorological, soil, land use, and topographical characteristics. The study shows that the geological characteristics dominate catchment response during high and low-flow conditions.

Various other groundwater studies analyzed the influence of topography, recharge and permeability on

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groundwater flow in the bedrock. According to the hydrologically active bedrock hypothesis (Uchida et al. 2008) the bedrock is an active reservoir that significantly contributes to baseflow (Tague and Grant 2004; Andermann et al. 2012; Welch and Allen 2012; Birkel et al. 2014). The hydraulic conductivity of the bedrock controls storage processes (Hale et al. 2016; Pfister et al. 2017). Most importantly, the ratio of the hydraulic conductivity to recharge rates has been shown to be relevant for water table elevation (Gleeson and Manning 2008). Haitjema and Mitchell-Bruker (2005) propose a criterion based on the Dupuit-Forchheimer approximation combining this ratio with geometrical aquifer properties and topographical characteristics to determine whether the water table is controlled by the topography or the recharge. Various studies have used spatially distributed, synthetic groundwater models to identify and explore how topography, recharge and/or bedrock permeability influence groundwater fluxes and flow patterns (e.g., Gleeson and Manning 2008; Welch et al. 2012; Welch and Allen 2012; Welch and Allen 2014). These studies highlight the complex interplay of topography and hydrogeology on groundwater flow. They, however, mainly focus on the geology of the bedrock.

Numerous hydrological studies were dedicated to characterize the mechanisms governing low flows and the relationship between low-flow dynamics, catchment properties and variations in storage in catchments (see, e.g., reviews by Smakhtin 2001; Price 2011; Van Loon 2015). As catchment storage is not directly measurable, its estimation is problematic (Kirchner 2009; Mcnamara et al. 2011; Birkel et al. 2014). Dynamic storage is commonly defined as the storage that governs streamflow dynamics (Spence 2007; Buttle 2016), and is generally inferred from river hydrographs. Estimates of dynamic storage can vary significantly depending on the calculation method (Staudinger et al. 2017). It is widely recognized that low flows mainly derive from groundwater (Dassargues et al. 1999; Smakhtin 2001; Peters et al. 2003, 2005; Matonse and Kroll 2013). However, hydrological low-flow studies (e.g., through models such as the HBV simulator) cannot include detailed geological or hydrogeological descriptors. The subsurface is represented by characteristics such as soil parameters (e.g., Kroll et al. 2004), and the conceptualization of groundwater systems is often represented by a lumped reservoir (Broda et al. 2012; Matonse and Kroll 2013). Groundwater storage can, however, occur in different geological units of distinct hydrogeological properties, leading to strongly differing storage dynamics. The simple representation of complex storage mechanisms through linear reservoirs results in poor predictions concerning low flow (Staudinger et al. 2011). Other hydrological approaches considered the subsurface in terms of the aquifer type such as fractured, porous, and karstic aquifers (Stoelzle et al. 2015) or used indices derived from streamflow such as the baseflow index (Institute of Hydrology 1980) and recession parameters (e.g., Kroll et al. 2004; Van Loon and Laaha 2015). However, the understanding of catchment controls on low flows and on storage and release processes is still

to be improved and remains an active research field in hydrology (Price 2011; Van Loon 2015).

Other approaches are based on analytical solutions of the groundwater flow problems. They can provide insights on the controlling parameters of groundwater to streams and thus low-flow dynamics. For example, based on Townley (1995), Haitjema (2006) formulated a dimensionless time parameter that predicts whether an aquifer responds quickly, slowly or with an intermediate lapse of time to transient forcing:

$$t = \frac{SL^2}{4KbP} \quad (1)$$

where S is the aquifer storativity (–), L (m) the average distance between surface waters, K (m/d) the hydraulic conductivity, b (m) the average saturated aquifer thickness, and P (d) the period of the forcing function. This criterion illustrates that the transmissivity (the product of K and b), the storage coefficient, the width of the aquifer and the forcing function control its transient behavior. Note that the transmissivity and the storage coefficient play an important role in many analytical solutions. Another example of an analytical approach is the widespread application of the Boussinesq equation to sloping aquifers, or of other approaches derived from it, used to relate catchment-scale aquifer properties to baseflow (Brutsaert 1994; Szilagyi et al. 1998; Verhoest and Troch 2000; Paniconi et al. 2003; Pauwels et al. 2003; Troch et al. 2003; Huyck et al. 2005; Rocha et al. 2007; Troch et al. 2013; Birkel et al. 2014; Bartlett and Porporato 2018). While analytical solutions have proven useful tools in identifying controlling parameters on the dynamics of catchments, they are always highly simplified in terms of geometry, climatic forcing, and geological conceptualization. For example, the joint consideration of the bedrock and the alluvial aquifer has so far not been treated through analytical solutions. Analytical equations found in the hydrogeological literature thus suffer from similar limitations than the hydrological approaches based on box models.

The aim of this study is to improve the process understanding of low-flow dynamics by explicitly taking into account groundwater storage processes and by focusing on catchment properties that govern groundwater flow. We assess the combined impact of topography as well as of the hydrogeological properties of the bedrock and alluvial aquifers on low flows and groundwater storage processes in a systematic way and thus overcome a range of simplifying assumptions made in previous studies. We use an integrated modeling approach coupling surface and groundwater processes. Open-book-like or so-called V-catchment models composed of homogeneous bedrock and a more permeable alluvial aquifer are developed with the HydroGeoSphere software (Aquanty 2015) to test the hydro(geo)logical response to transient precipitation. River slope, hillslope and hydraulic conductivity of bedrock and alluvial aquifers are varied systematically, and width-to-length ratios and bedrock porosity are tested with a limited number of catchments, leading to a total of

496 models. While the influence of these characteristics has been explored individually in other studies, the combined controlling mechanisms of these features on low-flow dynamics are assessed here. Furthermore, the characterization of feedback mechanisms between low flows and groundwater dynamics is made possible with the physically based models.

Based on the improved process understanding, key catchment properties that govern low flow dynamics and the relative importance of bedrock and alluvial aquifers are identified. Due to the simple structure of the synthetic models, the direct application of our results to real catchments is not straightforward and requires careful consideration of the local geological and hydrological conditions. However, the models provide an improved process understanding of low-flow dynamics and catchment properties influencing them, and offer insights on the relative importance of bedrock and alluvial aquifers.

Methods

Numerical Model and Data Analysis

The HydroGeoSphere (HGS) software by Aquanty (Aquanty 2015) is used, as it simultaneously simulates surface and subsurface flow in a physically based, distributed manner. The model has been successfully used in previous studies of surface water-groundwater interactions, for example, Kurtz et al. (2018). Three-dimensional variably saturated subsurface flow and 2D surface flow are solved by Richards equation, respectively, with the diffusion wave approximation to the Saint-Venant equations. The relation between suction, saturation, and relative hydraulic conductivity in the unsaturated zone are conceptualized through the Van Genuchten approach (Van Genuchten 1980). The two domains are coupled through a first-order leakage coefficient based on head differences, allowing water to flow from one domain to the other in a physically based way. Groundwater and surface water flow equations are solved simultaneously using a control-volume finite element approach. An adaptive time stepping approach is employed, which means that the temporal discretization changes according to pre-defined numerical criteria. In a post-processing step the fluxes for daily time steps can be readily computed. Further details on HGS can be found in Aquanty (2015), Sudicky et al. (2008), Therrien et al. (2010) and Brunner and Simmons (2012). The numerous HGS outputs, such as discharge time series and storage variations in the different aquifers, are managed and analyzed using the R code (R Core Team 2017) and Tecplot (Tecplot Inc. 2013), a software environment developed to post-process simulations of fluid dynamics. Tecplot is a versatile tool that allows for example to temporally integrate water fluxes or storage dynamics for individual storage units.

