



Hydrogeological and topographical controls on catchment dynamics and their implications for low flows

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Summary

Periods with scarce precipitation will likely occur more frequently and last longer under changing climatic conditions, even in relatively humid regions like Switzerland. To assess the sensitivity of water resources to dry spells and to identify regions that might experience water scarcity issues, a thorough understanding of the mechanisms governing catchment dynamics in the absence of rain is essential. During dry periods, streamflow is mainly fed by groundwater reservoirs and thus reflects the ability of the catchment to release water that has been previously stored during precipitation events. Catchment characteristics that govern groundwater processes are consequently inherent to low-flow dynamics. The sensitivity of catchments to dry periods thus has to be assessed from a hydrogeological perspective.

This PhD thesis, with the global aim of providing tools for the identification of catchments sensitive to dry conditions, explores the physiographic controls on catchment dynamics with emphasis on low flows and on the role of hydrogeological factors. Previous studies dedicated to the relationship between catchment properties and streamflow dynamics often disregard the subsurface characteristics. Moreover, unravelling the various physical controls on hydrological signatures is complex based on observed data. To cope with these limitations, two approaches are developed: (1) the use of hydrogeological synthetic models, which allow the systematic assessment of topographical and hydrogeological influence on low flows and groundwater storage, and (2) an investigation of streamflow dynamics of 22 Swiss catchments with the consideration of detailed geological and hydrogeological descriptors of both the general geological environment (bedrock lithologies) and alluvial quaternary aquifers.

In the first approach, catchment hydrogeological and topographical features (bedrock and alluvial hydraulic conductivity, hillslope and river slope) are systematically varied using the numerical model HydroGeoSphere. This software simulates surface and subsurface flow in a fully coupled, distributed way. It thus allows the explicit consideration of groundwater processes and the quantification of the impact of each physical property on catchment dynamics. The synthetic models provide great insights on the relationship between low flows and groundwater processes, on the relative importance of the bedrock and the alluvial aquifer, and on the combined impact of hydraulic conductivity and slope gradients. Moreover, the role of catchment properties whose observation in the field is bound to high uncertainties, such as the hydraulic conductivity of the bedrock, can be explored with the synthetic models. The only catchment property exerting an overall impact on low flows is indeed the hydraulic conductivity of the bedrock. Relatively high hydraulic conductivities (e.g. 10^{-6} m/s to 10^{-5} m/s) of the bedrock guarantee sustained low flows. Depending on this value, the contribution of the bedrock to low flows can be increased respectively diminished by steep respectively flat hillslopes. When the capacity of the bedrock to sustain the stream (quantified by the proposed *bedrock productivity index BPI*) is limited, the relative contribution of the alluvial aquifer can become significant.

In the second approach, the catchment properties of the 22 selected catchments, encompassing land use, soil, topography and geology, as well as precipitation characteristics, are compared to numerous streamflow indicators describing the entire range of dynamics over 20 years. Absolute (e.g. Q95 to Q5) as well as relative indicators (e.g. Q95 divided by mean discharge) are used. The normalisation of the discharge indicators filters the influence of precipitation, which allows focusing on the impact of catchment properties on discharge dynamics. The meteorological and the catchment controls on hydrological signatures thus become distinguishable. The impact of precipitation is consequent on the absolute discharge indicators except for the low-flow range. The relative indicators, which describe both high and low normalised discharges, are however only correlated to the geological properties of the catchments (% of sandstone and % of productive quaternary deposits). The ability of the catchment to “buffer” the precipitation signal can thus be attributed to its geological and hydrogeological characteristics. The results suggest that this “stabilisation” effect on streamflow, quantified for instance by Q_{95}/Q_{mean} , is sustained by the presence of sandstone in the catchment. Moreover, productive quaternary deposits with a large extent or volume also seem to have a favourable effect on normalised low flows.

The two approaches are complementary and enable to identify similar processes and governing mechanisms, which are of high relevance for the characterisation of catchment and of low-flow dynamics. According to both approaches, a relatively permeable bedrock (e.g. 10^{-5} m/s, sandstone) is a prerequisite for sustained streamflow during dry periods. The influence of local productive deposits on catchment dynamics is also highlighted by both methods. Based on these findings, two guidelines are developed to assess the sensitivity of rivers and alluvial aquifers to dry periods. The assessment can be quantitative if adequate time series and data describing the resource exist, whereas it has a qualitative value if scarce discharge or groundwater head data are available. In the latter case, monitoring strategies can for instance be established on the basis of this guideline. Furthermore, it provides a framework for catchment inter-comparison with regards to their behaviour under dry conditions.

Keywords : streamflow dynamics, groundwater, low flows, numerical modelling, geology, topography

Résumé

Même dans des régions relativement humides comme la Suisse, des périodes de sécheresses plus intenses et prolongées sont attendues à cause des changements climatiques. Afin d'appréhender la sensibilité des ressources en eaux aux sécheresses et d'identifier les régions à risque, une compréhension profonde des mécanismes gouvernant la dynamique des bassins versant en l'absence de précipitation est cruciale. Pendant les périodes de sécheresses, les rivières sont principalement alimentées par l'eau souterraine. Leur débit reflète donc la capacité du bassin versant à libérer de l'eau stockée lors de précédents événements pluvieux. Les caractéristiques des bassins versants qui influencent les processus hydrogéologiques sont ainsi inhérents à leur dynamique de basses eaux. La sensibilité des bassins versants doit donc être évaluée d'une perspective hydrogéologique.

Afin de développer des outils pour l'identification des ressources en eaux sensibles aux sécheresses, cette thèse de doctorat explore les influences des propriétés physiographiques sur la dynamique des bassins versants, en mettant l'accent sur leur comportement de basses eaux et sur le rôle de l'hydrogéologie. Les précédentes études consacrées au lien entre les propriétés physiques des bassins versant et leur dynamique négligent souvent leurs caractéristiques souterraines. De plus, l'identification des effets de chaque propriété physique sur le comportement hydrologique des bassins reste complexe. Afin de contrer ces limites, deux approches sont développées : (1) l'utilisation de modèles hydrogéologiques synthétiques permettant d'évaluer systématiquement l'influence des paramètres hydrogéologiques et topographiques sur les basses eaux, et (2) l'étude de la dynamique hydrologique de 22 bassins versants suisses avec la prise en considération détaillée de leurs caractéristiques géologiques et hydrogéologiques (roche en place ou cohérente – "bedrock" en anglais – et dépôts quaternaires).

Dans le cadre de la première approche, les propriétés hydrogéologiques et topographiques des bassins (conductivité hydraulique de la roche en place et de l'aquifère alluvial, pente des versants et de la rivière) sont variées systématiquement avec HydroGeoSphere. Ce modèle numérique et distribué simule de manière couplée et simultanée les flux souterrains et de surface. Ainsi, les processus hydrogéologiques sont considérés explicitement et l'impact de chaque propriété physique sur la dynamique des bassins versants peut être quantifié. Ces modèles synthétiques bénéficient grandement à la caractérisation : du lien entre dynamiques de basses eaux et de l'eau souterraine, de l'importance relative de la roche en place et des dépôts alluviaux, et de l'influence combinée de la conductivité hydraulique et de la topographie. En outre, le rôle de propriétés difficilement mesurables sur le terrain, comme la perméabilité de la roche en place (p.ex. la Molasse en Suisse), peut être étudié. Cette caractéristique est d'ailleurs la seule à exercer un effet global sur les basses eaux de tous les bassins synthétiques. Une conductivité relativement haute (p.ex. 10^{-6} m/s à 10^{-5} m/s) de la roche en place garantit des débits de basses eaux importants. En fonction de cette valeur, la contribution de la roche en place aux basses eaux peut être favorisée par des versants raides

ou diminuée par un relief limité. Lorsque la capacité de la roche en place à subvenir aux bas débits est limitée (quantifiée par le *bedrock productivity index BPI*), la contribution relative de l'aquifère alluvial peut devenir significative.

Dans la seconde approche, les propriétés physiques des 22 bassins versants suisses sélectionnés (utilisation et types de sol, topographie, géologie et paramètres météorologiques) sont comparées à une multitude d'indicateurs hydrologiques décrivant toutes les gammes de débits sur 20 ans de mesure. Des indicateurs de débits absolus (p.ex. Q95 à Q5) ainsi que des indicateurs relatifs (p.ex. Q95 divisé par le débit moyen) sont utilisés. La normalisation des indicateurs de débit permet de filtrer l'effet des précipitations et donc de se concentrer sur l'influence des propriétés physiques du bassin sur sa dynamique. Ainsi, les effets de la précipitation et des paramètres physiques sur le comportement hydrologique deviennent distinguables. Les indicateurs absolus de débit, à part les bas débits, dépendent principalement de la météorologie. Les indicateurs relatifs, décrivant tout autant les bas que les hauts débits relatifs, sont en revanche uniquement corrélés aux paramètres géologiques et hydrogéologiques des bassins (% de grès, % de dépôts quaternaires productifs). La capacité d'un bassin versant d'"amortir" le signal de la précipitation peut donc être attribuée à ses caractéristiques géologiques et hydrogéologiques. Les résultats suggèrent que ce potentiel de "stabilisation" des débits, quantifié par exemple par le ratio $Q95/Q_{mean}$, est favorisé par la présence de grès dans le bassin. De plus, des dépôts quaternaires importants semblent également exercer un effet positif sur les bas débits normalisés.

Les deux approches sont complémentaires et permettent d'identifier des processus similaires, cruciaux pour la caractérisation de la dynamique générale et de basses eaux des bassins versants. Selon les deux lignes de recherche, une roche en place relativement perméable (p.ex. 10^{-5} m/s, du grès) est un prérequis pour des débits soutenus lors de périodes sèches. L'influence de dépôts productifs locaux sur la dynamique des bassins est soulignée par les deux approches. Sur la base de ces résultats, deux aides à l'évaluation de la sensibilité des rivières et des aquifères alluviaux aux sécheresses sont développées. Les méthodes dépendent du type et de la qualité des données disponibles. Si celles-ci sont suffisantes, l'estimation de la sensibilité peut être quantitative, alors qu'elle a une valeur qualitative si les données de débits ou de hauteurs piézométriques sont rares. Dans le second cas, des stratégies de surveillance des ressources en eau peuvent notamment être établies sur la base des lignes directrices proposées. En outre, celles-ci proposent un cadre de comparaison du comportement des bassins versants en période sèche.

Mots clés : dynamique des débits des rivières, eau souterraine, basses eaux, modèles numériques, géologie, topographie

Zusammenfassung

Längere und häufigere Trockenheitsperioden sind aufgrund der Klimaänderung auch in relativ feuchten Regionen wie der Schweiz zu erwarten. Um die Sensitivität von Wasserressourcen bezüglich Trockenzeiten zu bestimmen, sowie um Risikoregionen zu identifizieren, ist ein gründliches Verständnis der Dynamik von Einzugsgebieten während trockenen Perioden deshalb unverzichtbar. In Trockenzeiten werden Flüsse hauptsächlich von Grundwasserspeichern gespeist. Niedrigabflüsse spiegeln also die Fähigkeit eines Einzugsgebiets wider Wasser abzugeben, welches während vorheriger Regenereignisse gespeichert wurde. Die physikalischen Charakteristiken, die Grundwasserprozesse beeinflussen, sind dementsprechend von hoher Relevanz für die Niedrigwasserdynamik. Die Empfindlichkeit von Einzugsgebieten gegenüber Trockenzeiten sollte demnach aus einer hydrogeologischen Perspektive bewertet werden.

Das übergreifende Ziel dieser Doktorarbeit ist die Entwicklung von Ansätzen für die Identifizierung von Einzugsgebieten, die empfindlich auf Trockenperioden reagieren. Dafür werden die Einflüsse von physiographischen Eigenschaften auf die Abfluss- und Grundwasserdynamik untersucht, unter dem Schwerpunkt des Niedrigwasserverhaltens und der Rolle hydrogeologischer Faktoren. Die hydrogeologischen Charakteristiken wurden in bisherigen Studien über den Zusammenhang zwischen Einzugsgebietseigenschaften und Abflussdynamik oft vernachlässigt. Außerdem sind die Einflüsse der hydrogeologischen, topographischen und klimatischen Eigenschaften auf die Abflussdynamik komplex. Die folgenden zwei Ansätze sind angewandt: (1) die Benützung von synthetischen hydrogeologischen Modellen, die die systematische Bewertung von topographischen und hydrogeologischen Einflüssen auf den Niedrigwasserabfluss und die Grundwasserspeicherung erlauben, und (2) die Untersuchung der hydrologischen Dynamik von 22 schweizerischen Einzugsgebieten, welche die Geologie (Molasse und quartäre Ablagerungen) und die Hydrogeologie detailliert betrachtet.

Im ersten Ansatz werden mit dem numerischen Modell HydroGeoSphere die hydrogeologischen und topographischen Parameter der Einzugsgebiete (hydraulische Leitfähigkeit vom Festgestein und vom alluvialen Aquifer, Hang- und Flussneigung) systematisch variiert. Mit dieser Software werden die oberflächlichen und unterirdischen Flüsse physikalisch gekoppelt und räumlich verteilt simuliert. Dementsprechend sind die Grundwasserprozesse explizit berücksichtigt und der Einfluss von jeder physikalischen Eigenschaft auf die Einzugsgebietsdynamik kann bestimmt werden. Die synthetischen Modelle sind besonders informativ um den Zusammenhang zwischen Niedrigwasserverhalten und Grundwasserprozessen besser zu verstehen, um die relative Wichtigkeit von Festgestein und von alluvialen Ablagerungen zu bewerten, sowie um den kombinierten Effekt von hydraulischer Leitfähigkeit und Topographie besser zu beurteilen. Ausserdem kann die Rolle von schwierig messbaren Eigenschaften wie die hydraulische Leitfähigkeit des Festgesteins untersucht werden. Die synthetischen Modelle zeigen, dass die hydraulische Leitfähigkeit des

Festgesteins nämlich einen übergreifenden Einfluss auf das Niedrigwasserverhalten ausübt. Relativ hohe hydraulische Leitfähigkeiten (z.B. 10^{-6} m/s to 10^{-5} m/s) gewährleisten stabile Niedrigwasserabflüsse. In Abhängigkeit der hydraulischen Leitfähigkeit kann der Grundwasserbeitrag des Festgesteins während Niedrigwasserbedingungen wegen steilen bzw. flachen Hangneigungen erhöht bzw. erniedrigt werden. Falls das Festgestein nur bedingt zum Oberflächenabfluss beiträgt (quantifiziert mit den vorgeschlagenen *bedrock productivity index BPI*), kann der Beitrag des alluvialen Aquifers von Wichtigkeit sein.

Im zweiten Ansatz werden die Eigenschaften (Landnutzung, Boden, Topographie, Geologie sowie Niederschlagsdaten) der 22 ausgewählten Einzugsgebiete mit zahlreichen Abflussindikatoren verglichen, welche die Abflussdynamik über einen Zeitraum von 20 Jahre beschreiben. Absolute Abflussindikatoren (z.B. Q95 bis Q5) sowie relative Abflussverhältnisse (z.B. Q95 dividiert durch mittleren Abfluss) werden benutzt. Die Normalisierung der Indikatoren erlaubt es, den Einfluss des Niederschlags herauszufiltern, um auf der Rolle der Einzugsgebietseigenschaften zu fokussieren. Dadurch werden die Effekte des Niederschlags und der physikalischen Eigenschaften auf die Abflussdynamik unterscheidbar. Die meisten absoluten Abflussindikatoren, mit Ausnahme der Niedrigwasserabflüsse, werden hauptsächlich vom Niederschlag bestimmt. Hingegen sind die relativen Indikatoren, die sowohl die Niedrig- sowie die Hochwasserverhältnisse beschreiben, nur zu den geologischen Eigenschaften (% Sandstein und % produktiven Quartärablagerungen) korreliert. Die Fähigkeit eines Einzugsgebiets, das Niederschlagssignal zu "dämpfen", kann demnach auf seine geologischen und hydrogeologischen Charakteristiken zurückgeführt werden. Die Resultate zeigen, dass diese "Stabilisierung" der Abflussdynamik, quantifiziert z.B. mit Q95/Qmean, stark von der Anwesenheit von Sandstein im Einzugsgebiet bestimmt wird. Ausserdem haben ergiebige und weitverbreitete Quartärablagerungen auch einen positiven Einfluss auf die relativen Niedrigwasserabflüsse.

Die zwei Ansätze ergänzen sich und erlauben es, Prozesse zu identifizieren, die für die Charakterisierung der Niedrigwasserdynamik in einem Einzugsgebiet grundlegend sind. Beide Ansätze zeigen, dass ein relativ durchlässiges Festgestein (z.B. 10^{-5} m/s, Sandstein im zweiten Ansatz) eine Voraussetzung für hohe Niedrigabflüsse ist. Der Einfluss von ergiebigen alluvialen oder Quartärablagerungen auf Einzugsgebietsdynamik wird auch durch die beiden Ansätze bestimmt. Darauf basierend werden zwei Richtlinien zur Bestimmung der Empfindlichkeit von Flüssen und alluvialen Aquiferen bezüglich Trockenperioden entwickelt. Die vorgeschlagenen Methoden hängen von der Datenverfügbarkeit ab. Falls ausreichend Daten zu Oberflächenabfluss und Grundwasserständen vorhanden sind, kann die Bestimmung der Empfindlichkeit quantitativ sein. In Abwesenheit solcher Daten ist diese Einschätzung qualitativ. Im zweiten Fall können basierend auf der Richtlinien Monitoringstrategien entwickelt werden. Ausserdem stellen diese Richtlinien einen Rahmen für den Vergleich des Verhaltens von Einzugsgebieten unter trockenen Bedingungen dar.

Schlüsselbegriffe: Abflussdynamik, Grundwasser, Niedrigwasser, numerische Modelle, Geologie, Topographie

Contents

1	Introduction	1
1.1	Context	1
1.1.1	The “Low flow” project	2
1.2	Physical processes	4
1.3	Literature review	5
1.3.1	Studies relating stream dynamics and catchment properties	5
1.3.2	Studies relating groundwater dynamics and catchment properties	7
1.4	Methodology and structure of the thesis	8
2	Exploring geological and topographical controls on low flows with hydrogeological models	11
2.1	Introduction	13
2.2	Methods	15
2.2.1	Numerical model and data analysis	15
2.2.2	Catchment configuration	15
2.2.3	Experimental design	17
2.2.4	Mesh and simulation specifications	19
2.2.5	Low-flow and groundwater dynamics indicators	20
2.3	Results	21
2.3.1	Low flows and groundwater storage dynamics	21
2.3.2	Identification of controlling properties on low flows	23
2.3.3	Influence of hydraulic and geometrical characteristics	25
2.3.4	Bedrock productivity index (BPI)	27
2.3.5	Bedrock and alluvial valley aquifer	28
2.4	Discussion	30
2.4.1	Applicability of the synthetic model approach	30
2.4.2	Influence of the hydraulic conductivity of the bedrock	31
2.4.3	Influence of topography	31
2.4.4	Bedrock productivity index BPI	32
2.4.5	Contribution of the alluvial aquifer	33

2.5	Conclusions and implications	33
3	Assessment of catchment controls on streamflow dynamics: the importance of geology	37
3.1	Introduction	39
3.2	Method and catchment characteristics	42
3.2.1	Catchment selection	42
3.2.2	Topography	46
3.2.3	Soil and land use	46
3.2.4	Geology and hydrogeology	46
3.2.5	Precipitation and evapotranspiration	47
3.2.6	Discharge	47
3.2.7	Water balances	48
3.3	Results	50
3.3.1	Analysis of interdependency among catchment properties and meteorological conditions	50
3.3.2	Relationship between streamflow signature and catchment and meteorological properties	50
3.4	Discussion	58
3.4.1	Climate and catchment controls on streamflow dynamics	58
3.4.2	The influence of geology on the buffering potential of catchments	60
3.4.3	Buffering potential and dynamic storage: a groundwater perspective	62
3.4.4	Importance of other catchment properties for streamflow dynamics	63
3.5	Conclusions and implications	64
3.5.1	Implications for hydrological sciences	64
3.5.2	Implications for water resources management and data acquisition	65
4	Implications for catchment sensitivity to dry periods	67
4.1	Comparison of findings of Chapters 2 and 3	67
4.1.1	Dynamic groundwater storage and buffering potential of the catchment	68
4.1.2	The role of geology and the relative importance of the bedrock and the alluvial deposits	69
4.1.3	The role of topography	70
4.1.4	The configuration of the outlet	70
4.2	Application to the assessment of the sensitivity of water resources to dry periods	70
4.2.1	Assessment of streamflow sensitivity to dry periods	71
4.2.2	Assessment of the sensitivity of an alluvial aquifer to dry periods	75

5 Conclusion	79
5.1 Implications for practice	80
5.1.1 Suggestions for data acquisition	81
5.2 Implications for further research	82
Bibliography	85
A Parameters and main outputs of the synthetic models (Chapter 2)	95
B Characteristics of the 22 Swiss catchments (Chapter 3)	107

Chapter 1

Introduction

1.1 Context

Meteorological droughts are expected to increase in frequency and intensity in Europe due to changing climatic conditions (IPCC (2014)). In Switzerland, warmer and drier summers are foreseen as a consequence of the northward expansion of the North African high-pressure zone, itself supported by the global warming trend (Fischer et al. (2015), CH2011 (2011)). Already in 2003, 2011 and 2015, the country experienced exceptionally dry meteorological conditions that significantly impacted streamflow, lakes and groundwater levels (FOEN (2016), FOEN (2011), Rebetez et al. (2006)). The “CCHydro” project (climate change and hydrology in Switzerland), which assessed the impacts of climate changes on water resources (FOEN (2012)), showed that water scarcity issues will likely occur more often in summer.