Catchment Configuration

As topographical and hydrogeological characteristics influence catchment dynamics in a complex, interrelated

way, the catchment configurations should cover a wide range of possible combinations of these parameters. The synthetic models should also be simple enough to be representative of a broad spectrum of catchments and yet include the complexity of physical processes that occur in reality. We choose an “open-book” or tilted-V geometry as it represents the simplest hydrographic landscape unit. This setup approximates conditions typically encountered in headwater catchments. Besides, this setup permits a straightforward parametrization of topography and is an ideal framework to generate a wide range of hydrograph dynamics. This geometry results in the occurrence of various hydrological processes: saturated and unsaturated groundwater flow, infiltration/exfiltration, overland flow and streamflow (Partington et al. 2012).

The standard catchment setup is shown in Figure 1. The models have a surface area of 12 km² with a length (y axis) to width (x axis) ratio of 3:1, a valley width of 100 m and a 1 m deep and 8 m wide river bed. These scales are typical for headwater catchments located in the Swiss Plateau and the Prealpes. The surface outlet is located 29 m higher than the base of the model at this x-y location. The synthetic catchments are characterized by two slope gradients: the hillslope that corresponds to the slope lateral to the stream (x axis), and the river slope that defines both the longitudinal valley slope and the slope of the catchment base. The models are composed of two hydrogeological units: bedrock and alluvial deposits. The alluvial unit has a constant thickness of 10 m and extends over the whole width of the valley bottom (100 m). The remaining volume of the model is defined as bedrock. The permeability of the alluvial unit is either higher or equal to the bedrock permeability, the latter case representing a catchment with no alluvial deposits.

Experimental Design

The study is based on a central model batch (group 1) elaborated to systematically test the influence of hydraulic conductivity and slope gradients. A limited number of additional models (group 2) are developed to test the

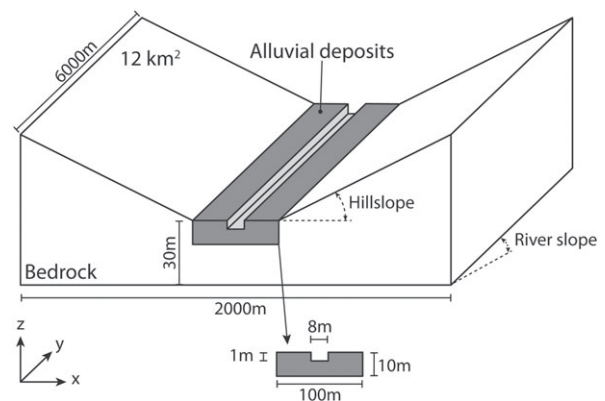


Figure 1. Standard setup of the synthetic models. The hydraulic conductivity of the bedrock and of the alluvial aquifers, the river slope and the hillslope are varied systematically.

Table 1
Catchment Properties

Parameter	Values			
Hydraulic conductivity of bedrock	10^{-8} m/s	10^{-7} m/s	10^{-6} m/s	10^{-5} m/s
Hydraulic conductivity of alluvial deposits	None	10^{-4} m/s	10^{-3} m/s	10^{-2} m/s
Hillslope	5%	18%	35%	50%
River slope	0.5%	3%	9%	15%

impact of single modifications of bedrock porosity, width-to-length ratio (aspect ratio) and meteorological forcing.

Catchment Group 1: Systematic Parameter Variations

We vary four catchment parameters: the hydraulic conductivities of bedrock and alluvial deposits, as well as the hillslope gradient and the river gradient (see Figure 1). To each of the four parameters, four discrete values are assigned and all possible combinations of parameter values are simulated. Hence 256 (4^4) catchments with different parameter combinations are generated and run. Table 1 indicates the four values assigned to each tested catchment property. The bedrock hydraulic conductivities chosen for this study cover a wide range of values observable in reality: from a low permeability of 10^{-8} m/s corresponding to an aquitard, to a relatively high permeability of 10^{-5} m/s corresponding to a porous aquifer (e.g., sandstone). The hydraulic

conductivity of the alluvial deposits varies between bedrock permeability (no distinct hydrogeological valley unit) to a high permeability of 10^{-2} m/s typical for gravels. Three values were defined for hillslope and river slope (Table 1), corresponding to low, medium, and high values typically observable in catchments of moderate elevation of Switzerland. A fourth value is added (35% for hillslope and 9% for river slope) to complete the parametrization.

Figure 2 shows four examples of catchment configurations: hillslope (HS) is set to the lowest value 5% (a, c) and highest value 50% (b, d), combined to a low river slope (RS) of 0.5% (c, d) and high river slope of 15% (a, b). The parameter hillslope delineates topography in two ways: by defining the lateral surface gradient converging to the valley bottom as well as by determining the volume available to store water. The river slope sets the slope of the inclination plane forming the base of the catchment, but does not impact available storage volume. These differences will be considered in the analysis of the result and discussed. When changing the slopes, the total volume of the bedrock aquifer changes while the geometry of the alluvial aquifer remains the same. The change in volume of the bedrock aquifer has, however, little influence on the low flow behavior as the lower part of the bedrock aquifer remains fully saturated and thus increasing its thickness has no effect (see also in the upcoming results).

Catchment Group 2: Assessment of Importance of Porosity, Aspect Ratio, and Meteorological Forcing

The supplementary catchments are only composed of bedrock (no alluvial aquifer) and all have a river slope of 3%. Twenty new combinations of hillslope-hydraulic conductivity of bedrock are modeled to sample the parameter

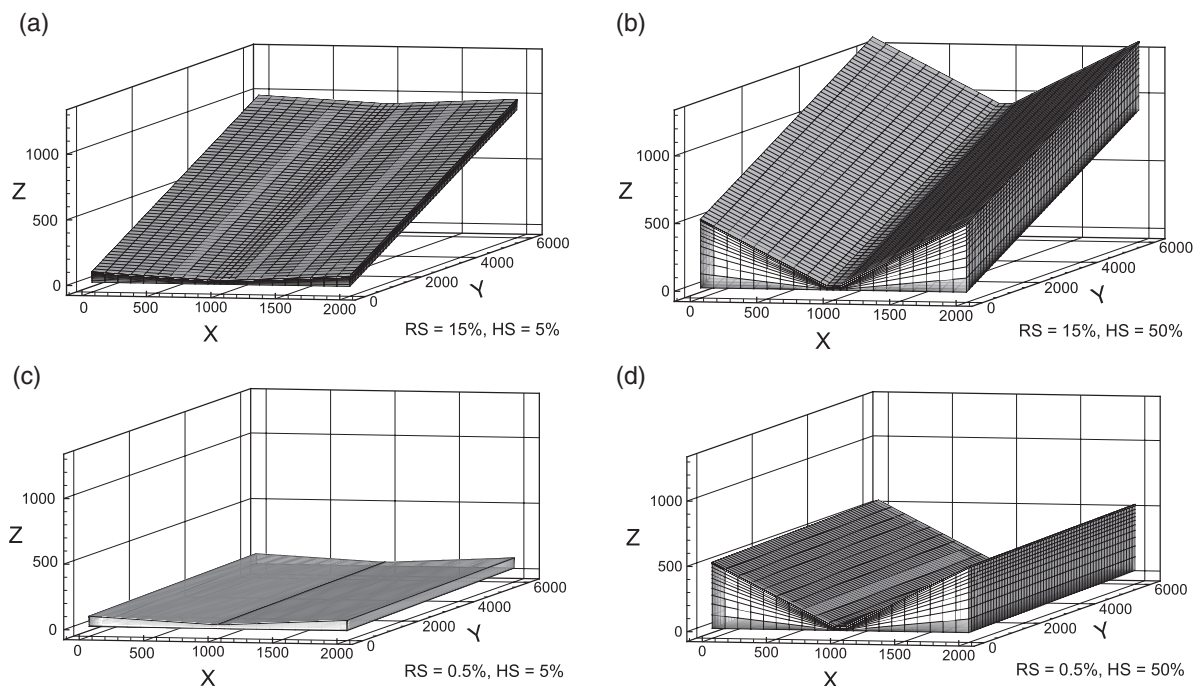


Figure 2. Examples of different topographical configurations (RS = river slope, HS = hillslope). A change in hillslope implies a change in catchment volume, whereas it is not the case for river slope variations.

space more densely (permeability of 4×10^{-7} , 7×10^{-7} , 4×10^{-6} , 7×10^{-6} , and 10^{-4} m/s combined to the four standard hillslope values). Along with all combinations of hillslope-hydraulic conductivity of “group 1” except those composed of the lowest hydraulic conductivity (10^{-8} m/s), these additional combinations result in 32 hillslope-hydraulic conductivity couples, which are used as a basis to test the following elements:

- *Role of bedrock porosity*: bedrock porosities of 0.05 and 0.2 are tested with 16 hillslope-permeability combinations (32 models). The high upper value is deliberately chosen to explore endmembers of the parameter distribution.
- *Role of aspect ratio*: widths to lengths in meters of 1000:12000, 3000:3000, and 6000:2000 are tested with all hillslope-permeability combinations (96 models).
- *Variation in meteorological input*: three other net precipitation time series measured during the same period in other geographic extremes of Switzerland (Cimetta, St. Gallen, Aigle, MeteoSwiss) are applied to the 32 models group (96 models).

Mesh and Simulation Specifications

The 2D-mesh structure is composed of 1560 rectangles (1647 nodes) reproduced in the 28 vertical layers, the 3D structure including 43'680 elements (47'763 nodes). The elements have a constant y -axis discretization of 100m, whereas the discretization in the x -direction varies between 100 and 2 m from the hillslope top to the riverbed. The top 10 m of the model is composed of 18 layers of increasing thicknesses with depth ranging from 6 cm to 1 m. The thickness of these top layers is constant over the entire model extent. This discretization is sufficiently high to guarantee a robust solution of Richards equation in the most dynamic areas of the model domain (top soil). The discretization of the 10 lower layers is proportional to the depth of the catchment: it is fixed in the valley, varying from 1 to 4 m with depth, and decreases laterally depending on the hillslope gradient. The coarser discretization of the lower layers is sufficient to simulate the saturated conditions that prevail.

A no-flux boundary is assigned to the bottom of the model and all lateral faces. A critical-depth boundary is applied to the whole surface perimeter of the catchment and groundwater consequently exits by the surface domain. This boundary condition forces the surface water depth to be at its critical depth. Due to the slope configuration, catchment discharge only occurs at the lowest point, that is, at the outlet, of the catchment and water flow is concentrated in the valley bottom. The simulated discharge considered in this study thus represents the entire catchment dynamics, integrating both groundwater and streamflow.

All the models are first run with a constant rainfall applied to each surface element for 10'000 days to ensure steady state (net rainfall = discharge $\pm 0.1\%$). Starting from the obtained steady state, models are then run over a period of 4 years with daily rainfall obtained from

a measuring station (Huttwil, Switzerland, national meteorological service of Switzerland *MeteoSwiss*) between the January 1, 2000 and the December 31, 2003, 2003 being an especially dry year in Switzerland. Because of the long time series, these initial antecedent conditions are not influencing the results: different initial conditions would affect the flow dynamics of the first few rain/drought events but not beyond that. The results of this study are focused on this 4-year, transient simulation period.

We chose not to explicitly simulate evapotranspiration with HGS and simply corrected the rainfall signal for evapotranspiration by dividing it by 2, which corresponds to the water balance of the Huttwil region. Having the same input to all models is required to identify the effect of interacting aquifer units on low flow. Moreover, as this study focuses on comparing the response of catchments with respect to their different physical properties, the input itself, being the same for all model realizations, is of lesser concern as long as it produces a wide spectrum of catchment hydrographs. Note, however, that this setup allows to consider the time-delay between infiltration and recharge in the unsaturated zone.

Even though groundwater can partially flow in fractures in the bedrock, this process must not necessarily be simulated explicitly on a catchment scale and can be represented through simpler approaches. The numerical models are thus defined as porous equivalent matrices. Except for the variations of hydraulic conductivity and porosity mentioned previously, the same values for subsurface parameters are used for bedrock and alluvial deposits in order to capture the influence of these varied characteristics on model outputs. The Van Genuchten parameters (alpha and beta) are defined to represent sand-to sandstone-like flow unsaturated dynamics adequate for both hydrogeological units: values of 8 m^{-1} resp. 2 (–) are used for alpha resp. beta. The sensitivity of catchment dynamics to these parameters was tested for a selection of models and showed that they can slightly impact the saturation distribution in the unsaturated zone but not significantly the storage and streamflow dynamics. Therefore, they are kept constant. Note, however, that sensitivity was tested for the given climatic forcing functions. It is not impossible that under significantly different conditions (e.g., an arid climate) the relative importance of these parameters could change. For the remaining subsurface and surface model parameters, the standard HGS values are kept (see Aquanty 2015 for more information).

Low-Flow and Dynamic Catchment Indicators

Q95 and Q95/Q50 are used to describe the magnitude of low flows of each catchment. Q95 characterizes the absolute low-flow magnitude, whereas the ratio Q95/Q50 can be interpreted as an indicator of low-flow dynamics. Q95 is the discharge exceeded 95% of the time and Q50 is the median discharge. The values are calculated with daily simulated discharge values for each year and averaged over the investigated period (4-year simulation period). Q95 is a widely used low-flow indicator both in research (Smakhtin 2001; Laaha and

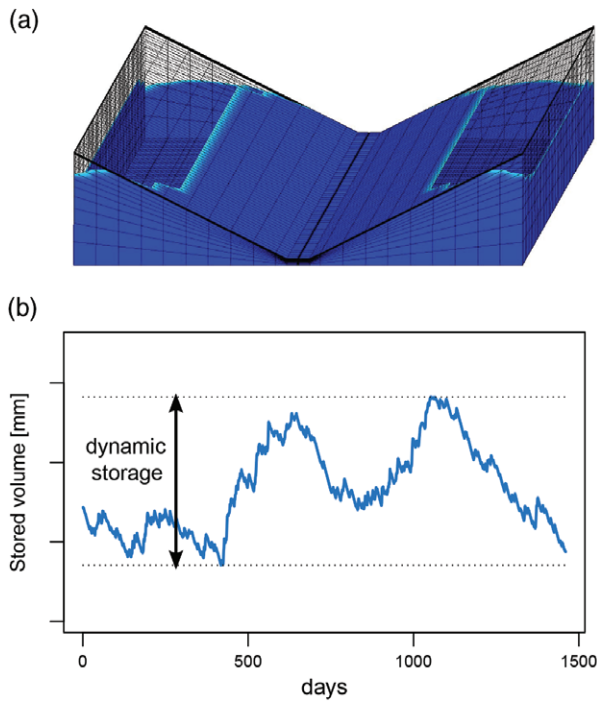


Figure 3. (a) Visualization of water storage in an example catchment (here only the saturated volume and hence the water table is represented for visual clarity). (b) Representation of dynamic storage for an example catchment (the difference between minimal and maximal absolute water volume stored during the 4-year simulation).

Blöschl 2005) and water management where it serves as a basis to define minimum flow rates required by ecosystems. Dividing Q_{95} by the median flow to obtain Q_{95}/Q_{50} is useful to compare catchments of different size and climate forcing. Q_{95}/Q_{50} can be interpreted as a descriptor of low-flow dynamics as it focuses on the lower part of the flow duration curve (FDC). It describes the variability of these lower discharges: stable and rather high low flows lead to high Q_{95}/Q_{50} ratios, whereas low ratios imply notable fluctuations of the low discharges and potentially low-flow related problems.