The combination of the impacts of climate change and the growth of the Swiss population exerts a considerable stress on water resources. In this context, the Swiss National Research Programme “Sustainable Water Management” (NRP 61, 2008-2014) developed the transdisciplinary foundations necessary to establish strategies to guarantee water resources in Switzerland in the future. The importance of integrated water resources management applied at catchment scale was highlighted by various projects of the program. The “GW-trend” project showed, for instance, that aquifers that react relatively slowly compared to other storage units are especially relevant during dry periods. The contribution of these aquifers to low flows, as well as groundwater storage processes in general, are however difficult to quantify both in time and space. The synthesis report of the NRP 61 (Leitungsgruppe NFP 61 (2015)) therefore emphasised the need to better assess groundwater processes and their relevance for water resources management during dry periods.

1.1.1 The “Low flow” project

To cope with the above mentioned limitations identified by the NRP 61 programme, the Federal Office for the Environment (FOEN) launched the so-called “Low flow” project (2014-2017, see report by Arbeitsgruppe Low flow (2018)) dedicated to the impact of climate change on groundwater and low flows in Switzerland. A short overview of the purpose and the methodology of this project is given here.

With the final aim of proposing a guideline for the assessment of water resource sensitivity, this project assessed catchment dynamics under dry conditions by considering hydrological processes of both the surface and the subsurface. The present thesis was carried in the framework of this project. The project group was composed of hydrologists from the University of Freiburg (Germany) and the University of Zurich, as well as hydrogeologists from the University of Neuchâtel. An interdisciplinary approach, combining surface and groundwater research perspectives and concepts, was crucial to improve the characterisation of groundwater and low-flow dynamics under dry conditions.

To provide the authorities (e.g. FOEN, cantons) with information on how to assess catchment sensitivity to dry spells, the mechanisms governing low flows and groundwater storage have to be characterised. Besides, modelling tools that are easily implementable and applicable to a large number of catchments are necessary for the quantification of this sensitivity. The project thus combined the strengths of hydrogeological models (HydroGeoSphere) for process understanding purposes and hydrological models (HBV) for a straightforward implementation. The understanding of low-flow processes was supported by the analysis of observed data. A new version of the HBV model, more adapted to low-flow situations, was developed by the University of Zurich notably by comparing the outputs of the hydrogeological and the hydrological models. The process understanding part of the project was mainly carried out in Neuchâtel, whereas the developments of the HBV model and climate scenarios, as well as the characterisation of the applicability of low-flow indicators were accomplished in Freiburg and in Zurich. In the framework of regular meetings throughout the project, the FOEN provided numerous inputs and directions to the research.

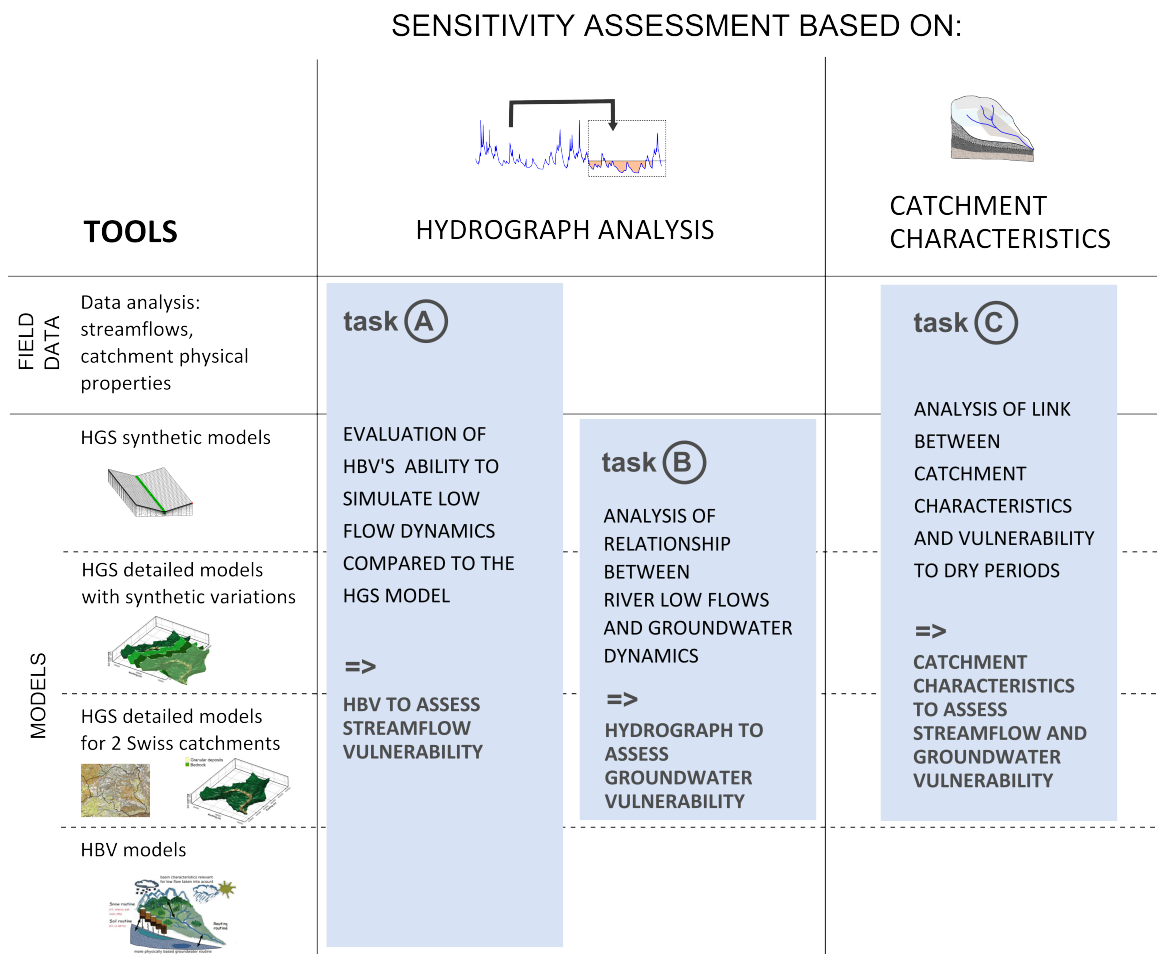


Figure 1.1: Structure of the “Low flow” project (Arbeitsgruppe Low flow (2018)): main tasks (light blue), carried out with various tools (left column) necessary to develop the sensitivity assessment methods (two main columns). Many interactions between the different tasks took place. This thesis focuses on the sensitivity assessment based on catchment characteristics with the use of synthetic models and data analysis (“task C” and two top tools).

The structure of the “Low flow project” is illustrated in Figure 1.1. The sensitivity of a catchment to dry periods can be assessed based on discharge data (observed or simulated, “Hydrograph analysis” column) or based on the physical characteristics of the catchment when no discharge data is available (“Catchment characteristics” column). The mains tasks of the project are defined for each of these assessment methods. To carry out these tasks, different tools such as models and field data analysis are used and listed on the left side of the figure. This thesis focuses mainly on the sensitivity assessment based on catchment characteristics with the use of synthetic models and data analysis (“task C” and two top tools). The relationship between low flows and groundwater dynamics is also characterised by this work (“task B”). The present study thus develops the underlying scientific principles – the characterisation of streamflow and groundwater dynamics under dry conditions – necessary to elaborate the guideline for the assessment of water resource sensitivity.

The methodology of the thesis is described more thoroughly after the description of the main physical processes relevant to the present work and a brief literature review.

1.2 Physical processes

Figure 1.2 gives a schematic overview of the hydrological cycle in a catchment and illustrates the important surface and groundwater fluxes (in blue). Storage and discharge processes taking place in the catchment, i.e. the catchment response to the meteorological input, are governed by its physiographic properties (Smakhtnin (2001)). Soil and land use properties, topography and subsurface characteristics determine overland and channel flow, infiltration, groundwater recharge, flow and discharge to the stream. The outflow of the catchment thus reflects the combination of multiple processes.

In the absence of precipitation, surface hydrological processes and their related properties become less relevant and streams are mainly fed by groundwater (Smakhtnin (2001), Peters et al. (2003), Peters et al. (2005), Matonse and Kroll (2013)). The contribution of aquifers to the stream depends on previous meteorological conditions, on their hydrogeological properties and topographical settings as well as on their connection to the stream. Catchment dynamics under dry conditions therefore also depends on storage processes during precipitation events.

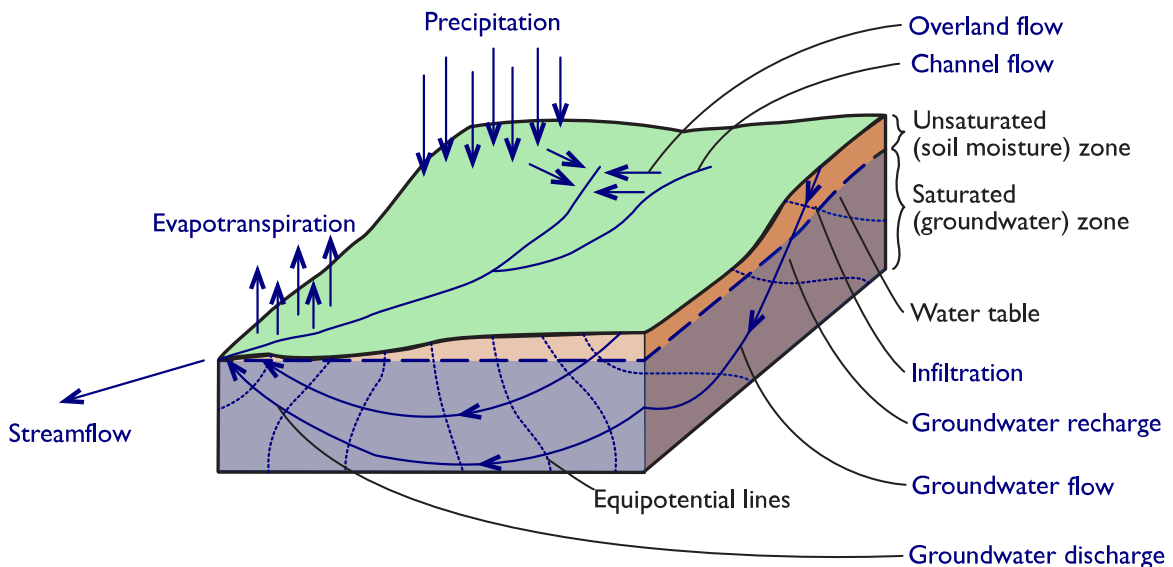


Figure 1.2: Schematic representation of the hydrological cycle (after Freeze and Cherry 1979). Fluxes are indicated in dark blue.

Understanding the physical processes determining the dynamics of rivers and aquifers is thus crucial to assess the water resources sensitivity to dry spells. These mechanisms remain, however, still poorly characterised (Van Loon (2015)). To cope with these limitations, the features that determine the storage and releasing processes in a catchment and

thus groundwater contribution to streamflow should especially be considered, such as the geological settings, hydrogeological properties and topography. Based on these considerations, the scope of the thesis can be refined as follows:

The catchment controls on streamflow dynamics are investigated, with the emphasis put on the low-flow range and on the role of hydrogeological and topographical characteristics. This exploration should allow distinguishing the physiographic properties that substantially influence the catchment behaviour under dry conditions, hence providing tools for the identification of regions sensitive to dry spells.

A short literature review is now proposed, followed by the methodology of the thesis. In the introductions of Chapters 2 and 3, a more exhaustive description of previous findings is made.

1.3 Literature review

Research carried out in both the fields of hydrology and hydrogeology is relevant for the present work. Previous findings on the relationship between physical catchment properties and streamflow dynamics with a focus on low flows are first summarised, followed by groundwater studies dedicated to topographical and hydrogeological controls on groundwater flow.

1.3.1 Studies relating stream dynamics and catchment properties

Assessing the relationship between physiographic characteristics and stream dynamics is crucial for understanding hydrological processes, for determining the behaviour of ungauged catchments and for the prediction of streamflow under changing climatic, land use or water use conditions. Numerous studies have thus been dedicated to assess the impact of vegetation, soil, topography and geology on the catchment response to the meteorological signal. As illustrated by Hrachowitz et al. (2013) or Blöschl et al. (2013) in their reviews, a whole panel of articles investigates the role of catchment properties in governing streamflow dynamics for the purpose of hydrological prediction in ungauged basins. Various studies aim for instance at expressing the flow duration curve based on meteorological and geomorphological characteristics (e.g. Müller et al. (2014), Pugliese et al. (2014), Castellarin et al. (2004), Castellarin et al. (2007), Botter et al. (2007a), Botter et al. (2007b), Doulatyari et al. (2015), Cheng et al. (2012), Coopersmith et al. (2012), Ye et al. (2012)). As reviewed by Razavi and Coulibaly (2013), most of the studies in the field of streamflow focus on identifying the best methods to transfer model parameters from one catchment to the other, typically using hydrological models such as HBV (Seibert and Vis (2012)). Numer-

ous studies also aim at better characterising the effect of catchment properties on low-flow behaviour (see e.g. reviews by Van Loon (2015), Price (2011), Smakhtnin (2001)).

From this profusion of articles that investigate catchment controls on streamflow dynamics, relatively few consider actual geological or hydrogeological characteristics. Razavi and Coulibaly (2013) illustrate this in their review on regionalisation methods: catchment area, elevation, and slope are the most widely used properties considered by researchers. Another similar review suggests that drainage area, land use, slope, soil classification and elevation are the most recurrent physiographic characteristics in such studies (He et al. (2011)).

Nonetheless, various studies have shown that specific geological units or hydrogeological characteristics substantially influence streamflow dynamics. A few studies carried out in California and Oregon highlighted the importance of geology in determining the streamflow regime and its response to climate change (Tague and Grant (2004), Mayer and Naman (2011), Jefferson et al. (2008)). The role of sandstone in stabilising streamflow has been identified by different case studies (e.g. Jencso and McGlynn (2011), Nippgen et al. (2011), Naef et al. (2015)). Various articles indicate that the bedrock can substantially contribute to baseflow (Bloomfield et al. (2009), Uchida et al. (2008), Andermann et al. (2012), Birkel et al. (2014), Welch and Allen (2012)). The importance of quaternary formations such as alluvial deposits for streamflow generation has been less characterised, although research in Switzerland suggest that these local geological units can impact low-flow dynamics (Käser and Hunkeler (2016), Naef et al. (2015)).

Despite the numerous studies dedicated to the subject, the understanding of catchment controls on streamflow dynamics, and especially on low flows, is still limited. We identify two main reasons to explain this:

- The physiographic influences on streamflow are manifold, can be combined and are site-specific. It is thus highly complex, based on observed data, to disentangle the effect on hydrological signatures of each characteristic in a systematic and independent manner.
- Although subsurface processes can play a predominant role in the hydrological cycle (Freeze and Cherry (1979)), especially under dry conditions, geological and hydrogeological descriptors are only rarely considered in these studies. Catchment controls on streamflow dynamics are generally assessed with a “surface perspective” and consequently a simplistic conceptualisation of groundwater processes.

Whereas the first limitation is inherent to the complexity of physical processes occurring in nature, the rare consideration of (hydro)geological descriptors in hydrological studies is mainly attributable to the choice of considered parameters. Of course, the characterisation of the subsurface is difficult, and detailed hydrogeological characteristics are thus often scarce. However, the limited availability of geological data is partially responsible for the

rare inclusion of geology in such studies. The fundamental reason for this poor consideration of geology may be more likely bound to the conceptualisation of storage processes in catchment hydrology. Streamflow variations are commonly associated to the storage behaviour of the catchment in the field of hydrology (Kirchner (2009)), the importance of the subsurface domain being in a sense acknowledged. In fact, groundwater theory has considerably contributed to the conception of catchment dynamics and to hydrological modelling, as illustrated by multiple approaches derived from the Boussinesq equation for sloping aquifer (Troch et al. (2013)). However, storage in hydrology is traditionally represented by a single or a few lumped reservoirs and this conceptualisation is widely used in hydrological models such as HBV. The parameters related to these storage units, either modeled or extracted by hydrograph analysis, are then commonly interpreted as the reflection of catchment-scale hydraulic properties (Kirchner (2009)). Various studies, for instance, use streamflow-based indicators such as the baseflow index (e.g. Cheng et al. (2012)) or model parameters (e.g. De Felice et al. (1993), Castellarin et al. (2004), Castellarin et al. (2007)) as descriptors of the contribution of groundwater. This simplistic conceptual structure potentially hinders the consideration of the actual complexity of subsurface processes, and thus the general understanding of hydrological processes.

1.3.2 Studies relating groundwater dynamics and catchment properties

Although research in the field of groundwater presented here do not implicitly deal with streamflow dynamics, their findings can be relevant for surface hydrology because subsurface flow contributes to streamflow and especially low flows.

The influence of topography, recharge and permeability on groundwater flow in the bedrock has been investigated by various hydrogeological studies using physically-based models. Gleeson and Manning (2008) have shown that the water table elevation depends on the ratio of the hydraulic conductivity to recharge rates. Haitjema and Mitchell-Bruker (2005) propose a criterion to determine whether the water table is topography- or recharge-controlled. The developed combination based on the Dupuit-Forchheimer approximation is composed of the ratio between recharge and hydraulic conductivity, as well as geometrical aquifer properties and topographical characteristics. In regions with high precipitation rate or limited permeability, the water table is often topography-controlled and it evolves parallel and close to the surface. In arid regions, during dry periods or when hydraulic conductivity values are high, the water table is lower and thus less influenced by topography and governed by recharge instead. Other studies have explored the impact of topography, recharge and/or bedrock permeability on groundwater fluxes and flow patterns using synthetic catchments developed with groundwater distributed models (e.g. Gleeson and Manning (2008), Welch et al. (2012), Welch and Allen (2012), Welch and Allen (2014)). The findings of

these studies suggest that topographical and hydrogeological features, as well as recharge rates, influence groundwater processes in a combined way.

With regards to the objectives of the thesis, following gaps can be identified in the mentioned groundwater research:

- The consequences of the results for streamflow dynamics are not discussed, as it is not the scope of these studies.
- The studies mainly focus on groundwater processes in the bedrock, whereas the contribution of more local alluvial aquifers might be relevant for streamflow dynamics.
- They do not assess systematically the combined influence of topographical and hydrogeological properties on groundwater flow under transient recharge conditions.