Groundwater dynamics are described by the total dynamic storage of the catchment, referred to simply as “dynamic storage” or V_{dyn} in some figures and encompassing both the fluctuations of storage in the bedrock and the alluvial aquifer. Based on the numerical simulations, time series of total stored water volume in the catchment throughout the simulation can be generated (illustrated in Figure 3). We can calculate the actual dynamic storage and we define it as the difference between the maximum and the minimum water volume (black arrow in Figure 3b) over the 4-year simulation period.

Results

Low Flows and Groundwater Storage Dynamics

The 256 catchments (group 1) cover a broad range of configurations causing very different low-flow and storage dynamics. The two extreme scenarios are: dynamic

storage close to 0 with a corresponding near to zero Q_{95}/Q_{50} ratio, and dynamic storage of nearly 250 mm with very high low flows and a Q_{95}/Q_{50} ratio of 0.99. The low-flow and groundwater dynamics of the 256 models are compared in Figure 4. Q_{95} and Q_{95}/Q_{50} are plotted versus dynamic storage (Figure 4a and 4b). Both indicators are strongly correlated to dynamic storage. The correlation is higher and more linear in the case of the absolute low flows Q_{95} ($R^2 = 96\%$) than for Q_{95}/Q_{50} , as Q_{50} is less dependent on groundwater contribution. Large dynamic storage ensures high groundwater contribution during low flows and high Q_{95} and Q_{95}/Q_{50} ratios. The absolute volume of water stored or *absolute storage*, averaged for the entire simulation period and per surface unit, ranges from 3 to 26 m. Neither low flows nor dynamic storage are correlated to this value. Relating absolute water storage to total porous volume indicates the proportion of the catchment volume that is filled with water. Subsequently, the difference between 1 and this ratio represents the average empty porous space in the catchment, which is correlated to dynamic storage (Figure 4c). When free porous space is limited, less water is stored during precipitation events (higher surface runoff) and therefore, less water is released during dry periods. In this case, dynamic storage is limited and low flows are less sustained.

This confirms that the magnitude of low flows is governed by groundwater, and more specifically by the catchments ability to store and release water described by dynamic storage. As the two components are closely correlated, a better characterization of the mechanisms controlling dynamic storage is beneficial for the understanding of low-flow processes. Likewise, low-flow dynamics are a valuable proxy to assess groundwater dynamics, provided most of the groundwater is drained by the river.

To illustrate the buffering effect of storage on streamflow, we highlight (highlighted points) two extreme configurations in Figure 4. Figure 5 shows the entire simulated time series of daily storage variations ΔV (subplot 5a) and streamflow Q (subplot 5b) of the two catchments *sim A* (blue) and *sim B* (red). Effective rainfall is plotted in gray in the background. Catchments A and B have a dynamic storage of 213 mm and 4 mm, respectively. Daily storage variations ΔV of *sim A* are close to effective rainfall: storage buffers the rainfall signal, that is, most of the rainfall infiltrates and streamflow is close to constant throughout the simulation. In the case of *sim B*, dynamic storage is limited and streamflow is very flashy and almost coincides with the rainfall signal. Q_{95} is close to average rainfall for *sim A* and close to zero for *sim B*. Dynamic groundwater storage hence not only governs low flows but significantly influences the overall catchment dynamics.

Identification of Controlling Properties on Low Flows

Although various approaches exist to quantify the relationship between catchment properties and dynamics (Kroll and Song 2013), the systematic experimental design used in the present study prevents multicollinearity

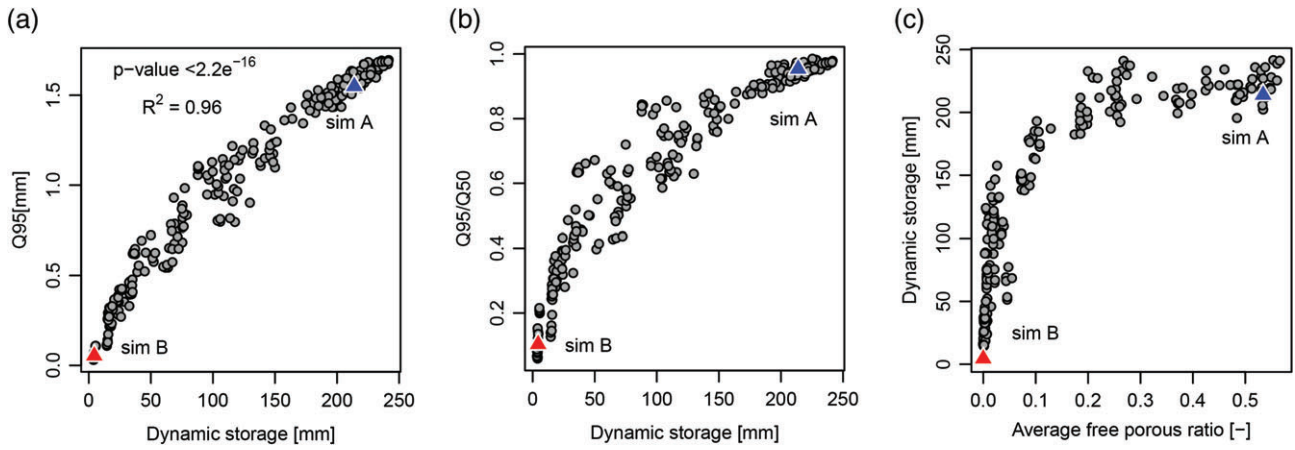


Figure 4. Outputs of the 256 models are represented by gray dots. “sim A” and “sim B” indicate two catchments with opposite dynamics (see also Figure 5). (a) Dynamic storage versus Q95, (b) dynamic storage versus Q95/Q50, (c) average free porous ratio versus dynamic storage.

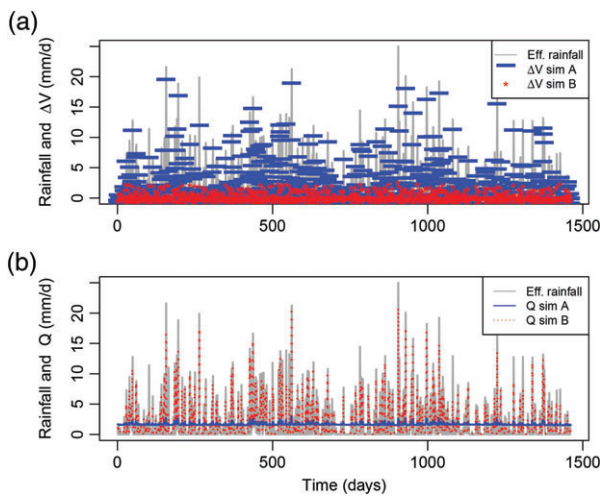


Figure 5. Daily specific storage (a) and discharge dynamics (b) of model examples “sim A” and “sim B” (see also Figure 4) for the entire simulation period of 4 years. These time series are plotted along with daily effective rainfall (PET).

issues caused by interdependencies between parameters, which can typically occur if observed data are considered. Simple linear regressions are thus preferred to more complex methods to quantify how much of the variance of Q95/Q50 is explained by catchment properties. The coefficient of determination R^2 between Q95/Q50 (y) and the linear model (LM) composed of a single catchment parameter $LM(p)$ (p being hillslope, river slope, and logarithms of bedrock and alluvial hydraulic conductivity) is calculated as follows (n : number of synthetic catchments, i : each catchment):

$$R^2 = 1 - \frac{\sum_i^n (y_i - LM(p)_i)^2}{\sum_i^n (y_i - \bar{y})^2}. \quad (2)$$