1.4 Methodology and structure of the thesis

To tackle the limitations mentioned previously, this thesis is based on two main research lines that explore the relationships between catchment properties and dynamics using hydrogeological models (Chapter 2) and observed data (Chapter 3).

Classical hydrological models are of great utility to assess river dynamics of large-scale catchments and efficiently simulate floods. However, their reproduction of low-flow dynamics is poor (Staudinger et al. (2011)). These models, as they represent hydrological and groundwater processes in a simplistic way, neglect the complexity related to the the main contribution to streamflow in the absence of rain. Besides, the structure and the parametrisation of this type of models can significantly influence the simulated low flows (Vansteenkiste et al. (2014)). Numerical, physically-based models allow coupling groundwater and river dynamics and are thus more appropriate for low-flow simulations (Dassargues et al. (1999)). Because of their complex parametrisation and the important computational requirements, their application to large and numerous catchments in the perspective of identifying regions vulnerable to droughts is nonetheless not conceivable yet.

In the first approach, simple but numerous numerical models are thus developed, which take advantage of the physically-based reproduction of surface and subsurface processes offered by such models. The influences of topographical and hydrogeological features on low flows and groundwater dynamics are systematically assessed with these synthetic models. As the catchment configurations are defined in the experimental design, the physical characteristics are known. It is thus possible to test the impact of hard to obtain or highly uncertain properties such as the permeability of the bedrock. The topographical and hydrogeological features can be varied independently and their impact on flow dynamics can be identified and quantified systematically. This method thus allows disentangling artificially the effect of various properties on the hydrological signatures.

The HydroGeoSphere software (*HGS*, Aquanty (2015)) is used, which simulates surface and subsurface hydrological processes in a fully coupled, physically based way. Owing to this integrated consideration of streamflow and groundwater, the relationship between low flow and storage dynamics can consequently be analysed in detail. All processes relevant for the water cycle, from precipitation to the stream discharge, can be simulated by the HGS model. This software thus allows, for instance, a full consideration of topography, land use and vegetation properties, soil layers, geological formations and their inherent hydrogeological properties, as well as precipitation input. A control-volume finite element approach is used to solve groundwater and surface water flow equations simultaneously. The diffusion wave approximation to the Saint-Venant equations are used to solve the 3D variably saturated subsurface flow. The 2D surface flow is solved by Richards equation. Water can move freely from one domain to the other according to a first-order leakage coefficient based on head differences that couples the two compartments. Thanks to this integrated consideration of surface and subsurface processes, the river location does not have to be defined and “naturally” forms according to the meteorological conditions. This point is essential for the assessment of low-flow dynamics and consequently for the present work. Further details on HGS are provided for instance by Brunner and Simmons (2012).

In the second approach (Chapter 3), the relationships between catchment properties and streamflow dynamics are explored with observed data using linear regression analysis. This study mainly distinguishes itself from aforementioned similar research by its more explicit consideration of geology and hydrogeology. The investigation focuses on 22 catchments of the Swiss Plateau and Prealpes, located in the Molasse basin. The properties of these catchments are also used as a basis for the physical properties values of the synthetic approach. This region is of particular interest for water resources management, as it is densely populated. Besides, it provides a rich hydrogeological variety: the sedimentary rocks of the Molasse are characterised by very diverse lithologies such as clayey deposits, sandstones and conglomerates. These different bedrock formations are often combined to alluvial quaternary deposits of large extent and permeability.

In this approach, both the bedrock and the alluvial quaternary deposits are thus characterised in detail. Various other catchment descriptors related to land use, soil and topography are included in the analysis, along with precipitation characteristics. The entire range of streamflow dynamics is considered and quantified using numerous discharge indices. This observation-based study offers the possibility to validate and widen the findings of the synthetic approach. Whereas only a limited number of catchment properties are varied in the first investigation and processes remain synthetic, the assessment of existing catchments allows upgrading the results to a higher complexity level of physiographic combinations and catchment configuration.

CHAPTER 1. INTRODUCTION

In Chapter 4, the results of the two approaches developed in Chapters 2 and 3 are compared and the complementarity of the approaches is discussed. Based on their findings, a guideline for the assessment of sensitivity of water resources to dry periods is proposed. In Chapter 5, the general conclusions of the PhD thesis and their implications for further research, data acquisition and monitoring are discussed.

Chapter 2

Exploring geological and topographical controls on low flows with hydrogeological models

This chapter has been submitted to *Groundwater* as an original research article.

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Keywords: low flow, groundwater, numerical modelling, catchment hydrology, geology, topography

Key points:

- Hydrogeological and topographical controls on low flows are assessed using numerical models with systematically varied physical properties
- The permeability of the bedrock exerts a dominant control on groundwater storage dynamics and on low flows
- We characterise the combined influence of slopes and bedrock permeability on low flows and the relative contribution of the alluvial aquifer

Abstract

This study investigates how catchment properties influence low-flow dynamics. With 496 synthetic models composed of two geological units (bedrock and 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 the following streamflow and groundwater indicators: Q95/Q50 (discharge exceeded 95% of the time divided by median discharge), Q95 and dynamic groundwater storage. Q95 is highly correlated to dynamic groundwater storage ($R^2=96\%$). The hydraulic conductivity of the bedrock K_{bedrock} 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 catchments with no alluvial aquifer, 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. Besides, it can enhance dynamic storage in the surrounding bedrock and produce an additional stable contribution to streamflow. The 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.

2.1 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.

Numerous hydrological studies were dedicated to better characterise the mechanisms governing low flows and the relationship between low-flow dynamics and catchment properties (see, e.g. reviews by Price (2011), Smakhtnin (2001) and Van Loon (2015)). It is widely recognized that low flows mainly derive from groundwater (Smakhtnin (2001), Peters et al. (2003), Peters et al. (2005), Matonse and Kroll (2013), Dassargues et al. (1999)). A few 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) shows 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) associates higher low flows with slowly draining porous bedrock and low streamflow during dry periods for catchments dominated by Moraine deposits.

However, broader low-flow studies rarely include detailed geological or hydrogeological descriptors. If the subsurface is considered, it often refers to shallow characteristics such as soil parameters (e.g., Kroll et al. (2004)), to wide classes such as fractured, porous and karstic aquifers (Stoelzle et al. (2015)) or it is defined using 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)). In hydrological models, the conceptualization of groundwater systems is often represented by a lumped reservoir (Matonse and Kroll (2013), Broda et al. (2012)). In a catchment, groundwater storage can, however, occur in different geological units of distinct hydrogeological properties, leading to strongly differing storage dynamics. These complex storage mechanisms are rarely addressed in hydrological studies, as groundwater storage is typically represented by a simple or a series of reservoirs. While these approaches theoretically represent different storage units, they are not intended to and cannot represent the feedback mechanisms between the reservoirs.

Another example is the widespread application of the Boussinesq equation for sloping aquifers, or of other approaches derived from it, used to relate catchment scale aquifer properties to baseflow (Troch et al. (2013)). As a result, 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 (Van Loon (2015), Price (2011)). This is illustrated by the often limited ability of classical hydrological models to reproduce low flows (Staudinger et al. (2011)).

A better understanding of low-flow dynamics thus implies a more detailed consideration of storage variations in distinct geological units. Due to the heterogeneity of subsurface properties, groundwater level data are often only representative of the local settings. Consequently, catchment storage is not directly measurable and its estimation is problematic (Kirchner (2009), Birkel et al. (2014), Mcnamara et al. (2011)). Dynamic storage is commonly defined as the storage that governs streamflow dynamics (Buttle (2016), Spence (2007)), and is generally inferred from river hydrographs. Estimates of dynamic storage can vary significantly depending on the calculation method (Staudinger et al. (2017)).

Various groundwater studies analyzed the influence of topography, recharge and permeability on 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 (Andermann et al. (2012), Birkel et al. (2014), Welch and Allen (2012), Tague and Grant (2004)). 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 and Allen (2012), Welch et al. (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.

In a study case, 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. Moreover, alluvial valley aquifers are of great importance for water supply purposes. The impact of the hydrogeological characteristics of both the bedrock and the alluvial aquifer on low flows, combined to different topography, has not been explored explicitly so far.

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. We use an integrated modelling 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 characterisation 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.

2.2 Methods

2.2.1 Numerical model and data analysis

The HydroGeoSphere (HGS) software is used, as it simultaneously simulates surface and subsurface flow in a physically based, distributed manner. 3D 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 two domains are coupled through a first-order leakage coefficient based on head differences, allowing water to move 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 and time steps are homogenized to daily values in the post-processing step. Further details on HGS can be found in Aquanty (2015) or 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.

2.2.2 Catchment configuration

As topographical and hydrogeological characteristics influence catchment dynamics in a complex, interrelated way, the catchment configurations should cover a wide range of pos-

sible 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. Besides, this set-up 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 set-up is shown in Figure 2.1. 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 catchments of this size located in the Swiss Plateau and the Prealpes. The surface outlet is located 30 m higher than the base of the model at this x-y location. The synthetic catchments are characterised 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). Its permeability is either higher or equal to the bedrock permeability, the latter case representing a catchment with no alluvial deposits.

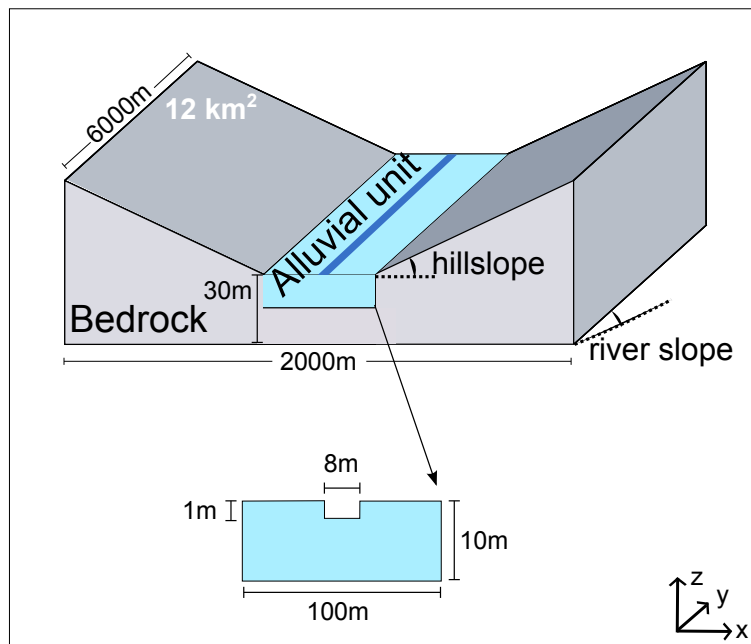


Figure 2.1: Standard setup of the synthetic models. The hydraulic conductivity of the bedrock and of the alluvial aquifers, the river slope and the hillslope are varied systematically.

2.2.3 Experimental design

The study is based on a central model batch (group 1) to systematically test the influence of hydraulic conductivity and slope gradients. A limited number of additional models (group 2) are developed to test the 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 2.1). 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 2.1 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 of 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 2.1), 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.

Table 2.1: Values of catchment properties

Parameters:	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:	0.50%	3%	9%	15%

Figure 2.2 shows four examples of catchment configurations: hillslope HS is set to the lowest value 5% (a and c) and highest value 50% (b and d), combined to a low river slope RS of 0.5% (c and d) and high river slope of 15% (a and 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 result analysis and discussed.

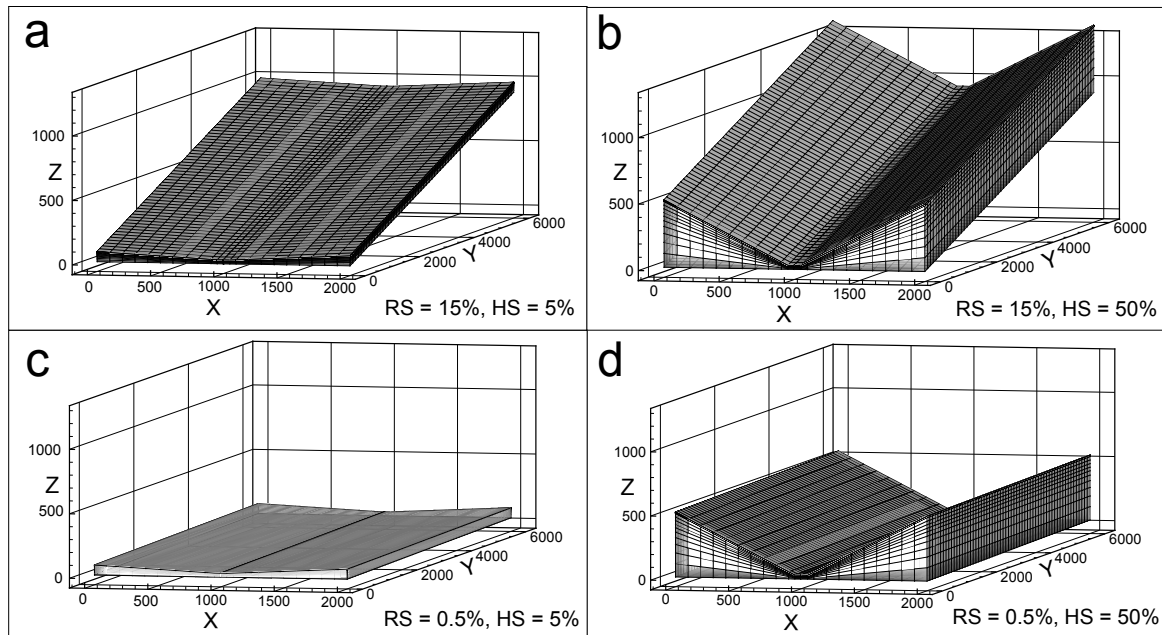


Figure 2.2: Examples of different topographical configurations (RS = river slope, HS = hillslope). A change in hillslope implies a change in catchment volume, whereas it is not the case for river slope variations.

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%. 20 new combinations of hillslope-hydraulic conductivity of bedrock are modeled to sample the parameter space more densely (permeability of $4e^{-7}$, $7e^{-7}$, $4e^{-6}$, $7e^{-6}$ and 10^{-4} m/s combined to the 4 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 1000:12'000, 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).

2.2.4 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 100 m, whereas the discretization in the x-direction varies between 100 m 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. The discretization of the ten lower layers is proportional to the depth of the catchment: it is fixed in the valley, varying from 1 m to 4 m with depth, and decreases laterally depending on the hillslope gradient.

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. Due to the slope configuration, catchment discharge only occurs at the lowest point, i.e., 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 equals discharge with 0.1% margin). 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 01.01.2000 and the 31.12.2003, 2003 being an especially dry year in Switzerland. The results of this study are focused on this four years transient simulation period. We chose not to explicitly simulate evapotranspiration with HGS and simply corrected the rainfall signal for evapotranspiration by dividing it by two, which corresponds to the water balance of the Huttwil region. 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.

Even though groundwater can partially flow in fractures in the bedrock, this dual porosity is of less relevance for catchment-scale processes. 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 essentially capture the influence of these varied characteristics on model outputs. The Van Genuchten parameters 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. For the remaining

subsurface and surface model parameters, the standard HGS values are kept (see Aquanty (2015) for more information).

2.2.5 Low-flow and groundwater dynamics indicators

Q95 and Q50 are used to describe the magnitude of low flows of each catchment. Q95 characterises 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 (Laaha and Blöschl (2005), Smakhtnin (2001)) and water management where it serves as a basis to define minimum flow rates required by ecosystems. Dividing Q95 by median flow to obtain Q95/Q50 is useful to compare catchments of different size and climate forcing. Q95/Q50 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 Q95/Q50 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 2.3). 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 b) over the 4-years simulation period.

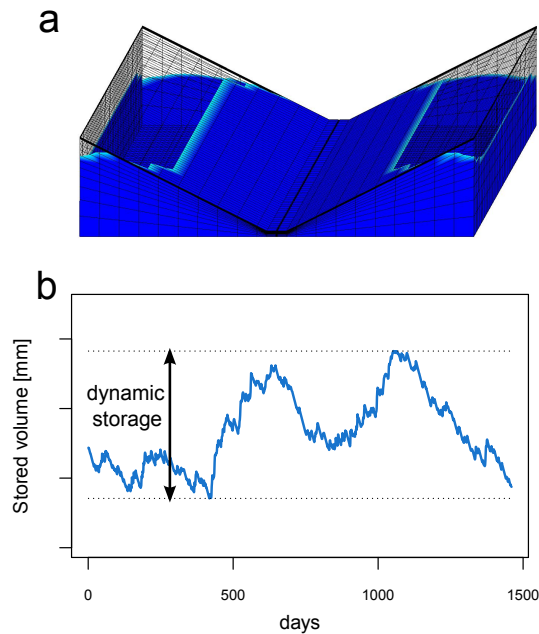


Figure 2.3: Visualisation of water storage in an example catchment in a (here only the saturated volume and hence the water table is represented for visual clarity). b: representation of dynamic storage for an example catchment (the difference between minimal and maximal absolute water volume stored during the 4-years simulation).

2.3 Results

2.3.1 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 being: 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 2.4. Q_{95} and Q_{95}/Q_{50} are plotted versus dynamic storage (a and b, Figure 2.4). 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 2.4, c). When free porous space is limited, less water is stored during precipitation events (higher surface runoff) and 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 characterisation of the mechanisms controlling dynamic storage benefits 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.

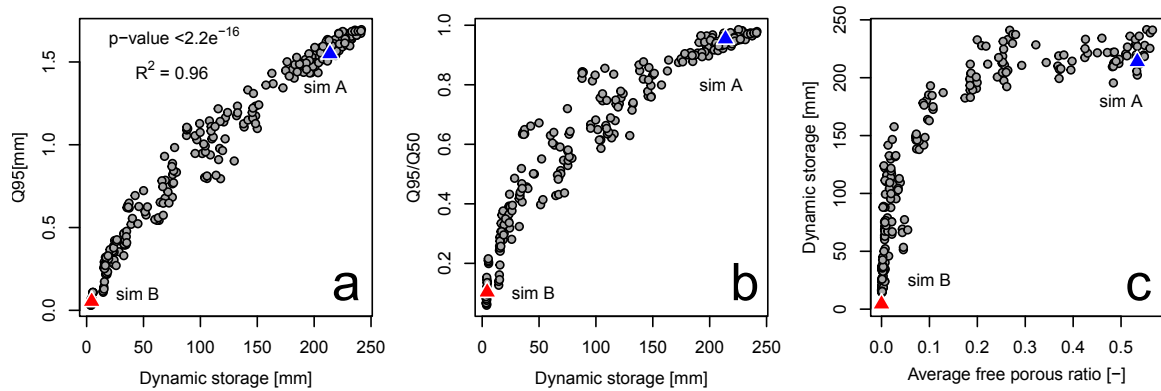


Figure 2.4: Outputs of the 256 models are represented by grey dots. “sim A” and “sim B” indicate two catchments with opposite dynamics (see also Figure 2.5). a: dynamic storage versus Q95, b: dynamic storage versus Q95/Q50, c: average free porous ratio versus dynamic storage.