Figure 6 illustrates the results using dots whose size are proportional to the explained variance of low flows

for all simulations (first row) and for each category of bedrock permeability. Q95/Q50, Q95 and dynamic storage V_{dyn} ranges are indicated as boxplots (right side). For Q95 and dynamic storage, the results are very similar and lead to the same conclusions. The hydraulic conductivity of bedrock K_{Bedrock} is the only parameter that has an overall impact on low flows for all simulations: it explains 60% of the low-flow variance. The impact of K_{Bedrock} on Q95/Q50 ranges is appreciable (boxplots, second to fourth row): the higher K_{Bedrock} , the higher the median Q95/Q50 and the smaller the low-flow ranges. The variance of low flows explained by other properties is assessed for each category of bedrock permeability to exclude the overall influence of K_{Bedrock} . For low K_{Bedrock} (10^{-8} m/s), the capacity of the bedrock to store and release water is limited and dynamic storage can only occur in alluvial deposits. Hydraulic conductivity of these hydrogeological compartments thus considerably influences low flows ($R^2 = 54\%$) when storage in bedrock is limited. When K_{Bedrock} is increased, dynamic storage in the bedrock increases and the relative importance of alluvial deposits therefore decreases. With a higher K_{Bedrock} , we also observe a higher influence of the hillslope: 66% of the variance is explained by the hillslope gradient for K_{Bedrock} of 10^{-6} m/s, for instance. As the bedrock becomes active, its storing and releasing capacity is enhanced by steeper hillslopes because of both large storage volumes and steeper gradients. When bedrock permeability is high (10^{-5} m/s), dynamic storage and low flows reach maximal values and their variance is low. The importance of the hillslope gradient is thus smaller. No significant impact of river slope on low flows can be observed.

The influence of hydraulic and geometrical characteristics, both individually and in combination, is discussed hereafter.

Influence of Hydraulic and Geometrical Characteristics

Intuitively, pronounced streamflow dynamics and consequently smaller low-flow rates are expected for steeper catchments. However, simulation results suggest

R²: Q95/Q50 and catchment properties

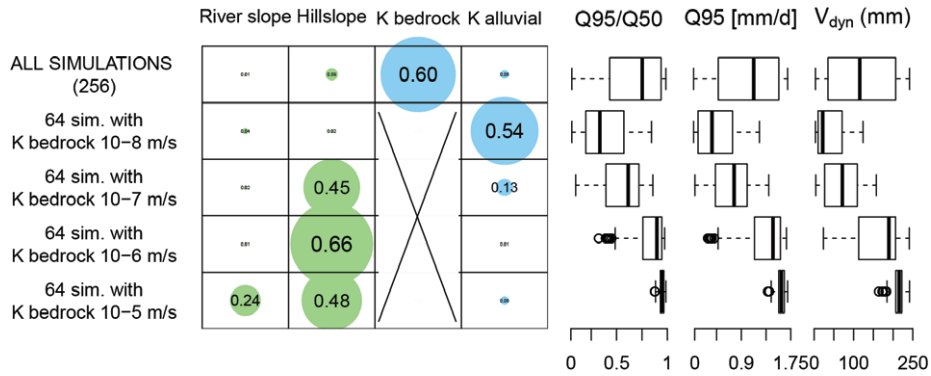


Figure 6. For all simulations with systematically varied parameters (first row) and for the different bedrock classes separately (rows 2 to 5), the ratio of Q95/Q50 variance explained by catchment properties is illustrated by circles of proportional diameters (left part of the figure, simulations of group 1). Topographical and hydrogeological features are represented in green and blue, respectively. Within groups of the same bedrock permeability, K_{bedrock} is constant and cannot explain the variance of low-flow dynamics (black cross). The right part of the figure shows the variability of Q95/Q50, Q95 and dynamic storage for each category of models.

the contrary. For the range of bedrock permeability investigated here, steeper topographical gradients do not lead to a more significant surface-runoff component. On the contrary, slope gradients can increase dynamic storage, that is, the ability of bedrock to store water and to contribute to low flows. As can be observed in Figure 7, higher hillslope values have a positive impact on low flows especially when bedrock is active but dynamic storage is not maximal (bedrock permeability of 10^{-7} and 10^{-6} m/s).

We here focus on the combined influence of hydraulic conductivity of bedrock and hillslope gradient on Q95, excluding variations of the hydraulic conductivity of alluvial deposits and river slope. Additional models (group 2) are run to further explore the parameter space by including other hillslope- K_{Bedrock} combinations, and to test the effect of aspect ratio and porosity. Q95 (mm) is plotted against the logarithm of bedrock hydraulic conductivity, and different hillslopes are illustrated by varying point styles (Figure 7). The effects of aspect ratio and porosity on Q95 are represented by gray and blue boxplots in the background of subplots a and b. Low-flow sensitivity to aspect ratio and porosity is generally not significant and the influence of these variations is relatively limited compared to the impact of hillslope and hydraulic conductivity.

Figure 7a shows that the sensitivity of Q95 regarding the hillslope gradient depends on the hydraulic conductivity of the bedrock. We can distinguish between three sections from left to right:

- In case of a very low hydraulic conductivity (here 10^{-8} m/s), the bedrock is essentially inactive as indicated by the very low Q95: even bigger slope gradients and storage volumes do not lead to an increase of its ability to store and release water. Low flows are not significantly sensitive to hillslope.
- If hydraulic conductivity is high enough for the bedrock to be active, an increase of hillslope causes an increase

in dynamic storage. In this case, low flows are strongly sensitive to hillslope.

- For a very high hydraulic conductivity of bedrock, the maximum dynamic storage is reached independently of the hillslope. Low flows are not sensitive to hillslope.

The lower hillslope curve (5%) in Figure 7a shows that a low hillslope gradient can also partially limit the catchment ability to drain water: an increase of hydraulic conductivity has only little influence on Q95 for values between 10^{-8} and 10^{-7} m/s. However, maximal Q95 values can be reached even for this limited hillslope gradient when K_{Bedrock} is high. The opposite is not true: for low K_{Bedrock} values (10^{-8} and 10^{-7} m/s) even steep hillslope gradients do not allow reaching high Q95 values. This suggests that the hydraulic conductivity is the controlling factor. Nonetheless, the influence of the hillslope on low-flow dynamics depends on the bedrock permeability and vice versa. Hence, the two properties influence low-flow dynamics in a combined way.

Bedrock Productivity Index

As low flows are strongly dependent on both hillslope and hydraulic conductivity of the bedrock, an estimation of Q95 based on a combination of these two parameters should be achievable in this synthetic framework. Using a trial-and-error approach, various dimensionless combinations of these catchment properties are plotted against the dimensionless low-flow indicator, which is Q95 divided by mean net precipitation, to force the points in Figure 7 to collapse into a single curve. The combination of catchment parameters producing the most satisfying output is detailed in the following equation. We call this ratio the bedrock productivity index (BPI).

$$\text{BPI} = \log \frac{K_{\text{bedrock}} \text{HS}^{3/2}}{P_{\text{net,mean}}} \quad (3)$$

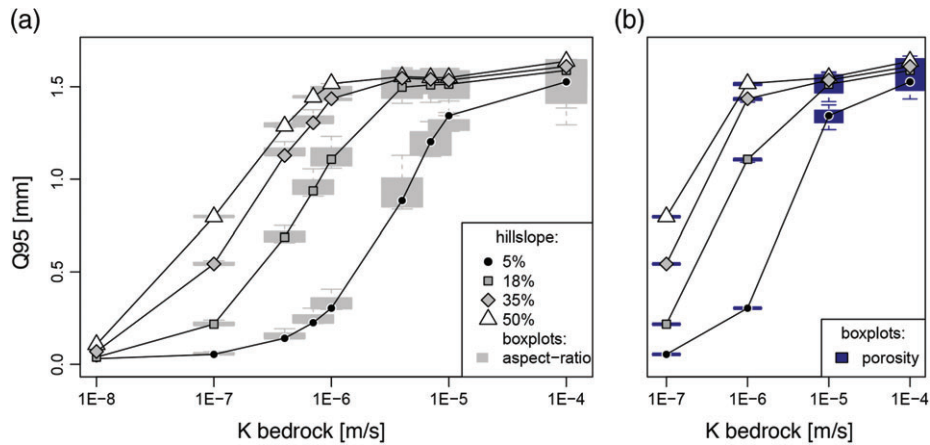


Figure 7. Q95 is plotted against the hydraulic conductivity of the bedrock (logarithmic scale) for two selections of models (constant river slope of 3% and no alluvial deposits): (a) all 36 hillslope- K_{bedrock} combinations are plotted and the gray boxplots indicate the variability of these results with regards to aspect-ratio variation (width to length in meters of 1000:12000, 3000:3000, and 6000:2000, standard value: 2000:6000) and (b) for a selection of hillslope- K_{bedrock} combinations (16 models), the variability of the results associated with varied bedrock porosity is illustrated by the blue boxplots (porosities of 0.05 and 0.2, standard value: 0.1).

The hillslope exponent (HS) is calibrated by experimentally fitting the data. These ratios allow graphically relating low flows to catchment configurations (Figure 8). To validate the correlation for other meteorological conditions, 32 models with varying configurations of hillslope and hydraulic conductivity of bedrock are run with three different precipitation time series (models of group 2) and included in Figure 8 (black dots).

The BPI is strongly correlated ($R^2 = 82\%$ for linearized correlation, all points of Figure 8) in a logistic way to the ratio of Q95 and mean net precipitation $P_{\text{net,mean}}$ (P-ET). For catchments composed of bedrock only, the simple relationship is valid for a wide range of combinations of catchment properties: hillslope and river slope gradients, hydraulic conductivity of bedrock,

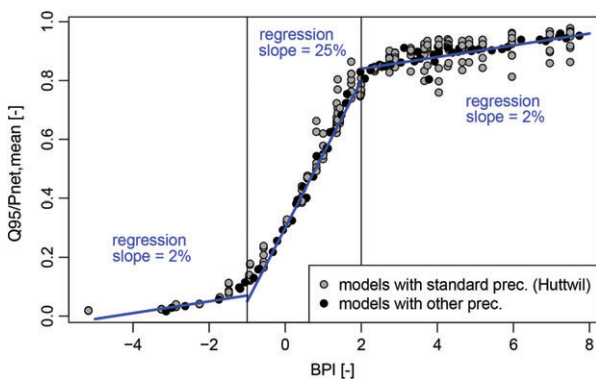


Figure 8. The ratio of Q95 to effective mean precipitation (P-ET) is plotted against the bedrock productivity index for all catchments of this study composed only of bedrock (no alluvial deposits). In total, 332 catchments are included with varying meteorological input (black dots), hillslope and river slope gradients, bedrock hydraulic conductivity, bedrock porosity and aspect-ratio values. Correlation for linearized logistic function: $R^2 = 0.82$, $p < 2.2e^{-16}$. Three sections of varying sensitivity of y to x are highlighted.

bedrock porosity and aspect ratios. Moreover, the relationship is also valid for catchments that were run with four distinct precipitation time series. The logistic behavior of the correlation illustrates the variable sensitivity of bedrock dynamics and low flows to catchment properties. Three sections in the curve of Figure 8 are observed and separated by vertical black lines. For inactive or close to inactive bedrock ($BPI < -1$), low-flow sensitivity to catchment properties is low as shown by the low regression slope of 2%. For moderate BPI values (-1 to 2), low flows are around 10 times more sensitive (regression slope of 25%) to BPI. For high BPI values ($BPI > 2$), the dynamic storage is close to maximum and the influence of catchment properties on low flows is low (regression slope of 2%). For the 130 catchments of moderate BPI values, the $Q95/P_{\text{net,mean}}$ ratio indicates a strong linear correlation to BPI ($R^2 = 97\%$). Catchments of moderate climate regions like Switzerland will likely be characterized by $Q95/P_{\text{net,mean}}$ values ranging between 0.2 and 0.8 and hence are potentially represented by the 130 catchments of moderate BPI (middle part of the plot).

Bedrock and Alluvial Valley Aquifer

We quantify the additional low-flow contribution and dynamic storage associated with the alluvial unit. Q95 values for all the catchments composed of an alluvial aquifer are plotted in Figure 9 versus the Q95 value of the corresponding catchment with no alluvial unit (same topographical and hydraulic conductivity of bedrock). The presence of an alluvial aquifer that is more permeable than the bedrock has a positive or neutral effect on Q95 but never decreases it, as no points fall under the 1:1 line. Alluvial contributions to low flows are influenced by alluvial hydraulic conductivity and river slope, as they define the groundwater flow gradient in this unit. Generally, higher values for both parameters imply higher alluvial contributions to low flows. It is not

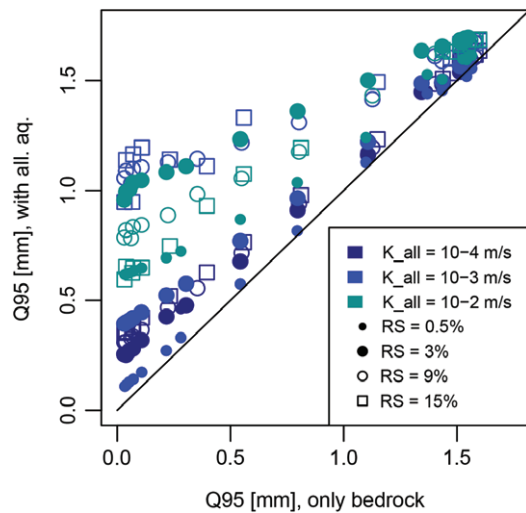


Figure 9. Q95 (mm) of all models with permeable alluvial unit versus Q95 of the corresponding model with bedrock only (same hillslope, river slope, and K_{Bedrock}). Colors indicate the hydraulic conductivity of the alluvial unit and point style the river slope “RS.”

the case when the highest river slopes of 9 or 15% are combined to the highest alluvial permeability of 0.01 m/s: low flows and dynamic storage decrease compared to settings with smaller gradients, indicating that water rapidly exits the catchment without being stored for longer dry spells. However, combinations of sandy- or gravel-like permeable alluvial deposits and steep river slopes are not likely to occur in nature as sediment transport dominates over deposition of such materials in such a setting. Models with river slopes of 9 and 15% are thus excluded from the assessment of alluvial contribution to low flows for the rest of the section. Focusing solely on realistic configuration, it can be concluded that higher river slopes and alluvial hydraulic conductivities generally lead to higher contributions to low flows.

For further illustration, Figure 10 indicates the partitioning of dynamic storage between the bedrock and the alluvial deposits, each column corresponding to a model configuration. We first observe that dynamic storage in the alluvial deposits is generally insignificant relative to dynamic storage in the bedrock when the hydraulic conductivity of this latter unit is high (10^{-6} and 10^{-5} m/s, right side of the plots). In this case, dynamic catchment storage is close to maximum, streamflow is very stable and alluvial deposits only transmit the groundwater flux from the bedrock, not influencing low flows. Even though the highest dynamic storages take place in bedrock, the relatively small alluvial deposits volume can however significantly increase dynamic storage when bedrock productivity is low (hydraulic conductivities of 10^{-8} and 10^{-7} m/s). Their ability to store and release water is enhanced by higher alluvial hydraulic conductivity and river slope. Regarding low flows, alluvial deposits with the higher river gradient (3%) can increase Q95 by 0.25, 0.75 resp. 1 mm/d for alluvial hydraulic conductivities of 10^{-4} , 10^{-3} resp. 10^{-2} m/s.