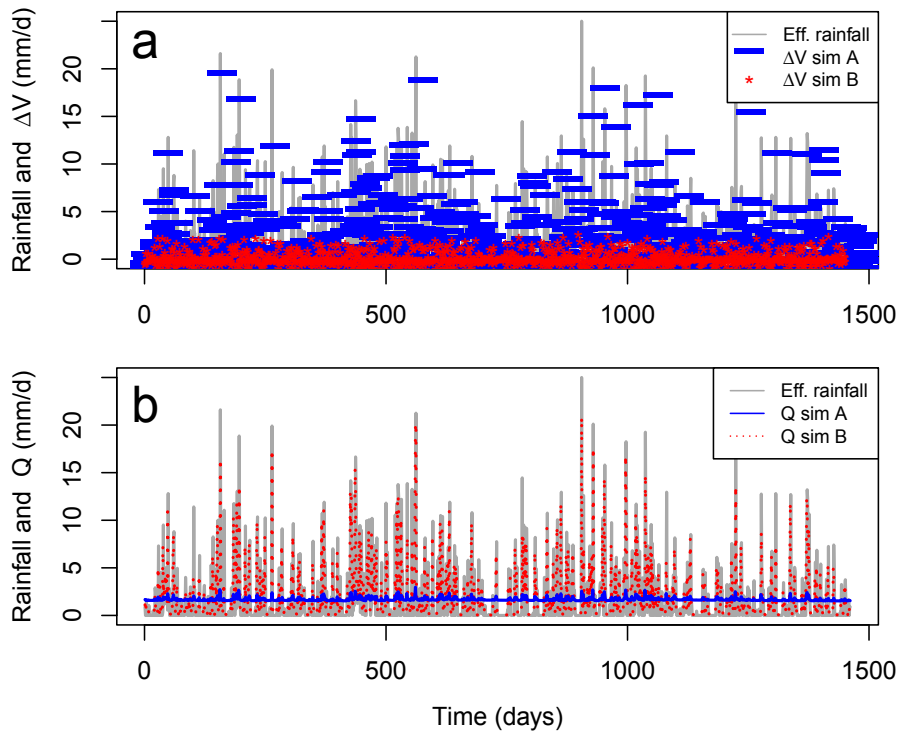


Figure 2.5: Daily specific storage (a) and discharge dynamics (b) of model examples “sim A” and “sim B” (see also Figure 2.4) for the entire simulation period of 4 years. These time series are plotted along with daily effective rainfall (P-ET).

To illustrate the buffering effect of storage on streamflow, we highlight two extreme configurations (see highlighted points in Figure 2.4). The entire simulated time series of daily storage variations ΔV (subplot a) and streamflow Q (subplot b) of the two catchments *sim A* (blue) and *sim B* (red) are plotted in Figure 2.5. Effective rainfall is plotted in grey in the background. Catchments A and B have a dynamic storage of 213 mm resp. 4 mm. Daily storage variations ΔV of *sim A* are close to effective rainfall: storage buffers the rainfall signal i.e. 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 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.

2.3.2 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 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 Q_{95}/Q_{50} is explained by catchment properties. The coefficient of determination

R^2 between Q95/Q50 (y) and the linear model 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):

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

Figure 2.6 illustrates the results using dots whose size is 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, 2nd to 4th 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.

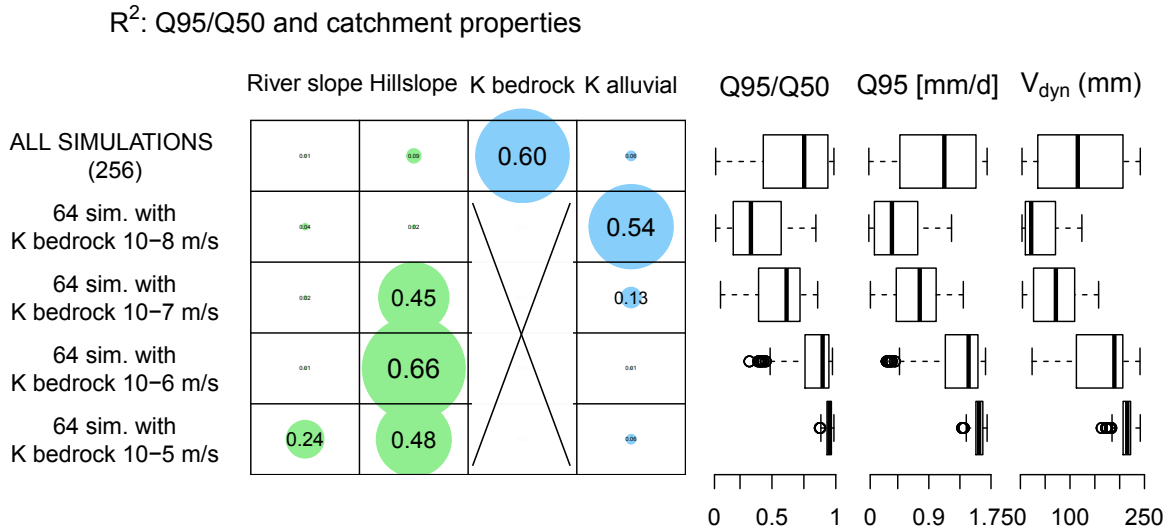


Figure 2.6: For all simulations with systematically varied parameters (1st row) and for the different bedrock classes separately (2nd-5th rows), the ratio of Q95/Q50 variance explained by catchment properties is illustrated by circles of proportional diameters (left part of the figure, simulations of 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 influence of hydraulic and geometrical characteristics, both individually and in combination, is discussed hereafter.

2.3.3 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 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, i.e. the ability of bedrock to store water and to contribute to low flows. As can be observed in Figure 2.7, 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 in mm is plotted against the logarithm of bedrock hydraulic conductivity, and different hillslopes are illustrated by varying point styles (Figure 2.7). The effects of aspect ratio and porosity on Q95 are represented by grey 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.

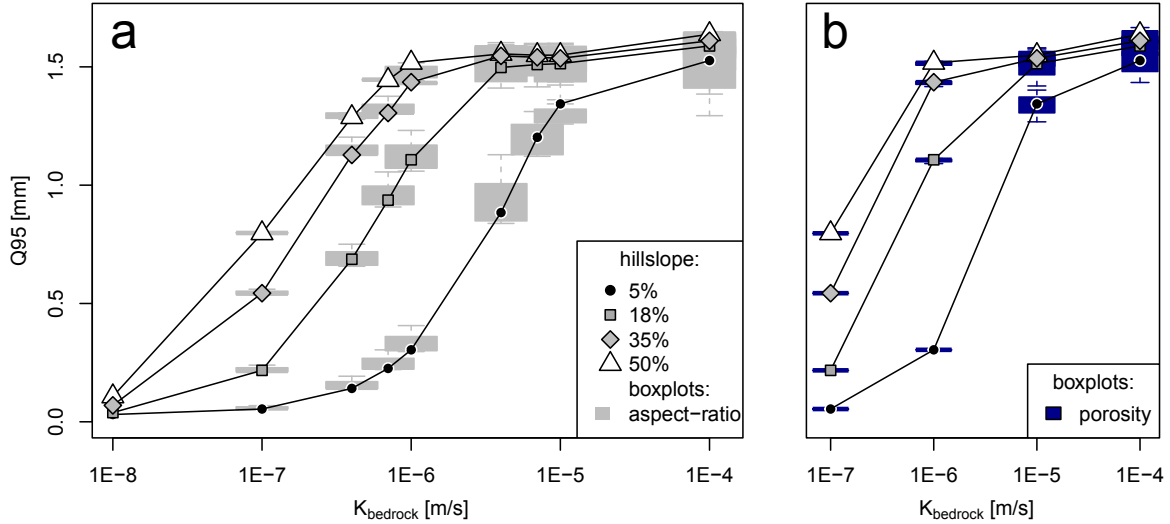


Figure 2.7: Q_{95} is plotted against the hydraulic conductivity of the bedrock (logarithmic scale) for two selections of models (constant river slope of 3% and no alluvial deposits). On the left (a), all 36 hillslope- K_{bedrock} combinations are plotted and the grey boxplots indicate the variability of these results with regards to aspect-ratio variation (width to length in meters of 1000:12'000, 3000:3000 and 6000:2000, standard value: 2000:6000). 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 left figure (a) shows that the sensitivity of Q_{95} regarding the hillslope gradient depends on the hydraulic conductivity of the bedrock. We can distinguish between 3 sections from left to the right:

- In case of a very low hydraulic conductivity (here 10^{-8} m/s), bedrock is essentially inactive as indicated by the very low Q_{95} : even bigger slope gradients and storage volumes do not lead to increase 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 implies 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 2.7 (a) 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 Q_{95} for values between 10^{-8} m/s and 10^{-7} m/s. However, maximal Q_{95} 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} m/s 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.

2.3.4 Bedrock productivity index (BPI)

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, Q95 divided by mean net precipitation, to force the points in Figure 2.7 to converge 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):

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

The hillslope exponent $3/2$ is calibrated by experimentally fitting the data. These ratios allow relating graphically low flows to catchment configurations (Figure 2.8). 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 2.8 (black dots).

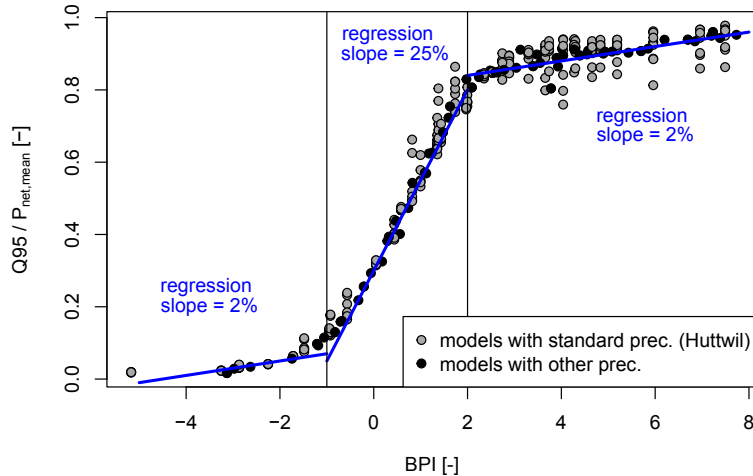


Figure 2.8: The ratio of Q95 to effective mean precipitation (P-ET) is plotted against the bedrock productivity index for all catchments of this study composed only of bedrock (no alluvial deposits). In total, 332 catchments are included with varying meteorological input (black dots), hillslope and river 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.

BPI is strongly correlated ($R^2=82\%$ for linearized correlation, all points of Figure 2.8) 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, 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 2.8 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 characterised 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).

2.3.5 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 2.9 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 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 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.

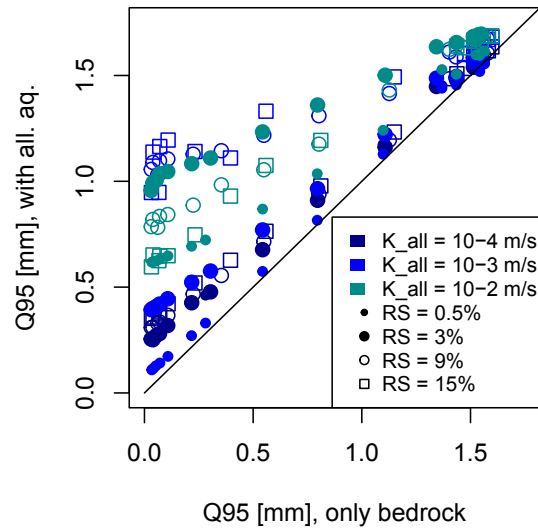


Figure 2.9: Q95 (mm) of all models with permeable alluvial unit versus Q95 of the corresponding model with bedrock only (same hillslope, river slope and $K_{bedrock}$). Colors indicate the hydraulic conductivity of the alluvial unit and point style the river slope RS .

For further illustration, Figure 2.10 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, catchment dynamic 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.

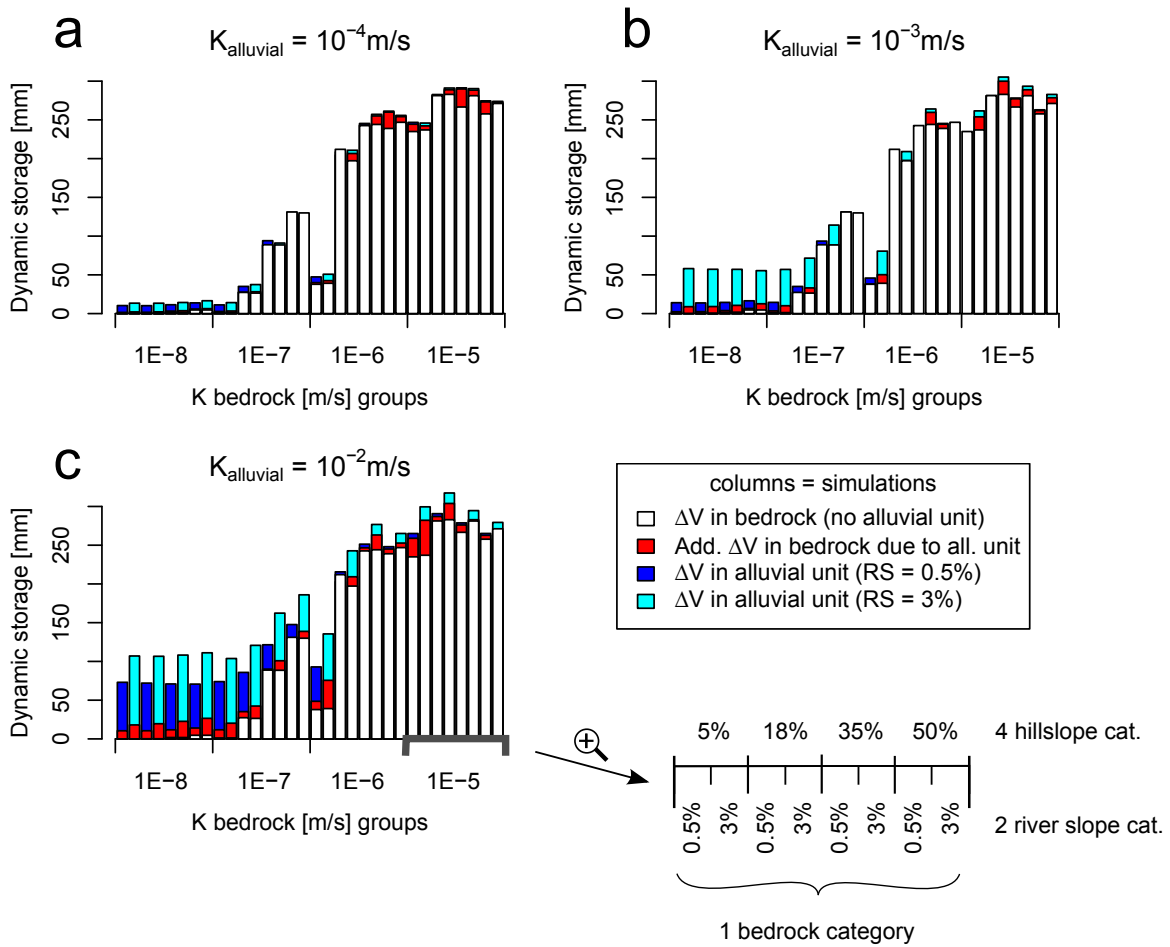


Figure 2.10: Illustration of dynamic storage partitioning between bedrock and alluvial deposits for 32 topographical- K_{bedrock} combinations (each column) and for three categories of alluvial hydraulic conductivity (each subplot a, b and c). Dynamic storage occurring in bedrock in the absence of a 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%).

2.4 Discussion

2.4.1 Applicability of the synthetic model approach

The synthetic models allow relating low-flow dynamics to the catchment properties. In existing catchments, the physical and geometrical properties of the bedrock and the alluvial formation are difficult to assess and therefore only speculative. 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 exactly 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 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 set-up 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.

2.4.2 Influence of 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 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 2.6). This is in agreement with various case studies that have identified the importance of the bedrock permeability (or highly permeable bedrock units) on low flows (Tague and Grant (2004), Pfister et al. (2017), Naef et al. (2015)). 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 measure in the field.

2.4.3 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 measuring the 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 2.7). 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 stor-

age 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 i.e., 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 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.

2.4.4 Bedrock productivity index BPI

The following discussion is relevant for catchments where the bedrock is the main productive hydrological unit. The dimensionless ratio Bedrock Productivity Index 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 2.6, right). Note that the BPI also allows inferring low-flow behaviors for vastly different meteorological conditions as shown in Figure 2.8.

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). Their index also includes the R/K ratio and a topographical gradient that can be associated with hillslope. Their criterion determines whether the groundwater table is topography- or recharge-controlled. 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 2.4). 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 characterised 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.

2.4.5 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 2.9). 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 2.10). 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.

2.5 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.

Synthetic models are useful to explore the effect of catchment properties that are particularly difficult to determine such as bedrock properties. Several important conclusions can be drawn. In an overall ranking, low-flow dynamics is highly dependent on the groundwater contribution from the bedrock. 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. 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.

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 characterisation 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 characterise 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 characterisation 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 analysed as significant infiltration from river to groundwater can occur and negatively impact streamflow. This proposed sensitivity assessment highlights the relevant catchment prop-

erties governing low flows and it provides for instance an interesting basis for catchment inter-comparison.

Chapter 3

Assessment of catchment controls on streamflow dynamics: the importance of geology

This chapter has been submitted under the title of **Geology controls streamflow dynamics** to *Journal of Hydrology* as an original research article.

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Key words: streamflow dynamics, catchment controls, geology, hydrogeological properties

Highlights:

- Studies on catchment controls on streamflow rarely consider geology explicitly
- We show that most permeable lithologies impact streamflow dynamics
- Geological features influence how the catchment buffers the precipitation dynamics
- Normalised high and low discharge percentiles are highly correlated

Abstract

Understanding the control of catchment properties on river dynamics is essential to anticipate the behaviour of streams subject to changing environmental conditions and to predict flows of ungauged rivers. Although the importance of subsurface processes in catchment hydrology is widely acknowledged, geological characteristics are rarely explicitly included in studies assessing physiographic controls on catchment dynamics. In this investigation of 22 catchments of the Swiss Plateau and Prealpes, we use a simple linear regression approach to analyse the relationship between streamflow indicators and various geological properties describing the hydrogeological quality of bedrock and quaternary deposits, along with meteorological, soil, land use and topographical characteristics. We use long-term discharge percentiles, as well as dimensionless flow duration curves (FDC, standardised by long term mean discharge) that allow focusing on the catchment response to climate forcing, inherent to its physical characteristics. We show that, whereas climate conditions dominate the high to medium discharge percentiles (Q5 to Q50), the capacity of the catchments to buffer the meteorological forcing can only be attributed to geological characteristics. The sandstone proportion in the catchments explains 54% of the variance of both extremities of the dimensionless FDC (Q5/Q_{mean} and Q95/Q_{mean}) and productive quaternary deposits are responsible of 55% resp. 58% of the variance of the two ratios. Examining the hydrogeological characteristics of both bedrock and quaternary lithologies considerably improves the understanding of catchment dynamics.

3.1 Introduction

Stream discharge, integrating hydrological processes across various spatial and temporal scales, is a valuable indicator for the assessment of water resources. Understanding stream dynamics implies a thorough characterisation of the influence of physical catchment properties on streamflow generating mechanisms. This knowledge is essential for apprehending the behaviour of ungauged rivers and predicting the dynamics of gauged ones under transient conditions such as climate change. Consequently, assessing how catchment properties influence streamflow dynamics is a central topic in hydrological research.

Stream dynamics reflects infiltration, evapotranspiration and interception, overland flow and subsurface flows and is consequently influenced by various catchment characteristics related to vegetation, soil, topography and geology. Numerous studies have been dedicated to assess the impact of these properties on the catchment response to the meteorological signal, for instance in the framework of hydrological prediction in ungauged basins (*PUB*, see reviews by Hrachowitz et al. (2013) or Blöschl et al. (2013)). Another series of studies focuses on expressing the flow duration curve (FDC) based on meteorological and geomorphological attributes (e.g. Müller et al. (2014), Pugliese et al. (2014), Castellarin et al. (2004), Castellarin et al. (2007), Botter et al. (2007a), Botter et al. (2007b), Doulatyari et al. (2015), Cheng et al. (2012), Coopersmith et al. (2012), Ye et al. (2012)). The relationships between catchment properties and dynamics are also widely used in regionalisation methods, which use these established correlations to extrapolate the hydrological understanding of gauged catchments to ungauged ones (e.g. review by Razavi and Coulibaly (2013)).

Among these numerous studies, geological features are rarely considered, while surface properties such as topography, land use and soil are often taken into account. Bloomfield et al. (2009), for instance, pointed out the often simplistic representation of geology in studies dedicated to catchment control on baseflow and advocated for a more systematic quantification of the effect of geology on the baseflow index. In continuous streamflow regionalisation studies, Razavi and Coulibaly (2013) highlighted catchment area, elevation, and slope to be the most widely used properties considered by researchers. He et al. (2011) showed that among the 39 characteristics used in the reviewed studies, drainage area is the most frequent followed by land use, slope, soil classification and elevation. They suggest that emphasis should be placed on subsurface descriptors whose influence on catchment dynamics is less understood. Groundwater storage and release mechanisms, defined by geological features, impact catchment dynamics and are of particular relevance during dry periods, when the contribution of aquifers to streamflow can be significant (Smakhtin (2001)). As stated by Oudin et al. (2008) in a comparison of regionalisation methods, the difficult characterisation of the subsurface remains a major obstacle for the identification of the relevant catchment controls on streamflow based on regression analysis.