Besides identifying which catchment properties influence the alluvial contribution to low flows, we gain insight on the water mobilizing mechanism by alluvial deposits. Additional dynamic storage not only occurs in the alluvial unit itself but also in bedrock (in red): more permeable valley deposits can enhance the dynamic storage of the bedrock. The strong hydraulic gradients in the valley aquifer supposedly drain the surrounding saturated bedrock, increasing its productivity.

Discussion

Insights, Limitations, and Applicability of the Synthetic Modeling Approach

The synthetic models allow relating low-flow dynamics to the catchment properties in headwater catchments. In existing catchments, the physical and geometrical properties of the bedrock and the alluvial formation are difficult to assess. Consequently, relationships between physical properties and the observed catchments response are highly uncertain. Numerical models, on the other hand, provide a simulation framework where the physical configuration is known, and the observations are 100% accurate. Within such frameworks, reproducible and quantitative relations between the catchment properties and the catchments response can be established. However, as numerical models are always a simplification of reality (especially the synthetic models we developed here), their results are not directly transposable to complex, observable catchments. Besides, the outputs can be influenced by the conceptualization of the boundary conditions.

A critical discussion point is the conceptualization of the outflow boundary condition. In this study, the outflow of the surface water represents the overall catchment dynamics because water can only exit the catchment through the river. This setup will influence the hydraulic heads in the direct vicinity of the outflow boundary but not the flow patterns at catchment scale. An alternative would have been to allow groundwater to leave the catchment through the subsurface. However, this requires the implementation of a constant hydraulic head as an outflow boundary, which will influence the overall water balance. As the hydraulic heads near the boundary are not the primary objective of this study, but rather the overall catchment dynamics, the implementation of a critical depth boundary in combination with a no-flow boundary for the subsurface is a sound approach. If the results of this study are related to settings where groundwater can leave the catchment through subsurface flow (e.g., if highly permeable alluvial deposits are present at the catchments outlet) surface and subsurface flow rates need to be jointly considered to represent the overall catchment dynamics.

Influence of Porosity and the Hydraulic Conductivity of the Bedrock

Our results confirm the importance of aquifers in sustaining streamflow during dry periods. The dynamic groundwater storage is highly correlated to Q95. Storage

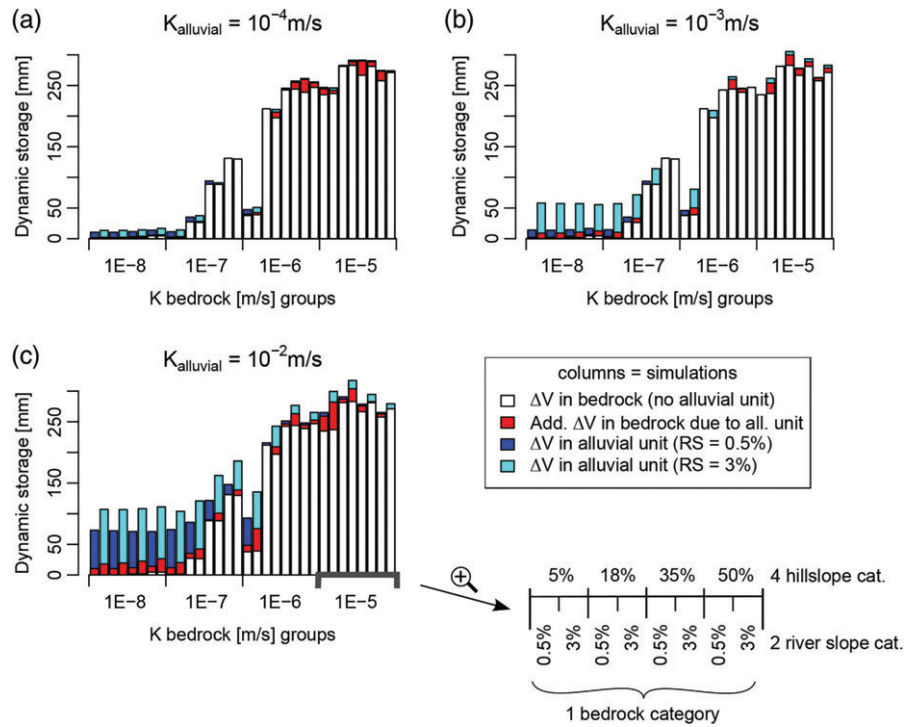


Figure 10. Illustration of dynamic storage partitioning between bedrock and alluvial deposits for 32 topographical- K_{bedrock} combinations (each column) and for three categories of alluvial hydraulic conductivity (each subplot a, b, c). Dynamic storage occurring in bedrock in the absence of a more permeable alluvial unit is represented in white. In the presence of an alluvial aquifer, additional dynamic storage is activated in the bedrock (red) and in the alluvial deposits themselves (dark blue for river slope = 0.5%, cyan for river slope = 3%).

dynamics in the subsurface and the inherent buffering effect of the catchment on the meteorological forcing is mainly governed by the hydraulic conductivity of the bedrock (Figure 6). This is in agreement with various case studies that have identified the importance of the bedrock permeability (or spatial extent of highly permeable bedrock units) for low flows (Tague and Grant 2004; Naef et al. 2015; Pfister et al. 2017; Carlier et al. 2018). The importance of this parameter cannot be understated. In fact, it is the only parameter that exerts a significant influence on low-flow dynamics throughout all proposed catchment configurations. Unfortunately, it is also a parameter that is extremely hard to determine at large scale in the field.

The relevance of the hydraulic conductivity and transmissivity are also shown by the dimensionless time parameter proposed analytically by Haitjema (2006). The analytical study further suggests that aquifer storativity is determining the aquifer dynamics. In this synthetic framework, the differences in saturated aquifer thickness between models are relatively limited compared to the wide range of hydraulic conductivity and in this sense, our results are in agreement with the analytical solutions. However, the model outputs show that the total volume of water stored in the catchment, porosity or absolute storage, are not correlated to the low-flow indicators. This is probably related to the climatic forcing we applied. While periods of drought are simulated, we have not tested conditions of arid or semi-arid areas. After a

severe drought or under arid conditions, the volume stored in the catchment will impact how long streamflow can be sustained, thus increasing the relative importance of porosity. These conditions were not observed for the meteorological conditions and the catchment setup of this study (see Figure 7). In this context, it is, however, important to consider that the experimental setting of the synthetic catchments is far more complex than the analytical conceptualizations, which can further explain the difference in controlling parameters.

Influence of Topography

The combined influence of topography and the hydraulic properties of the bedrock can to date only be assessed using numerical models, given the difficulties in quantifying the large-scale hydraulic properties of the bedrock. The discussion first focuses on bedrock properties and the hillslope. Steeper hillslopes increase the capacity of the bedrock to store and release water and are thus associated with a more stable streamflow signal and higher low flows (Figure 7). The relative importance of hillslope depends on the hydraulic conductivity of the bedrock. The hillslope gradient is oriented perpendicular to the valley bottom and consequently impacts the hydraulic gradient towards the stream. As most of water storage located above the stream occurs within the lateral bedrock flanks of the valley, this topographical feature exerts a salient control on groundwater contribution to stream.

The hillslope can be seen as a proxy for the degree of incision of the valley. Welch and Allen (2012) show that the baseflow contribution to streams of deeply incised valleys is generated by longer and deeper groundwater flow pathlines. Groundwater contributions to the stream are thus more important for a higher degree of incision, that is, steeper hillslopes. Similarly to the results presented by Gleeson and Manning (2008), our findings suggest that bedrock is drained more efficiently in case of greater valley incision.