Nonetheless, various studies have integrated geological characteristics and identified the influence of specific lithologies on streamflow. Ward and Robinson (1990) for instance

have highlighted the role of geology in influencing the FDC shape of catchments in the UK. Based on multiple regression models, Bloomfield et al. (2009) quantified the relative influence of various lithologies on the baseflow index. Both Mayer and Naman (2011) and Jefferson et al. (2008) have shown with their study based in California and Oregon that the geology of the studied catchments significantly determines their response to climate change. Besides, Tague and Grant (2004) pointed out the dominant control of a highly permeable volcanic unit on flow regime of this studied Oregon region. In other studies, the importance of sandstone for streamflow dynamics has been identified. Its influence on mean transit time and its buffering effect on streamflow has been illustrated in two studies in Montana (Jencso and McGlynn (2011), Nippgen et al. (2011)). In Switzerland, the importance of sandstone in sustaining streamflow during dry periods has also been stated by Naef et al. (2015). These findings suggest that the bedrock plays an active storage role, as proposed by the hydrologically active bedrock hypothesis (Uchida et al. (2008)) and that it can considerably contribute to baseflow (Andermann et al. (2012), Birkel et al. (2014), Welch and Allen (2012)). Especially the hydraulic conductivity of the bedrock seems to be of high relevance for storage processes (Hale et al. (2016), Pfister et al. (2017), Chapter 2).

While alluvial aquifers are of major interest in hydrogeology, their effect on streamflow has received little attention in hydrology. It has however been shown that these hydrogeological units, although limited in size, can notably impact the catchment outflow under dry conditions (Käser and Hunkeler (2016)). The presence of permeable quaternary deposits can also affect streamflow if infiltration from the stream to the groundwater is important. Naef et al. (2015) showed for instance that catchments for which discharge is measured after an infiltration section are often characterised by lower low flows.

These studies suggest that the understanding of catchment dynamics can benefit from considering the various geological units present in the catchment and their hydrogeological properties. Freeze and Cherry (1979) already articulated the importance of considering a catchment as a combination of the surface drainage area and of subsurface soils and geological formations. They even argued that subsurface hydrological processes might play a predominant role in the hydrological cycle, as subsurface materials govern infiltration rates and thus determine surface runoff. River networks are influenced by the configuration of the water table, which is in turn defined by groundwater processes and the inherent geology. Subsurface flow is constrained by the three-dimensional setting of geological deposits (Freeze and Cherry (1979)) and thus related to topography, as these features determine the gravimetric gradient available to mobilise groundwater. Moreover, the hydrogeological properties of the geological formations and especially their permeability determine groundwater flow. The combined importance of hydraulic conductivity and topography is expressed by Darcy's law. Moreover, subsurface flow and the associated water table are dependent on recharge and thus on meteorological forcing. Studies by Gleeson and Manning (2008), Haitjema and Mitchell-Bruker (2005), Welch and Allen (2012) and the previous chapter of this thesis have identified the influence of topography, recharge and hydraulic

conductivity on subsurface processes, which suggests that these features might also be relevant for catchment dynamics.

Our aim is consequently to improve the understanding of streamflow dynamics by integrating detailed geological descriptors in a study of catchment controls on discharge. The identification of the geological characteristics relevant for streamflow dynamics, along with other possibly important catchment properties, is primarily carried out using simple regression analysis. The influence of the identified descriptors on streamflow signatures is then investigated individually.

Although various statistical methods exist to assess this link (Kroll and Song (2013)), this simple approach is preferred to model-based or more complex statistical methods, as it prevents bias from the predefined model structure and parameterisation. Moreover, the multicollinearity effects inherent to multiple regression models (Kroll and Song (2013)) are avoided. Our scope is to provide observable predictors for the assessment of catchment dynamics for ungauged catchments or for changing environmental conditions. By quantifying the influence of the various catchment properties on the whole streamflow range, we aim at identifying the relevant physical features for water resources management.

Data on geology, soil, land use, topography and meteorological conditions are gathered for 22 Swiss catchments located in the Molasse basin and compared to their long-term streamflow signatures. The discharge indicators are composed of both absolute and normalised (divided by the long-term mean discharge) discharge percentiles. The dimensionless indices allow focusing on the dynamics of catchment response to precipitation (Sauquet and Catalogne (2011)), the meteorological impact being filtered out by the normalisation. The use of these various descriptors of stream dynamics might thus enable distinguishing between the meteorological and the catchment impacts on streamflow signatures.

This study is built on two hypotheses:

- Hypothesis 1: If geology influences low flows (as shown by various studies) by defining the slow drainage units contributing to the river during dry periods, i.e. determining releasing processes, it should also impact the higher streamflow range, i.e. storage processes during rain events. The control of geology should thus affect the whole streamflow range.
- Hypothesis 2: Geology, as it strongly determines storage and release processes, presumably influences the ability of the catchment to buffer the meteorological signal. This influence on streamflow signatures should be identifiable if geological descriptors actually describe the capacity of geological formations to store and release water.

3.2 Method and catchment characteristics

The relationship between streamflow signatures of a 20 years period (01.01.1993-31.12.2012) and catchment properties encompassing meteorological, topographical, soil and geological characteristics is analysed for 22 Swiss rivers using simple linear regression. The investigated time period covers exceptionally dry years (e.g. 2003, 2011) as well as major flood events (e.g. 2005). Data describing topography, soil, land use, geology and hydrogeology, precipitation and evapotranspiration as well as discharge are compiled.

The discharge indicators are obtained from both the absolute and the dimensionless flow duration curves (FDC). The flow duration curve is a widely used tool to characterise streamflow dynamics (see e.g. review by Smakhtin (2001)). The dimensionless version, obtained by averaging the discharge percentiles by a long-term discharge mean and also known as the “index flow approach”, has been used in various studies, notably for catchment intercomparison and regionalisation purposes (Castellari et al. (2004), Holmes et al. (2002), Sauquet and Catalogne (2011), Ganora et al. (2009)). The standardisation allows focusing on the shape of the curve and hence more on the dynamics than on the absolute magnitude of discharge. That way, the dependency of streamflow signatures on climate conditions is minimised and the specificities of the catchment response to meteorological forcing are better identifiable.

The control of meteorological and catchment characteristics on streamflow dynamics is quantified using a linear regression model between each streamflow indicator and the catchment descriptor. The coefficient of determination R^2 is computed as follows for each relationship and corresponds to the proportion of the variance of the streamflow indicator y explained by the linear model based on the catchment characteristic $LM(p)$, n being the number of studied catchments and i each catchment:

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

The calculation is also applied between catchment and meteorological characteristics. In this way, potential interdependencies between physical properties and/or climate conditions are identified.

3.2.1 Catchment selection

The geographic location of the 22 catchments is shown in Figure 3.1 and the most relevant characteristics are summarised in Table 3.1. All data describing the catchments are given in the Appendix B. We investigate catchments of the Swiss Plateau and Prealpes, located in the Molasse basin (indicated by yellow lines in Figure 3.1). Approaches that differentiate between fundamental types of aquifers, such as karstic, fractured and unconsolidated rocks, have a limited potential to link specific streamflow patterns to each group. Within each category, the hydrogeological characteristics of the aquifers can strongly differ. We thus

focus on catchments that are part of the same broad geological environment, the Molasse, to explore in detail its hydrogeological variability and the impact of its different lithologies on streamflow signature. Besides, this selection excludes regions dominated by glaciers and snow (see “hydrological regime” in Table 3.1). Additional criteria for the choice of the catchments are the absence of lakes and of important anthropogenic influences, as well as the quality of the discharge measurements, of the low-flow range particularly.

CHAPTER 3. STUDY OF SWISS CATCHMENTS

Table 3.1: Selection of discharge, meteorological, topographical and geological characteristics of the 22 catchments.

Catchments	Hydrological Regime	Qmean [mm/d]	Q5 [mm/d]	Q95 [mm/d]	Q95/ Qmean	Pmean [mm/yr]	ET [mm/yr]	Area [m]	Eleva- tion [m]	% 1st order stream [%]	Mean slope [°]	% 2D prod. quat. [%]	Prod. quat. vol. per surface [m]	Bedrock hyd. cond. [m/s]	Sand- stone [%]
Aach	Pluvial inferior	1.37	4.32	0.24	0.18	1045	578	47.4	467	45%	3%	13%	0.38	5.05E-08	0%
Alp	Prealpine nivo-pluvial	4.19	13.90	0.79	0.19	2014	369	46.7	1158	55%	15%	16%	0.99	1.00E-06	0%
Biber	Prealpine nivo-pluvial	3.01	10.62	0.44	0.14	1879	478	31.9	1003	55%	11%	6%	0.76	7.25E-07	0%
Broye	Pluvial inferior	1.58	4.88	0.35	0.22	1205	569	415.9	715	49%	7%	6%	1.29	1.14E-05	27%
Glatt	Pluvial superior	3.04	9.33	0.82	0.27	1542	529	16.7	830	52%	10%	0%	0.00	1.00E-07	0%
Goldach	Pluvial superior	2.44	7.73	0.41	0.17	1436	539	50.4	832	52%	11%	1%	0.28	9.78E-06	30%
Guerbe	Pluvial superior	1.97	4.87	0.68	0.35	1284	508	116.2	847	49%	12%	16%	5.02	2.12E-05	66%
Ilfis	Prealpine nivo-pluvial	2.47	6.79	0.66	0.27	1708	546	187.5	1039	57%	17%	7%	0.96	1.90E-07	0%
Langeten	Pluvial inferior	1.78	3.56	0.93	0.52	1322	571	59.9	760	42%	8%	21%	2.95	1.74E-05	55%
Luthern	Pluvial inferior	1.23	3.13	0.41	0.33	1319	582	104.7	750	52%	10%	17%	0.66	2.06E-05	65%
Mentue	Jurassic inferior	1.28	3.64	0.31	0.24	1086	589	105.3	675	46%	5%	1%	0.00	9.49E-06	30%
Murg Waengi	Pluvial inferior	1.98	5.47	0.54	0.27	1351	557	80.2	652	49%	9%	14%	3.80	1.00E-07	0%
Murg Frauenfeld	Pluvial inferior	1.62	4.45	0.44	0.27	1249	566	213.3	597	44%	8%	19%	3.59	1.59E-08	0%
Murg Walliswil	Pluvial inferior	1.57	3.19	0.83	0.53	1235	585	183.4	653	36%	8%	22%	4.07	2.23E-05	70%
Necker	Prealpine nivo-pluvial	3.21	10.48	0.52	0.16	1755	513	88.1	956	57%	14%	2%	0.00	5.50E-07	0%
Rappengraben	Prealpine nivo-pluvial	2.98	10.02	0.40	0.14	1676	610	0.6	1142	78%	18%	0%	0.00	1.00E-07	0%
Rietholzbach	Pluvial superior	2.86	10.13	0.38	0.13	1545	562	3.2	793	72%	11%	0%	0.00	1.00E-07	0%
Sellenbodenbach	Pluvial inferior	1.81	5.64	0.29	0.16	1234	571	10.4	608	48%	5%	0%	0.01	1.00E-09	0%
Sense	Prealpine nivo-pluvial	2.10	5.94	0.59	0.28	1444	491	351.2	1072	55%	14%	7%	0.86	2.55E-05	80%
Sitter	Prealpine nivo-pluvial	3.40	10.65	0.67	0.20	1731	478	261.1	1043	57%	15%	2%	0.01	3.86E-06	10%
Sperbelgraben	Prealpine nivo-pluvial	2.54	7.65	0.52	0.21	1664	610	0.6	1070	66%	19%	0%	0.00	1.00E-07	0%
Wigger	Pluvial inferior	1.33	2.94	0.55	0.42	1220	577	366.2	656	47%	9%	19%	2.02	1.96E-05	62%

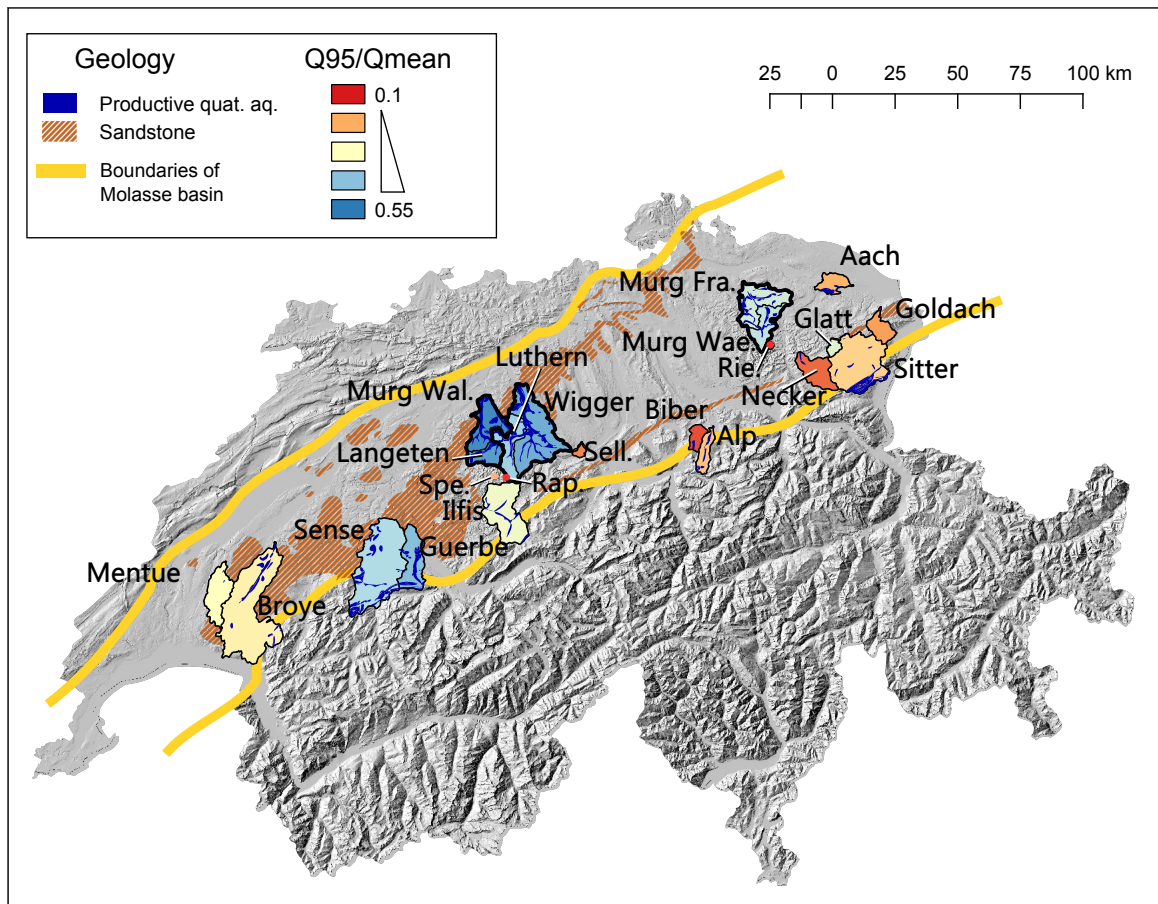


Figure 3.1: Location of the 22 investigated catchments in the Swiss Plateau and Prealpes. The results highlighted in this figure are detailed in the discussion. The Molasse basin is approximately delimited by the yellow lines. The presence of sandstone is indicated for whole Switzerland (hatched, brown), whereas productive quaternary deposits are only indicated for the selected catchments for visual clarity.

The surfaces of the catchments range from 0.6 to 416 km² and they are located at mean altitudes from 467 to 1159 m. The following hydrological regimes are represented, all of them being characterised by moderate seasonal amplitude: Prealpine nivo-pluvial, superior pluvial, inferior pluvial, Jurassic pluvial (Weingartner and Anschwanden (1992)). The annual precipitation for the studied period ranges between 1045 and 2014 mm and the actual evapotranspiration between 370 and 610 mm. The land cover consists principally of a mixture of rural fields and forest. The Molasse bedrock is composed of sedimentary rocks characterised by a high heterogeneity in grain size, such as clayey alluvial deposits, sandstones and conglomerates (Pfiffner (1986)). The sediments were deposited during a temporal succession of marine and terrestrial conditions. The Plateau Molasse is characterised by a horizontal or subhorizontal layering as it was subject to limited tectonic deformation. The subalpine Molasse is thrust onto the Plateau and is thus tectonically compacted.

3.2.2 Topography

The geographic information system Quantum GIS (QGIS Development Team (2014)) is used to obtain topographical features and for other operations requiring GIS support. Based on a digital terrain model (DHM25, grid cell resolution of 25 m, swisstopo), the following characteristics are calculated for each catchment: elevation, area, maximum elevation difference, longest distance (straight line) from catchment boundary to outlet (“max. L to outlet”), width to length ratio (aspect ratio), river network density, mean and maximum catchment surface slope, total catchment volume above outlet (“Total vol.”) and topographical wetness index (“TWI mean”) (see Beven and Kirkby (1979) for the calculation of the TWI). Combining the digital model and stream order data (Strahler stream order, Federal Office for the Environment FOEN) allows calculating following properties: mean slope of 1st order stream (“smallest stream slope”), main river slope, ratio of 1st order stream to total stream network (“% 1st order stream”).

3.2.3 Soil and land use

Land use (Areal statistics 2004/09, Swiss Federal Statistical Office) is classified into 4 categories: rural (vegetated surfaces that are not covered by forest), forested, urban and various (unproductive vegetation or no vegetation). Soil characteristics are derived from the aptitude map of Swiss soils (Swiss Federal Office for Agriculture), that define the following aspects: depth, stone content (“structure”), wetness, permeability and capacity for water storage.

3.2.4 Geology and hydrogeology

The GeoCover product (1:25000, Geological Vector Datasets, Federal Office of Topography, swisstopo) is mainly used to characterise geology. This dataset provides a digitalised compilation of Swiss geological maps. Geological and hydrogeological data are combined and a simplified classification is used to define four lithologies of the bedrock with corresponding hydraulic conductivities K : marine sandstones (“sandstone”, $K=10^{-4}$ to 10^{-5} m/s), fan conglomerates (“fan”, $K=10^{-6}$ to 10^{-8} m/s), fine-grained deposits (“fine grained”, $K=10^{-7}$ to 10^{-11} m/s), and the subalpine Molasse (“sub. Molasse”, $K=10^{-5}$ to 10^{-7} m/s). The attribution of hydrogeological characteristics to the various lithologies is based on existing reports concerning the Molasse (Balderer (1997), Gander (2004), Keller (1992), Waber et al. (2014)). The surface percentage of each lithology is obtained for every catchment (“% sandstone”, “% fan”, “% fine grained”, “% sub. Molasse”). The hydraulic conductivity of bedrock is estimated for each catchment based on the lithological composition.

Quaternary hydrogeology is characterised based on available 2D and 3D data. 2D hydrogeological data (Hydrogeological Map of Switzerland: Groundwater Resources 1:500'000, Federal Office of Topography Swisstopo) is used to spatially delineate product-

ive quaternary deposits in 2D, obtaining the productive aquifer surface as a percentage of the total catchment area (“% 2D prod. quat”). The GeoMol product, which models the top of the bedrock surface (Diepolder et al. (2013)) enables to calculate volumes of quaternary deposits. For each catchment, the raster of the top of the bedrock surface is subtracted to the surface raster. The total volume of quaternary deposits present in each catchment and per total catchment area is thus obtained (“Tot. quat. vol. per surface”). The raster of the top of the bedrock is also used to calculate the mean slope of the quaternary base (“Quat. slope”). Combining the GeoMol raster and the 2D hydrogeological map of productive aquifers, it is possible to calculate the productive quaternary volume present in each catchment, expressed as volume per total catchment area (“Prod. quat. vol. per surface”). To obtain it, the 2D extent of productive aquifers is used as a clip to extract the volume of productive quaternary deposits from the total quaternary deposits. In doing so, it is assumed that the aquifers marked as productive in the 2D dataset are productive across their entire thickness and thus homogeneous. The productive quaternary volume is also expressed as percentage of the total rock volume (or “Total vol.” defined previously) in the catchment, obtaining “% Prod. quat vol.”.

3.2.5 Precipitation and evapotranspiration

Daily precipitation data for the studied period (01.01.1993-31.12.2012) are calculated from gridded data (Frei (2014)) provided by the national meteorological service of Switzerland (MeteoSwiss) by averaging the spatial distributed values for each catchment area. Mean annual actual evapotranspiration is obtained from the spatially distributed model proposed by HADES (Hydrological Atlas of Switzerland, Table 4.1). The number of dry days per year is averaged over the 20 years studied. In order to evaluate precipitation dynamics, daily precipitation intensities are sorted separately for each year in the decreasing order. These classified values are then averaged over the 20 years and plotted against the number of days per year when the intensity is reached. The obtained curve is comparable to the flow duration curve (FDC, see below) for streamflows. For each catchment the obtained “precipitation duration curve” is fitted with following equation: $PDC(d) = a + b / d^k$, d being the days (1 to 365), and a , b and k (referred to as PDC_a, PDC_b and PDC_k) the calibrated parameters used to quantify the precipitation dynamics.

3.2.6 Discharge

All the investigated rivers are part of the Swiss national river-monitoring network and daily discharge measurements for the period 01.01.1993-31.12.2012 are obtained from the FOEN (Federal Office for the Environment). Three catchments of the selection are nested in other basins: Langete in Murg (Walliselen), Luthern in Wigger and Murg (Wängi) in Murg (Frauenfeld).

To assess the general behaviour of the 22 catchments, streamflow signatures are based on the 20 years period. Streamflow is described by means of (1) absolute percentiles of discharge (Q5 to Q95 expressed in mm/day), (2) ratios of percentiles Q5/Q50, Q95/Q50 and Q95/Q5 and (3) ratios and characteristics derived from the dimensionless flow duration curve FDC_{norm} . The percentiles are obtained from the flow duration curve FDC that is calculated for each year and averaged over the 20 years period. The absolute values describe the magnitude of discharge from high flows (Q5, the discharge exceeded 5% of the time) to low flows (Q95). The normalised flow signatures (2) and (3) allow filtering out the effect of climate and water balance issues and can thus be interpreted as descriptors of how catchments buffer the meteorological signal. From now on we refer to these indicators as “normalised streamflow” signatures, as opposed to the absolute streamflow indicators. We define the buffering potential as the dampening effect the catchment has on the precipitation signal: the more stable the streamflow dynamics, the higher this buffering potential. Conversely, a low buffering potential implies an erratic stream dynamics with high peaks and low flows close to zero.

The ratios Q5/Q50 resp. Q95/Q50 describe the variability of flows in the higher resp. the lower part of the FDC, whereas, Q95/Q5 is the ratio between low and high flows. The dimensionless flow duration curve FDC_{norm} is obtained by normalising the flow percentiles with a long-term index flow generally corresponding to the mean annual discharge. The yearly absolute discharge percentiles are divided by the yearly mean, and the resulting yearly FDC_{norm} is averaged over the 20 years. Specific points of the FDC_{norm} are analysed in this study: the standardised high flow and low flow percentiles Q5/Qmean resp. Q95/Qmean. The shape of the FDC_{norm} is also quantified with a parametric approach: the curve is fitted with following equation $FDC_{norm,calc}(d) = a + b / d^k$, d being the days (1 to 365), and a , b and k the calibrated parameters. The calibration is done on the logarithmic value of the FDC_{norm} to best reproduce low-flow dynamics. The k parameter of the equation, $k_{FDC,norm}$ is used as streamflow signature to describe the shape of the curve.

3.2.7 Water balances

A first step towards assessing the catchment response to the meteorological forcing is to look at the long-term water balance, which is established by averaging the equation terms on numerous years to exclude storage effects from one year to the other. The ratio of annual discharge to annual net precipitation (precipitation-evapotranspiration) is thus averaged for the 20 years period. To account for the uncertainty related to the estimation of evapotranspiration, the ratio is calculated with 10% higher and lower evapotranspiration rates. The resulting ratio with uncertainty margins is plotted in Figure 3.2. The majority of the catchments have ratios close to one, which indicates that their water balance is closed.

However, the ratio is consequentially smaller than one even when considering uncertainty margins for following rivers: Biber, Ilfis, Luthern, Sense and Wigger. In the case

of Luthern, for instance, only around 60% of the net input to the catchment comes out as discharge. This indicates that an important amount of water might exit the catchment as groundwater, “unnoticed” by the gauging station. The hydrometric stations should ideally be located on a geological unit that is impervious enough to prevent substantial groundwater flow under the station. This is, however, not the case for all catchments: except for Biber, the location of the gauging stations of the catchments with $Q/(P-ET)$ ratios lower than 1 is not adequate, as they are situated on top of permeable quaternary deposits. For the Luthern and Wigger catchments, a local study (Arbeitsgemeinschaft Grundwasserforschung Luthern- und Wiggertal (1978)) estimates the groundwater flow in the river section close to the gauging stations to 6500 l/min resp. 22'000 l/min. The water balance ratios corrected with the groundwater flow are shown in red in Figure 3.2. In both cases the ratio increases, although the improvement is limited. Further reasons for the mismatch of the water balance could be higher evapotranspiration uncertainties, a discrepancy between the hydrological and the hydrogeological catchment leading to groundwater losses benefitting neighbouring catchments, or inter-basin transfers that have not been identified. Although the water balance discrepancies are not corrected, identifying catchments with unclosed water balances allow better understanding potential unexpected differences between their behaviour and the dynamics of the other catchments.

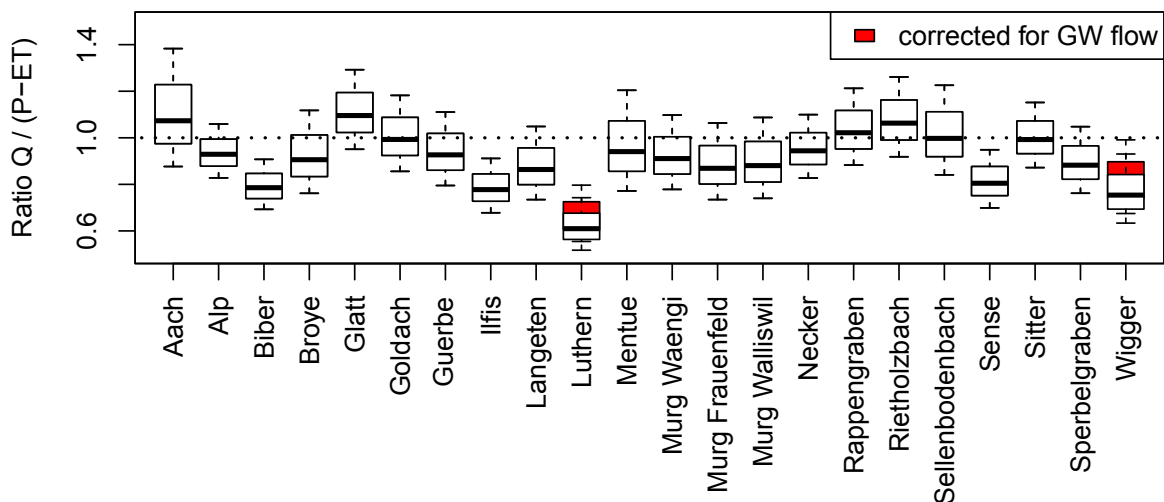


Figure 3.2: The ratio of discharge to net precipitation is illustrated for the 22 catchments with a 10% uncertainty margin for ET. In red: ratios for Luthern and Wigger are corrected by taking into account the groundwater discharge flowing under the gauging station.

3.3 Results

3.3.1 Analysis of interdependency among catchment properties and meteorological conditions

Before analysing the influence of catchment properties and precipitation on streamflow signatures, the interdependency among meteorological, topographical and geological characteristics is assessed. Identifying potential cross correlations between the descriptors is crucial to avoid attributing an effect of a specific catchment property on streamflow that is actually due to another characteristic. Mean elevation and mean net precipitation are strongly linearly and positively correlated ($R^2 = 74\%$) due to orographic lifting. Consequently, various catchment properties that vary with the altitude also exhibit a notable correlation with meteorological conditions. The following topographical properties are affected: mean catchment slope, smallest stream slope and the topographical wetness index are correlated to elevation (R^2 of 86%, 78% resp. 68%) and to mean net precipitation (R^2 of 59%, 47% resp. 44%). The soil depth and storage capacity decrease with elevation (R^2 of 61% resp. 71%) and are also correlated to mean net precipitation (R^2 of 81% resp. 60%). The high correlation between mean net precipitation and soil depth is due to both the elevation dependency of soil characteristics, and the fact that the evapotranspiration values used in this study are calculated based on the soil depth data. Finally, the percentage of subalpine molasse and fine grained material are to a lesser extent correlated to mean net precipitation (R^2 of 51% resp. 39%), which can partially be attributed to the dependency on altitude (R^2 of 28% resp. 46%). For all the mentioned catchment characteristics, potential correlations to streamflow signatures should be considered with care: as precipitation likely strongly governs streamflow, the listed properties might exhibit artefact relationships to discharge indicators although no physical link exists between them.

Besides, the estimated hydraulic conductivity of the bedrock of each catchment (see methodology section) is highly correlated to the percentage of sandstone present in the catchment ($R^2 = 99.5\%$). Sandstone is characterised by the highest permeability among the identified lithologies and thus exerts a dominating impact on the estimated hydraulic conductivity for catchments with sandstone. For the catchments lacking sandstone, the influences of the other lithologies on the calculated hydraulic conductivity are mixed.

3.3.2 Relationship between streamflow signature and catchment and meteorological properties

Overview

Figure 3.3 gives an overview of the influence of all climate and catchment characteristics on streamflow signatures and allows identifying relevant characteristics for stream dynamics whose importance will be quantified and discussed in next section. The size of the dots in

Figure 3.3 is proportional to the explained variance R^2 , illustrating the degree of correlation. Streamflow signatures are split into two groups: absolute indicators (discharge percentiles and mean discharge) and indicators related to the normalised flow duration curve along with ratios of discharge percentiles. The control of mean precipitation (P mean) and net mean precipitation (P-ET) on the absolute discharge percentiles Q5 to Q70, i.e. except the lower ones, is obviously dominant. Most of the catchment properties that seem to influence absolute streamflow indicators correspond to the characteristics that are strongly correlated to precipitation, as indicated by the red vertical dotted lines in Figure 3.3. Other features such as the proportion of 1st order stream and bedrock hydraulic conductivity (K bedrock) show a certain relationship to absolute indicators, but their impact is negligible compared to the dominant control of precipitation on these indicators. The discharge indicators Q90 and Q95, describing low flows, are the only streamflow indicators that are not correlated significantly ($R^2 < 20\%$) to any catchment or climate characteristics.

The results are distinctly different from the previous observations when the second group of indicators describing the shape of the dimensionless flow duration curve and the percentile ratios is considered. By expressing streamflow dynamics with ratios or percentiles normalised by mean discharge, the impact of precipitation is excluded as illustrated by the small variance explained by meteorological properties. Consequently, the catchment properties correlated to precipitation and thus to absolute streamflow indicators are not correlated to the relative streamflow indicators. The only characteristics revealing a notable relationship to the indicators describing streamflow dynamics are the geological properties: especially the quaternary feature “% 2D prod. quat.” (the surface proportion of catchment occupied by productive quaternary deposits) as well as the bedrock permeability and thus the proportion of sandstone are relevant. Also worth mentioning is the higher influence of the productive quaternary descriptors (“Prod. quat. vol. per surface”, “% Prod. quat. vol.”) compared to total quaternary descriptors (“Tot. quat. vol. per surface”). The proportion of 1st order stream and to a lesser extent the depth and permeability of the soil characteristics explain a certain part of the variance of the relative indicators, even though their explanatory value is smaller.

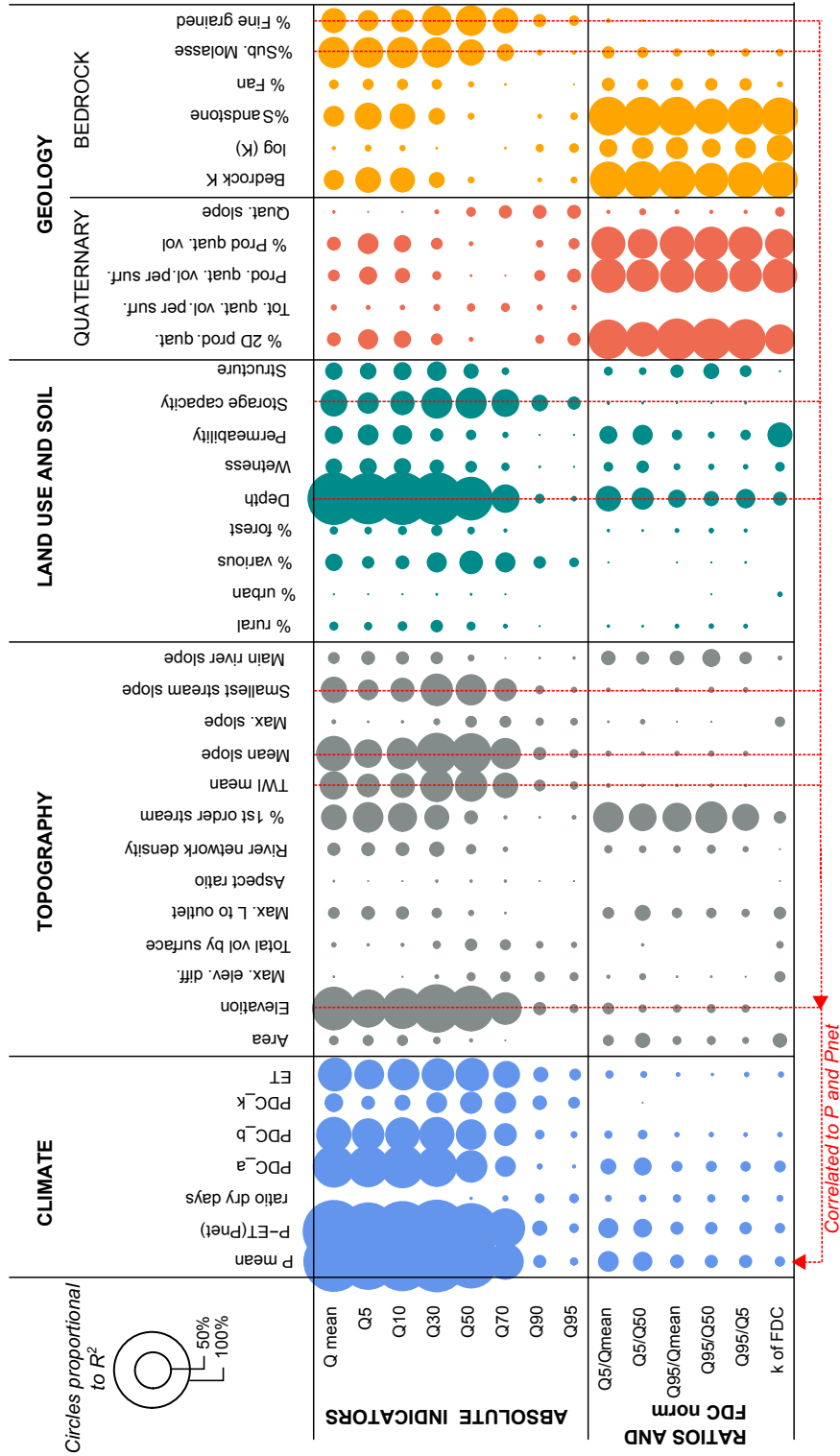


Figure 3.3: Illustration of the percentage of the explained variance of each streamflow signature (rows) by each catchment descriptor (columns), based on linear regression. The diameter of the circles is proportional to the R^2 of each relationship. The red dotted lines indicate catchment properties that are correlated to mean net precipitation.

Assessment of the influence of identified relevant characteristics on streamflow dynamics

Based on the previous section, the characteristics exerting the highest influence on streamflow indicators ($R^2 > 40\%$) are selected for further investigation (see Figure 3.4, detailed version of Figure 3.3). Catchment properties that are correlated to precipitation and thus to specific absolute streamflow indicators are left out, as we assume that precipitation, the input to the catchment, is the main driver of streamflow magnitude. For climate forcing, only mean net precipitation is kept. For quaternary features, we focus on the proportion of productive 2D quaternary deposits, as the correlation is slightly higher than for the 3D descriptor and the 2D descriptor is easier to obtain. The utility of the 3D characteristic will however be discussed subsequently.

		R²-values					p-values						
		Pnet	% 1st order stream	% 2D prod. quat.	Bedrock K	log (K)	%Sandstone	Pnet	% 1st order stream	% 2D prod. quat.	Bedrock K	log (K)	%Sandstone
ABSOLUTE INDICATORS	Q mean	0.88	0.35	0.48	0.27	.	0.28	2e-10	4e-03	5e-02	1e-02	3e-01	1e-02
	Q5	0.81	0.42	0.27	0.35	.	0.37	1e-08	1e-03	1e-02	4e-03	2e-01	3e-03
	Q10	0.85	0.40	0.23	0.34	.	0.35	1e-09	2e-03	2e-02	5e-03	2e-01	4e-03
	Q30	0.89	0.34	0.15	0.21	.	0.22	1e-10	4e-03	8e-02	3e-02	5e-01	3e-02
	Q50	0.79	0.18	.	.	.	.	3e-08	5e-02	3e-01	2e-01	1e+00	2e-01
	Q70	0.55	.	.	.	.	.	8e-05	4e-01	9e-01	8e-01	5e-01	8e-01
	Q90	0.20	.	.	.	.	.	4e-02	6e-01	1e-01	3e-01	2e-01	3e-01
	Q95	.	.	0.17	.	.	.	1e-01	3e-01	6e-02	2e-01	1e-01	2e-01
RATIOS AND FDC norm	Q5/Qmean	0.27	0.42	0.55	0.51	0.24	0.54	1e-02	1e-03	8e-05	2e-04	2e-02	1e-04
	Q5/Q50	0.25	0.38	0.48	0.52	0.29	0.54	2e-02	2e-03	3e-04	1e-04	1e-02	9e-05
	Q95/Qmean	0.17	0.40	0.58	0.52	0.30	0.54	6e-02	2e-03	4e-05	2e-04	9e-03	1e-04
	Q95/Q50	0.16	0.44	0.58	0.47	0.25	0.49	7e-02	8e-04	3e-05	4e-04	2e-02	3e-04
	Q95/Q5	0.16	0.37	0.56	0.49	0.28	0.51	6e-02	3e-03	6e-05	3e-04	1e-02	2e-04
	k of FDC	.	0.16	0.41	0.50	0.36	0.52	1e-01	6e-02	1e-03	2e-04	3e-03	1e-04

Figure 3.4: Selection of Figure 3.3 illustrating only the catchment properties that explain a significant part of the variance of some streamflow predictors ($R^2 > 40\%$, except log(K)). Catchment properties that are correlated to precipitation (red lines in previous figure) are left out. The ratios on the left indicate R^2 , whereas the corresponding p-values are given on the left.

Absolute streamflow indicators

Net mean precipitation (P-ET) explains 88% of the variance of mean discharge and between

81% and 89% of the variance of the discharge percentiles characterising the higher part of the absolute flow duration curve (Q5 to Q30). From Q30 to the low-flow indicator Q95, a clear decreasing trend of precipitation influence on discharge percentile is observed. Only 20% of the variance of Q90 is for instance explained by mean net precipitation and the correlation is insignificant for Q95 (p -value = 0.1). As mentioned previously, no catchment or climatic characteristic explains a substantial proportion of the variance of Q95. When combining geological characteristics (% of sandstone and % of 2D productive quaternary aquifer) with mean net precipitation into a multiple regression model, however, 47% of the variance of Q95 can be explained.