If bedrock productivity is limited, the relative importance of alluvial deposits is high (see also upcoming section). The contribution of this hydrological unit to low flows is strongly governed by its slope (in the synthetic framework the river slope), in accordance to Darcy's law.

The analysis suggests that the topographical characteristic relevant to low flows must be associated with the most productive hydrogeological unit. Approaches which lump catchment slopes into one single index might therefore not be appropriate for an association with low-flow dynamics.

Bedrock Productivity Index

The following discussion is relevant for catchments where the bedrock is the main productive hydrological unit. The dimensionless ratio BPI is proposed to assess the productivity of bedrock based on catchment properties (hydraulic conductivity and hillslope gradient) and mean net precipitation. The BPI is highly correlated to low flows. The relationship holds for different bedrock porosities and aspect ratios. This is not surprising as these characteristics have a limited influence on catchment dynamics (Figure 6, right). Note that the BPI also allows inferring low-flow behaviors for vastly different meteorological conditions as shown in Figure 8.

The BPI is comparable to the inverse of the ratio between recharge and hydraulic conductivity R/K explored notably in Gleeson and Manning (2008). This ratio significantly influences the configuration of the water table and groundwater flow in general, as it partially determines the ability of a geological unit to dampen the input signal (recharge). By combining the bedrock permeability with the hillslope gradient in the BPI formula, we take into account the influence of the hillslope that also determines groundwater dynamics. In essence, the BPI relates the potential groundwater flux in the bedrock with the mean inflow (recharge) to the system.

Besides, the BPI is comparable to the criterion proposed by Haitjema and Mitchell-Bruker (2005) to determine whether the groundwater table is topography or recharge-controlled. Their index also includes the R/K ratio and a topographical gradient that can be associated with hillslope. Although its application focuses on water table configurations, it shares some similarities to the BPI index proposed here. We have shown that catchments with limited free porous space exhibit a pronounced streamflow signature (Figure 4). In these simulations the water table is close to the surface, a configuration defined as topography-controlled environments by Haitjema and

Mitchell-Bruker (2005). These catchments are characterized by a low BPI (typically flat, of low permeability and/or in humid regions). Conversely, a high BPI implies a considerable dynamic storage associated with a pronounced depth to groundwater. The water table, in this case, is thus recharge-controlled.

The Contribution of the Alluvial Aquifer

In addition to low flows sustained by groundwater from the bedrock, the contribution of productive alluvial aquifers can also be significant. Our findings suggest that low flows are either unchanged or higher in the presence of more permeable alluvial deposits (Figure 9). If groundwater flow from the bedrock to the alluvial aquifer is higher than the flow rates in the alluvial aquifer, the latter unit will become saturated and the dynamic storage is small. In this case, the alluvial aquifer merely plays a transmission role. The flow rates in the alluvial aquifer are, according to Darcy's law and as observed in our simulations, proportional to its hydraulic conductivity and its slope (in this case the river slope).

Interestingly, our results suggest that dynamic storage in the alluvial deposits may also activate dynamic storage in the bedrock (Figure 10). Although this additional dynamic storage might be limited, it can be highly relevant for low flows. It can provide a slower and thus more stable flow than the alluvial unit itself, contributing to streamflow even after prolonged dry periods. In general, maximal values for the total dynamic storage in the catchment and the maximal low flows are, however, only reached when the bedrock is highly productive.

Conclusions and Implications

Our study employs state of the art, fully-coupled hydrogeological models for the systematic assessment of catchment controls on low-flow dynamics. The synthetic models allow quantifying the relative importance of topography and hydrogeological properties of both the bedrock and alluvial deposits, and to better understand their combined influence on catchment dynamics under dry conditions. This study highlights the importance of groundwater processes for catchment dynamics. It is a clear demonstration of the potential benefits of considering groundwater related research in hydrological sciences.

Although synthetic models are a simplification of reality and their results are not directly applicable to existing catchments, they are valuable tools to explore the effect of catchment properties that are particularly difficult to determine, for example, the bedrock properties. Several important conclusions can be drawn. In an overall ranking, low-flow dynamics are highly dependent on the groundwater contribution from the bedrock. Even though absolute groundwater fluxes are rather small in the bedrock, they provide a stable and longer-term contribution to streamflow that are highly relevant for low flows. This contribution itself is controlled by the combined influence of hydraulic conductivity and hillslope. The hydraulic conductivity of the bedrock is

the only parameter with significant explanatory value on low flows throughout all tested parameter combinations. Because the average saturated thickness did not vary significantly in the studies, the hydraulic conductivity can be considered as *proxy* of transmissivity.

Secondly, our study shows the complex interrelations between the bedrock and alluvial aquifers. Alluvial aquifers never have a negative impact on the low-flow magnitude. Their contribution during low flow is, however, only relevant in case of a low productivity of the bedrock, provided the alluvial deposits feature a sufficiently high permeability and slope. These findings clearly suggest that the association of geological properties to low-flow dynamics has to differentiate between local alluvial aquifers and the larger geological environment. This has critical implications for the characterization of catchments. We are not aware of the existence of classification frameworks (which are widely used in hydrological sciences) that differentiates the geology in these terms and consider the interactions between the various units.

Our study further suggests that low flows are only sensitive to the topographical indicators that are directly associated with the most productive hydrogeological unit. This suggests limitations in the use of average slope indices to characterize low-flow dynamics. Given the importance of bedrock properties, new approaches for a better characterization are required. In principal, direct and indirect methods are possible. Direct measurement of the bedrock properties, however are difficult. Aquifer tests, for example will only represent a certain sampling volume, a critical limitation given the potentially great depth of bedrock aquifers. We speculate that, combined with low-flow measurements and for a geologically uniform catchment, the established relationship between the BPI and the ratio of Q95 to net mean precipitation can be used to infer the hydraulic properties of the bedrock (inverse method). Moreover, as the simulations suggest that this relationship is valid for different meteorological conditions, low-flow magnitudes for changed precipitation signal can in theory be estimated if the Q95 and the precipitation conditions of the reference period are known. This, however, needs to be tested with field data. In any case, hydrogeological prospection for water management, which often focuses on the alluvial aquifer as it might be exploited, should urgently be oriented towards an improved characterization of the bedrock and its associated properties.

Based on these results, we propose the following procedure to assess streamflow sensitivity to dry periods, and thus to identify potentially vulnerable regions. The productivity of the bedrock in terms of contribution to the streamflow should first be assessed based on its permeability and on topographical gradients. The BPI offers in this regard a quantitative approach to estimate low flows based on the bedrock and on the hillslope configuration. Moreover, if the productivity of the bedrock is limited, the potential contribution of alluvial aquifers to low flows should be estimated. River-alluvial aquifer interactions should be analyzed as significant infiltration

from river to groundwater can occur and negatively impact streamflow. This proposed sensitivity assessment highlights the relevant catchment properties governing low flows and it provides an interesting basis for catchment inter-comparison.

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Authors' Note

The authors do not have any conflicts of interest or financial disclosures to report.

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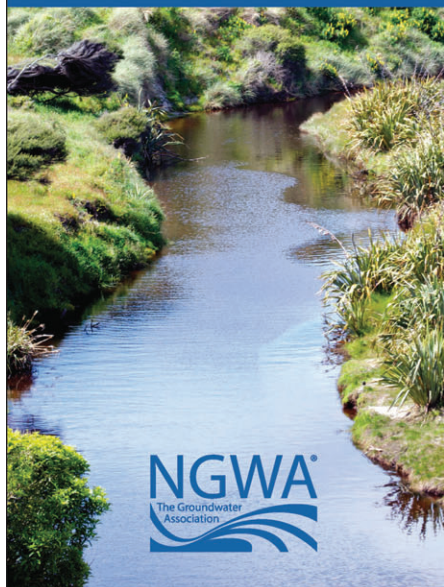
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