This is further illustrated in Figure 3.5. Q5 is plotted against the net mean precipitation (Pnet) in the left subplot (a). The coefficient of determination for the Q5 estimation based on mean net precipitation is of 81% (p -value: $9.74e^{-9}$). As Q95 is both dependent on precipitation and catchment properties, we divide the indicator by the net mean precipitation to focus on the influence of the latter (Q95/Pnet, right subplot b). In the x-axis, a linear regression model composed of the percentage of sandstone and the percentage of productive quaternary deposits, whose parameters are fitted against Q95/Pnet (see equation above Figure 3.5 b). The correlation between Q95/Pnet, or the part of net precipitation that will be released during dry periods, and the model based on geological parameters is characterised by a R^2 of 55% (p -value: $7.19e^{-5}$). For the Biber and especially the Luthern catchments, the Q95/Pnet ratio is considerably underestimated by the geological expression. As indicated by their unclosed water balance (Figure 3.2), this discrepancy might be owed to groundwater flowing out of the catchment without being measured by the gauging station. In the case of the Glatt, Langeten and Murg Walliswil catchments, actual low flows are higher than the estimation based on sandstone and quaternary deposits. Other storage units in the catchment such as soil or local geological units that are not accounted for might contribute substantially to the stream in the absence of rain.

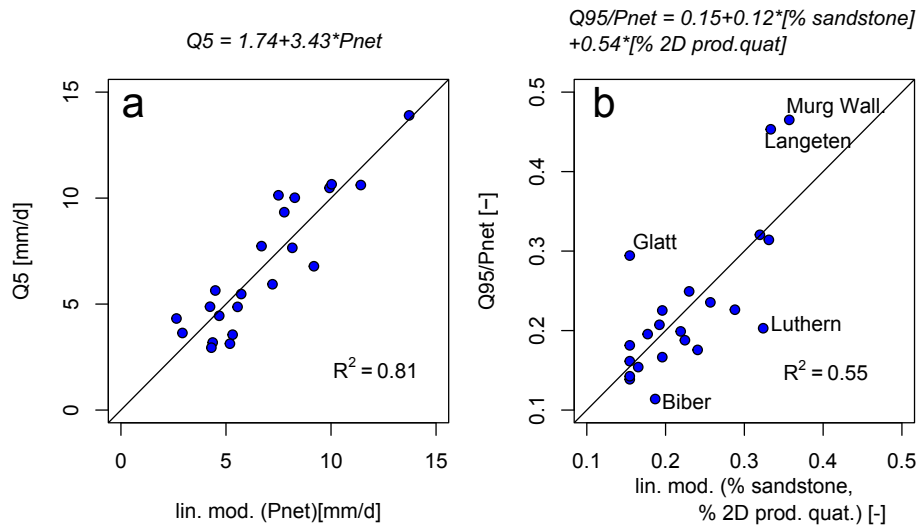


Figure 3.5: Simple linear regression between mean net precipitation and Q5 (a, p-value: $1e^{-8}$) and multiple linear regression based on sandstone and productive quaternary aquifer to estimate the ratio between Q95 and mean net precipitation (b, p-value: $7e^{-5}$)

Streamflow ratios and dimensionless FDC descriptors

The normalised flow percentiles describing both the high ($Q5/Q_{mean}$, $Q5/Q50$) and the low ($Q95/Q_{mean}$, $Q95/Q50$) parts of the dimensionless flow duration curve are characterised by similar percentage of explained variance attributed to the catchment properties: 37-44% by the topographical feature “% of 1st order stream”, 48-58% by the proportion of productive quaternary aquifer, 47-52% by the permeability of bedrock and 49-54% by the proportion of sandstone, with p-values equal or smaller to 10^{-3} for all these relationships (Figure 3.4). The recession parameter of the dimensionless flow duration curve (“k of FDC”), which also describes its shape, is slightly more correlated to bedrock (50-52%) than to quaternary (41%) characteristics, and not significantly explained by the topographical feature (16%).

As expected due to their high interdependency, bedrock permeability and proportion of sandstone indicate similar R^2 values. The correlation between the logarithm of the hydraulic conductivity of bedrock and streamflow relative indicators is however rather limited (R^2 of 24-36%). This suggests that the permeability of the bedrock might be a less efficient predictor for catchments with low permeability (i.e. the catchments without sandstone). When the permeability of bedrock is limited, other catchment characteristics can have a higher explanatory potential (see previous chapter). Moreover, the variability of estimated hydraulic conductivities in the absence of sandstone is smaller as the permeabilities of the other geological lithologies are more similar. Among these remaining geological units, none seem to exert a dominant impact on streamflow.

Figure 3.6 illustrates the relationship between the relevant catchment characteristics (% sandstone and % productive quaternary deposits) and the normalised high ($Q5/Q_{mean}$) and low ($Q95/Q_{mean}$) flow percentiles discussed above. Higher proportions of permeable

geological unit (sandstone and quaternary deposits) generally imply higher normalised low flow (subplots a and b) and lower normalised high flow percentiles (subplots c and d).

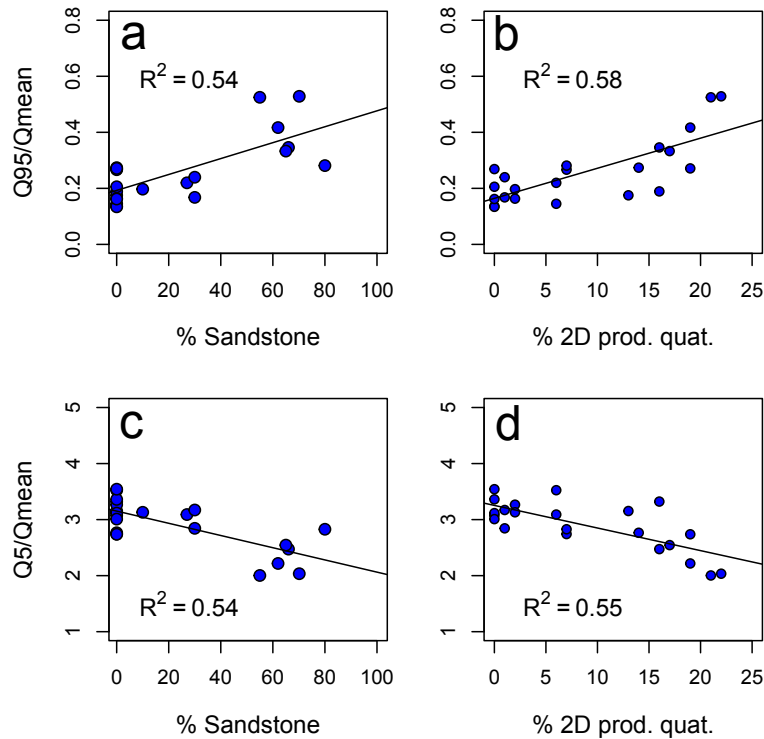


Figure 3.6: The normalised low and high discharge percentiles, $Q95/Q_{mean}$ (top) and $Q5/Q_{mean}$ (bottom) are plotted against the surface percentage of sandstone (a and c) and of productive quaternary deposits (b and d). The p-values are all below $1e^{-5}$.

Figure 3.7 explores more in detail the relationships between geology and the normalised discharge indicators. In the left scatter plots (a and b), the normalised high and low discharge percentiles are strongly correlated ($R^2 = 93\%$) to each other. The location of the catchment along that line strongly depends on geology, as indicated by the size of circles that are proportional to the sandstone proportion (a) and to the proportion of productive quaternary deposits (b).

On the right side of Figure 3.7 (c), catchments are sorted according to decreasing $Q95/Q_{mean}$, the classification hence approximately following the high-low percentile correlation line from top left to bottom right. High $Q95/Q_{mean}$ and low $Q5/Q_{mean}$ ratios imply a moderate streamflow dynamics and reflect a high buffering potential of the catchment, which substantially dampens the precipitation signal. The 6 catchments with the highest buffering potential correspond to the basins composed of the highest percentage of sandstone (orange bar plots, 60 to 80%). In the 6 cases, the proportion of productive quaternary deposits (coral bar plots) is also significant.

The buffering potential of the catchment is not guaranteed for high proportion of productive quaternary only, as illustrated for instance by the Alp and Aach catchments. To better quantify the importance of quaternary deposits, the volume of productive quaternary

averaged by catchment area is included in black in Figure 3.7. The productive quaternary deposits, although covering a considerable percentage of the Alp and the Aach catchments, are rather limited in terms of volume, which might explain the relatively low buffering ability of the two basins. The Guerbe catchment is characterised by the more important relative volume of productive quaternary. Despite these important deposits and similar sandstone percentage, its buffering potential is lower than in the case of Murg Walliswil, Langeten and Wigger. A more detailed investigation of the valley fillings of the Guerbe valley based on the Hydrogeological Map of Switzerland (Sarine region, 1:100'000, Federal Office of Topography Swisstopo) indicated, however, that the deposits are rather heterogeneous with local fine-grained and lacustrine clay units that act as aquitard. The volume of productive quaternary deposits is therefore overestimated in the case of the Guerbe. Considering this correction, Figure 3.7 thus suggests that, for catchments with a high percentage of sandstone, the volume of productive quaternary deposits (averaged by surface) might be the second factor determining the buffering ability of the catchment. We also observe that the Murg Wängi and Murg Frauenfeld catchments, although lacking sandstone, have a relatively high buffering potential that might be owed to the very important volume of productive quaternary deposits.

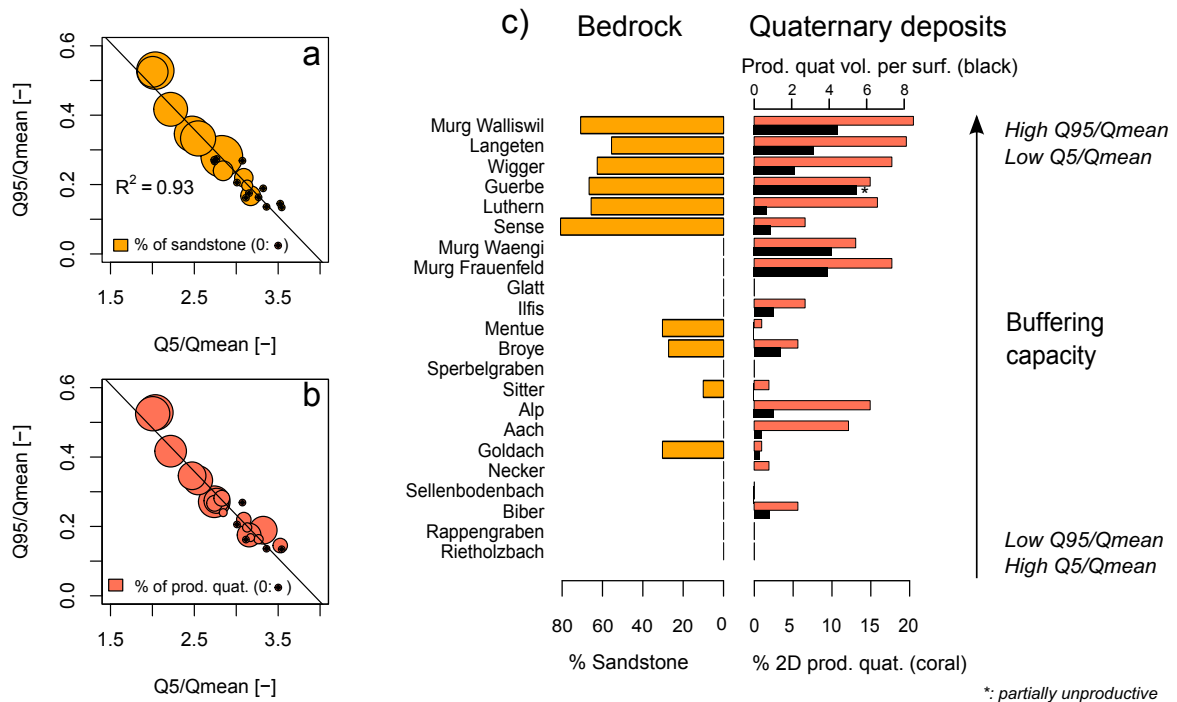


Figure 3.7: On the left (a and b), normalised low flows are plotted against normalised high flows for the 22 catchments (p-value: $6e^{-13}$): the presence of sandstone resp. productive quaternary deposits are indicated in the top resp. bottom subplot, the size of the circles being proportional to the ratio of the respective lithologies in each catchment. On the right (c): the 22 catchments are sorted according to decreasing Q_{95}/Q_{mean} , and the % of each relevant geological unit is shown for each catchment.

3.4 Discussion

3.4.1 Climate and catchment controls on streamflow dynamics

Numerous catchment properties describing topography, soil, land use and geology, as well as meteorological characteristics are compared to both absolute and normalised streamflow signatures. While climate forcing is dominant on the high to medium absolute flow indicators, this influence decreases for low flows and the buffering effect of the catchment becomes relevant. These results are consistent with the findings of Yaeger et al. (2012) who showed that, whereas the middle part of the flow duration curve is influenced by the precipitation, the low-flow end of the curve reflects catchment characteristics. Moreover, our results show that the use of the dimensionless flow duration curve and discharge indicators indeed allows distinguishing how the catchment buffers the precipitation signal.

Based on the results illustrated in Figure 3.3, we propose a conceptualisation of climate and catchment control on absolute and normalised long-term flow duration curve (Figure 3.8).

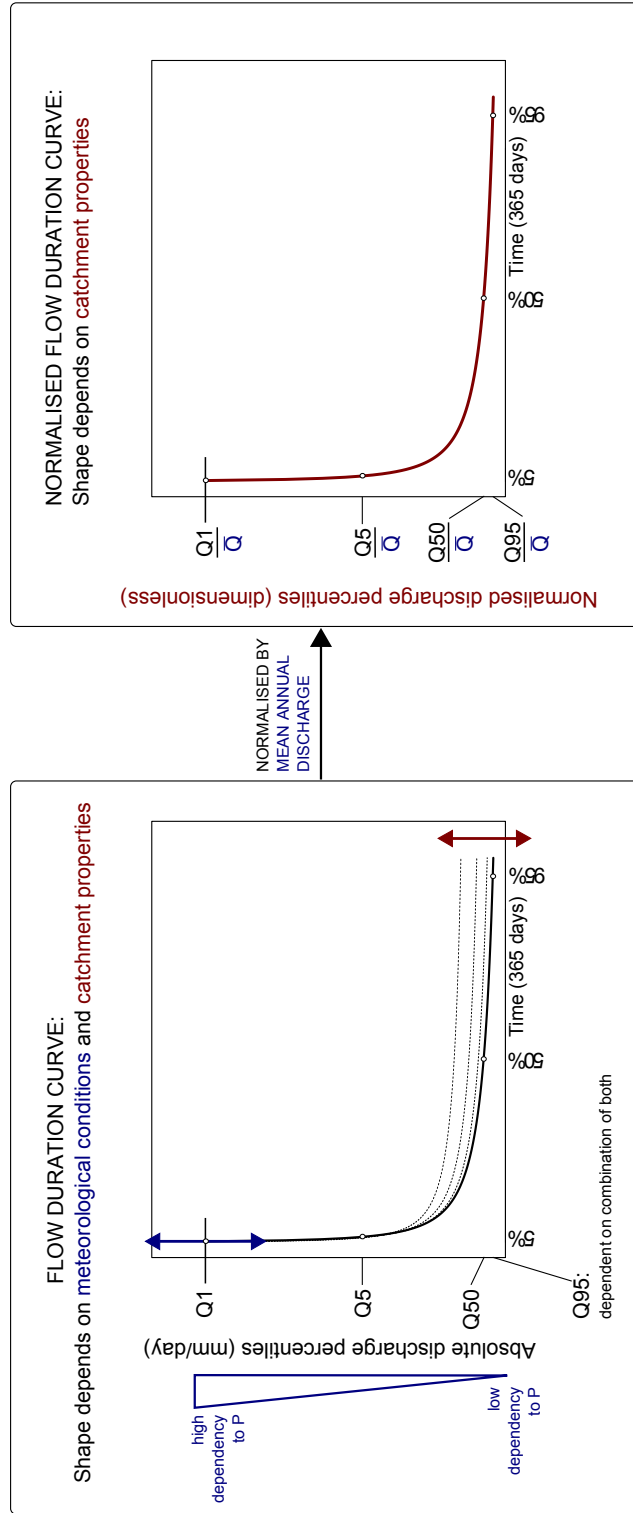


Figure 3.8: Conceptualisation of the flow duration curve (left) and the dimensionless flow duration curve (right). Blue indicates parameters or sections controlled by meteorological conditions, whereas red shows the control by catchment characteristics.

Both high- and low-flow normalised percentiles ($Q5/Q_{\text{mean}}$ and $Q95/Q_{\text{mean}}$), i.e. the two vertical extremes of the curve, are influenced by the catchment physical properties and are highly correlated to each other. Catchments with high $Q95/Q_{\text{mean}}$ and hence relatively high low flows are featured by an important buffering potential. For these catchments, storage is substantial during precipitation events and their normalised high flows are thus limited. The dimensionless flow duration curve of such catchments will be flatter than for catchments with low buffering potential, their curve following more closely the dynamics of precipitation. This distribution of streamflow between high and low ranges, i.e. the shape of the normalised curve, depends mainly on catchment properties.

Although the mean net precipitation varies considerably among the 22 studied catchments (up to 1000 mm yearly difference), the seasonal distribution of rain is rather homogeneous due to the limited geographic distances and altitude differences. In this study the different amplitudes of the dimensionless flow duration curve are thus mainly due to varying catchment properties. For catchments with different precipitation regimes, the shape difference of the curve might, however, also be influenced by the meteorological signal. Nonetheless, the comparison of dimensionless flow duration curves between catchments of similar precipitation regimes is a highly valuable approach to compare catchment buffering potentials. This way, the resilience of catchments to climatic changes and their sensitivity to dry periods can for instance be compared.

3.4.2 The influence of geology on the buffering potential of catchments

Figure 3.3 illustrates that, among the 33 catchment properties describing topography, soil, land use and geology, a clear relationship can only be observed between the geological characteristics and the normalised streamflow indicators. The obtained correlations (R^2 around 50%) are slightly lower than the values indicated for instance by Tague and Grant (2004) or Pfister et al. (2017): 76% for the correlation between summer streamflow and the portion of highly permeable volcanic rock, resp. 64% between the impervious part of the catchment and the ratio of summer and winter flow. These studies however focus on specific periods of the year, whereas we presently consider the whole streamflow range. The comparison to other results is limited as studies comparing catchment properties to streamflow dynamics on the basis of simple linear regression are scarce. The p-values of the correlations between the relevant geological descriptors and relative streamflow indicators, however, are all equal or smaller to 10^{-3} , suggesting that they are statistically significant considering the widely used 95% confidence interval. These findings suggest that the degree of buffering of the precipitation signal exerted by the catchment is mainly governed by geology. As assumed in the introduction (1st hypothesis), geology not only influences low-flow dynamics but equally impacts the entire dimensionless flow duration curve, including $Q5/Q_{\text{mean}}$. The consideration of geological units by taking into account their hydrogeological characterist-

ics thus leads to a better understanding of catchment dynamics. Our results suggest that both the bedrock and quaternary alluvial fillings considerably impact streamflow dynamics.

Bedrock geology

In the studied region of the Swiss Plateau and Prealpes, marine sandstone seems to significantly influence the ability of the catchment to stabilise streamflow, this geological unit being relatively permeable (10^{-5} to 10^{-4} m/s). As illustrated in Figure 3.7, catchments with the highest buffering potential are all mainly composed of sandstone (60-80 % of their surface). This Molasse type, or any geological formation with similar hydrogeological properties, seems to be a prerequisite for high normalised low flows. Its permeability is high enough to store water in the subsurface during precipitation events and low enough to still contribute to streamflow after prolonged dry spells. As an illustration, the estimated permeability of sandstone (10^{-5} m/s for the calculation) corresponds to a daily rate of 864 mm/d and the permeability of fine-grained material can optimistically reach a value of 8.64 mm/d (10^{-7} m/s). Sandstone can store large amounts of water and consequently buffer considerable rainfall events, whereas the second only allows infiltrating a limited portion. This buffering potential of sandstone on streamflow corresponds to the findings of various studies (Jencso and McGlynn (2011), Nippgen et al. (2011), Naef et al. (2015)). More generally, these results support the various case studies that highlighted the importance of the permeability of bedrock for low flows (Tague and Grant (2004), Pfister et al. (2017)), giving credit to the hypothesis of the hydrologically active bedrock (Uchida et al. (2008)).

Quaternary deposits

Our study also shows the relative importance of productive quaternary deposits for streamflow dynamics. These aquifers, although limited in size, can contribute substantially to outflow, as suggested by the case study by Käser and Hunkeler (2016). The integration of total versus productive quaternary deposits characteristics highlight the importance of using appropriate (hydro)geological descriptors. Whereas the total volume of quaternary deposits in the catchments (“Tot. quat. vol. per surface”) is not correlated to streamflow indicators, the exclusive consideration of the productive portion of these deposits (“Prod. quat. vol. per surface”) allows linking the presence of quaternary aquifers to streamflow dynamics (see Figure 3.3). It is thus crucial that the geological characterisation of catchments for hydrological purposes focuses on the hydrogeological productivity of the various geological units. Our results suggest that the use of 2D hydrogeological information describing the productivity of the aquifers already leads to a substantial explanatory power of quaternary deposits on streamflow dynamics (e.g. R^2 of 58% between Q_{95}/Q_{mean} and “% 2D prod. quat.”). Looking at the volumes of these deposits further improves the analysis of the relationship between geology and catchment dynamics in several cases (see Figure 3.7). However, the overall correlation between the 3D quaternary indicator (“Prod. quat. vol. per

surface”) and streamflow dynamics is not higher than with the 2D descriptor (“% 2D prod. quat.”). This can be attributed to the assumption, for the calculation of the 3D productive volumes, that quaternary deposits are homogeneous in terms of permeability. It highlights the importance of characterising the heterogeneity of these structures, as illustrated with the Guerbe catchment (Figure 3.7).

Moreover, in a more local context, the presence of permeable quaternary deposits under the gauging station of the catchment can have a determining impact on the measured streamflow and on the water balance. As illustrated in Figure 3.2, specific outlet configurations might cause unclosed water balance.

3.4.3 Buffering potential and dynamic storage: a groundwater perspective

What we here refer to as the buffering potential of the catchment on the precipitation signal can be assimilated to the dynamic storage of the catchment, commonly defined as the storage that governs streamflow dynamics (Buttle, 2016), which in other words determines how much water can be stored during precipitation events and then released to the stream. The results of the present study suggest that catchments with relatively permeable geological units have a high buffering potential on precipitation, and hence a notable dynamic storage. In the framework of groundwater studies, bedrock permeability and meteorological input expressed as recharge are commonly related to assess flow processes (Gleeson and Manning (2008); Haitjema and Mitchell-Bruker (2005); Welch and Allen (2012)). Gleeson and Manning (2008) and Haitjema and Mitchell-Bruker (2005) notably have highlighted the influence of the ratio between recharge and permeability (R/K), along with topographical considerations, on the water table configuration. Groundwater levels in turn impact the partitioning of precipitation into recharge to groundwater and contribution to local stream network. Briefly stated, the mentioned authors show that a high R/K ratio generally implies a water table located close to the surface (*topography controlled*), whereas a low ratio indicates that the water table is *recharge controlled*. In the first case (high R/K ratio), the dynamic storage of the catchment is limited as the water table is constrained by topography. During rain events, the overland flow is substantial, less water is stored and contributions to stream during dry periods are thus limited. When R/K is low, the water table fluctuates according to recharge: the dynamic storage and hence the buffering potential of the catchment is important.

The ratio of 1st order stream is the only topographical characteristic explaining a considerable part of the variance of the normalised discharge percentiles (38-44%), and provides another similarity with the study by Gleeson and Manning (2008). Our results suggest that streamflow dynamics of catchments with a less dense upper stream network will likely be more stable (low peaks and high low flows). Using a groundwater modelling approach in mountainous terrain, the study by Gleeson and Manning (2008) shows that the percentage

length of first-order stream with perennial flow (comparable to % of 1st order stream) is a function of the water table which in turn depends on the R/K ratio. They demonstrate that, in case of low percentage of 1st order stream (less developed upper stream network), the relative recharge contribution to regional groundwater flow is more important. Under the assumption that this groundwater flow contributes to the stabilisation of streamflow dynamics (i.e. higher buffering ability of the catchment), our results are consistent with the mentioned groundwater study. In this sense, the ratio of 1st order stream thus reflects the R/K ratio and the geological characteristics of the catchment, as it is directly impacted by infiltration and groundwater processes. These considerations should however be further investigated, as the resulting correlations are rather limited.

3.4.4 Importance of other catchment properties for streamflow dynamics

Topography and soil, as they impact overland flow, infiltration and subsurface processes, are expected to have an influence on streamflow. Some of their related characteristics are correlated to absolute streamflow indicators but these relationships seem to be side effects of their correlation to precipitation. Except for the percentage of 1st order stream discussed before, the results suggest that no soil and topography characteristics explain an important part of the variance of normalised streamflow signatures. Even though soil characteristics might be crucial e.g. in humid regions with low relief, it might be of less importance relative to deeper geological units in steeper regions subject to dry periods.

Moreover, as no detailed soil map exists for the extent of this study, the data used to characterise the soil is of rather poor resolution. As suggested by various studies (Haitjema and Mitchell-Bruker (2005), Welch and Allen (2012), Chapter 2), topography and hydrogeological properties constrain hydrogeological processes, and thus streamflow, in a combined way. Assessing topographical characteristics of distinct geological units might thus be a useful approach to better integrate topography in studies on the relationship between catchment properties and dynamics.

Various studies have highlighted the importance of spatial correlation between catchment streamflow signatures (e.g. Betterle et al. (2017); Pugliese et al. (2014)). Analogies in streamflow dynamics of neighbouring catchments can be observed in Figure 3.1: clusters of catchments roughly show similar colours representative of their buffering capacity. Catchments close to each other, as they likely are characterised by both comparable meteorological and general geological environment, can have a similar streamflow behaviour. Local geological characteristics should however be considered as they can considerably impact stream dynamics.

Numerous catchment properties have not been considered in this study and some represented characteristics, such as topography, could be described more accurately. The focus here is set, however, on geological and hydrogeological descriptors, as subsurface charac-

teristics have rarely been explicitly integrated in previous studies. Although our results suggest that geology substantially determines the streamflow dynamics of the catchments in the Swiss Plateau and Prealpes, other physiographic characteristics might be relevant for regions with different climate and relief.

3.5 Conclusions and implications

In this study, a total of 33 characteristics describing catchment topography, soil, land use and geology are compared to streamflow indicators, along with various meteorological indices. Our approach distinguishes itself from previous studies by including geological characteristics that describe the capacity of different lithologies to store and release water, i.e. their hydrogeological properties, and by considering both the large-scale geological environment (bedrock) and the local scale quaternary deposits. Combined to the use of various long-term streamflow signatures, composed of both absolute and standardised indicators, this detailed geological characterisation allows distinguishing the catchment influence from the meteorological influence on stream dynamics.

3.5.1 Implications for hydrological sciences

Our results suggest that the geology substantially determines the ability of the catchment to buffer the meteorological signal. Among the soil, land use and topography properties considered in this study, only the geological descriptors are notably correlated to the dimensionless streamflow indicators. These results emphasise the crucial need to take into account groundwater dynamics in hydrological studies. We show that both the general geological environment (bedrock) and the more local scale quaternary deposits influence the catchment response to precipitation. This highlights the potential, for catchment classification and characterisation in hydrological science, of considering the hydrogeological productivity of both large and local scale lithologies. In general, these results suggest that the mere classification of aquifers into wide categories (e.g. unconsolidated, porous and fractured) is not adequate for describing the hydrogeological setting of catchments and should not be used in catchment classification schemes.

The relative importance of these geological units implies that multiple groundwater reservoirs exist and should be modelled accordingly. A more explicit consideration of subsurface processes in classical hydrological models could thus lead to notable improvements, especially for low-flow studies. Although this aspect has not been explored here, it can be assumed that the bedrock and the alluvial aquifers impact streamflow over different time scales, as flow rates are generally substantially superior in quaternary deposits than in the bedrock. These different dynamics should be considered to better assess catchment dynamics.

3.5.2 Implications for water resources management and data acquisition

The outputs of this study, by identifying the catchment properties that determine low-flow dynamics, suggest new perspectives for water resources management. The presence of relatively permeable lithologies is for instance an indicator of an important dynamic groundwater storage, and thus sustained low flows. Sandstone-like porous lithologies, which are characterised by a rather high permeability (e.g. 10^{-5} m/s), have a potentially high buffering effect on climate forcing and are thus favourable for the contribution to low flows. The presence of permeable and deep quaternary deposits is also correlated to higher normalised low flows. Whereas a high percentage of sandstone seems to be a prerequisite for a high buffering potential for the investigated catchments, it seems that the mere presence of productive alluvial aquifer is, however, not always a guarantee for sustained low flows. Although sandstone and quaternary deposits have been identified as important in the Swiss Plateau and Prealpes, other similar lithologies might be of relevance for low flows elsewhere. Catchments lacking any permeable geological unit will likely be characterised by a pronounced stream dynamics, implying potential flooding and low-flow issues.

The importance of high quality geological data describing both the bedrock and the alluvial aquifers is pointed out by this study. More specifically, the hydrogeological properties of the various geological formations should be characterised. Especially bedrock, whose permeability is tied to significant uncertainties, should gain more attention as a groundwater reservoir relevant for low flows. The 3D structure and heterogeneity of quaternary deposits should also be considered in the framework of water resources projects. Projects like *GeoMol* (“Assessing subsurface potentials of the Alpine Foreland Basins for sustainable planning and use of natural resources”, Diepolder et al. (2013)), that characterise bedrock and quaternary deposits are thus crucial data sources for water resources management.

Chapter 4

Implications for catchment sensitivity to dry periods

4.1 Comparison of findings of Chapters 2 and 3

In this section, a synthesis of the two preceding chapters is proposed and their main findings are compared. The two approaches investigate various physiographic controls on catchment and low-flow dynamics with complementary methods. Both with the synthetic models and the field data analysis, similar processes and governing mechanisms are highlighted that support the understanding of catchment dynamics in general and of low-flow behaviour in particular. The similarities and complementarities of these outputs are discussed here. Based on this, a guideline for the assessment of water resources sensitivity to dry periods is proposed. The key findings of Chapters 2 and 3 are listed below and then put in a joint perspective.

Chapter 2: Exploring geological and topographical controls on low flows with hydrogeological models. The synthetic models improved the characterisation of the link between low flows and groundwater processes, of the relative importance of the bedrock and the alluvial aquifer, and of the combined impact of hydraulic conductivity and slope gradients:

- The dynamic groundwater storage determines low-flow dynamics.
- The hydraulic conductivity of the bedrock exerts a dominant control on storage and low-flow dynamics.
- The alluvial aquifer can also contribute substantially to low flows, especially if dynamic storage is limited in the bedrock.
- The combined influence of topographical gradients and hydraulic conductivity is identified.

Chapter 3: Assessing catchment controls on streamflow dynamics: the importance of geology. The analysis of the 22 Swiss catchments allowed to differentiate between the meteorological and the catchment controls on streamflow, and to identify the importance of geology for streamflow dynamics:

- The impact of climate conditions and catchment properties on streamflow signatures are identified, the catchment exerting a buffering effect on the meteorological signal.
- With the available data, the ability of the catchment to buffer the climate signal can clearly be attributed to geological characteristics.
- Both the bedrock and the quaternary deposits significantly impact streamflow dynamics, although the presence of sandstone seems to be a prerequisite for a high buffering potential.
- The presence of highly permeable alluvial deposits under the gauging station can lead to unclosed water balances.

4.1.1 Dynamic groundwater storage and buffering potential of the catchment

Both the synthetic and the observation based approaches characterise the response of numerous catchments with different physical features to the meteorological forcing. The first study (Chapter 2) focuses on low flows, whereas the second (Chapter 3) considers the entire streamflow range. They illustrate that the variety of streamflow dynamics is the result of different degrees of attenuation of the climate signal inherent to catchment properties. The synthetic models show that high low flows reflect an important dynamic groundwater storage. Although the synthetic approach focuses on the lower discharge range, Figure 2.5 (Chapter 2) for instance illustrates that the general streamflow dynamics is impacted by groundwater dynamics. A pronounced storage dynamics implies that a significant amount of water is stored in the subsurface during precipitation events, hence attenuating high flows, and that groundwater contribution to the stream during dry periods is substantial. Conversely, a small dynamic storage is associated to flashier streamflow dynamics with pronounced high flows and limited low flows.

The second approach (Chapter 3) highlights similar results, relating the ability of the catchment to buffer the meteorological signal to the presence of highly productive lithologies. Moreover, this approach indicates that the buffering potential impacts both the normalised high and low discharge percentiles, and that these two extreme indicators are consequently highly correlated. This reflects the water balance of the catchment: substantial low flows can only be generated by a significant contribution of groundwater storage (i.e. high dynamic storage), which is provided by high recharge rates during rain events (hence the limited high flows). To sum up, the buffering potential of the catchment is related to the

dynamic groundwater storage. The first approach thus provides insights on the processes that govern this storage and release capacity of the catchment.

4.1.2 The role of geology and the relative importance of the bedrock and the alluvial deposits

With the synthetic models, catchment properties can be varied systematically and their influence on catchment response can be quantified independently. However, the number of parameter combinations increases exponentially with every additional parameter. In the synthetic approach, the influence on low-flow dynamics of a limited number of catchment properties is thus tested. The relationships between physiographic characteristics and streamflow dynamics are less clear with the analysis of the 22 catchments, but this second study allows considering a larger panel of physical properties, notably soil and land use characteristics. The two approaches, however, lead to similar results and suggest that the degree of buffering exerted by the catchment on the precipitation input is mainly governed by the geology. More specifically, the hydrogeological properties of the different lithologies are relevant. The synthetic approach indicates that the hydraulic conductivity of the bedrock exerts a dominant control on low flows and dynamic groundwater storage. The investigation of the 22 Swiss catchments highlights the importance of sandstone, this lithology having a stabilising effect on streamflow dynamics. In both cases, a relatively permeable bedrock seems to guarantee sustained low flows.

The results of both investigations suggest that permeable alluvial aquifers, referred to as productive quaternary deposits in Chapter 3, can also significantly impact streamflow dynamics. The synthetic models allow quantifying the relative parts of dynamic groundwater storage taking place in the bedrock resp. in the alluvial unit. Their outputs show that the alluvial unit becomes especially relevant for low flows when the dynamic storage is limited in the bedrock, i.e. when the bedrock is close to inactive. Besides, the results also suggest that a highly permeable alluvial unit can enhance dynamic storage in the surrounding bedrock. However, maximal dynamic storage levels are only reached when the bedrock is productive.

The investigation of the 22 catchments does not permit the quantification of the relative dynamic storage in the bedrock and the quaternary deposits. Moreover, the catchments with the higher buffering potential are characterised by both a high proportion of sandstone and of productive alluvial deposits (Figure 3.7, Chapter 3), complicating the identification of the most relevant hydrogeological unit. However, whereas a high proportion of sandstone seems to imply a rather stable streamflow signature, voluminous productive quaternary deposits alone do not guarantee a high buffering potential. This corroborates the synthetic findings and suggests that a bedrock with relatively high hydraulic conductivity (e.g. 10^{-5} to 10^{-6} m/s) is permeable enough to support an important dynamic groundwater storage but, as a rather slow draining unit, sustains streamflow even after prolonged dry periods.

4.1.3 The role of topography

With the synthetic models, characterised by a simple geometry, the importance of hillslope gradients for catchment dynamics is highlighted. Steeper hillslopes, as they lead to more important storage volumes drained by the river and influence the hydraulic gradient, enhance the productivity of the bedrock and dynamic storage. The formulation of the BPI index illustrates the combined control of hillslope gradient and hydraulic conductivity of the bedrock on the catchment dynamics. As shown in Figure 2.6 (Chapter 2), however, the impact of slope gradients is not observable when considering all the synthetic models and only becomes visible once the results are analysed for different hydraulic conductivities of bedrock.

The influence of topography is less obvious on the streamflow dynamics of the 22 Swiss catchments. Due to the limited number of investigated rivers, the real case study does not allow analysing the control of slope gradients separately for different bedrock categories, as done with the synthetic models. Moreover, the identification of topography control is impeded by the correlation between slope gradients and precipitation. Finally, the geometry of existing catchments is far more complex than the synthetic model setting. It is consequently difficult to identify a topographical descriptor, such as the hillslope gradient for the synthetic models, which impacts the overall catchment dynamics. Considering Darcy's law and the synthetic results, however, it seems appropriate to conclude that topographic gradients are necessary for groundwater flow to occur as they determine groundwater gradients, and are thus relevant for streamflow dynamics.

4.1.4 The configuration of the outlet

In the synthetic models, the entire catchment dynamics is assessed, as the boundary conditions are set to force groundwater to the surface at the outlet of the catchment. To relate the results of the synthetic approach to an existing catchment, its outlet configuration should be assessed. If permeable deposits are present at the outlet, the groundwater flow that potentially exists the catchment without being measured by the gauging station should be estimated. As shown in Chapter 3 (Figure 3.2), this issue can impact the water balance of certain catchments.

4.2 Application to the assessment of the sensitivity of water resources to dry periods

During the exceptionally dry years of 2003, 2011 and 2015, for instance, various regions of Switzerland were impacted by water scarcity. As the frequency and the intensity of these dry periods are expected to increase in the future, it is crucial to characterise the ability of water resources to fulfil specific demands. More importantly, water related services that

might not be fulfilled should be identifiable. For instance, will the discharge of a stream fall under a minimal ecological flow after 30 consecutive dry days? For how long is the drinking water supply guaranteed by an aquifer in the absence of rain?

Based mainly on the previous results, two guidelines for assessing the sensitivity of rivers and alluvial aquifers to dry periods are proposed. These guidelines constitute a central output of the “Low flow” project and have already been described in the final report of the project (Arbeitsgruppe Low flow (2018)). The main objective of these approaches is to identify water related services that might be sensitive to dry conditions. Separate guidelines are developed for water services related to rivers and to groundwater. As groundwater is generally exploited in valley aquifers in Switzerland, the groundwater guideline focuses on the sensitivity of alluvial aquifers. However, both this procedure and the surface water guideline propose a sensitivity assessment based on physical properties where the bedrock is explicitly considered. As highlighted by the previous results, the bedrock exerts a significant control on catchment dynamics and thus presumably affects groundwater dynamics in the valley deposits. To characterise the behaviour of the alluvial aquifer, it is therefore necessary to consider the surrounding geology. Each guideline suggests the use of specific approaches according to the data availability related to the investigated resource.

The proposed guidelines are in line with the call of the NRP 61 Programme for a more integrated, catchment-scale approach to water resources management. Surface water and groundwater in the catchment are taken into account in both stream and alluvial aquifer guidelines. The importance of groundwater for catchment dynamics under dry conditions, which was already highlighted by the “GW-trend” project, is fully considered here and methods are suggested to characterise it. The structure of the guidelines is based on data availability and they are thus applicable to a wide spectrum of cases. Moreover, as their starting point is the definition of water related services, they should respond to practice oriented questions of water resources management. Finally, the following guidelines propose an overview of what physical characteristics should be assessed and monitored to better characterise both streamflow and groundwater dynamics.

4.2.1 Assessment of streamflow sensitivity to dry periods

The guideline for the assessment of streamflow sensitivity to dry periods is illustrated by Figure 4.1, where each step of the procedure is labelled by a letter. Hereafter, each step of the procedure is described. The sensitivity assessment is based on the outflow of the catchment. If the analysis indicates that a stream is not sensitive, it does not guarantee that the statement is valid for the whole length of the river. For instance, the discharge at the outlet might respect a fixed threshold, although a segment of the stream can dry out

periodically. For a spatially distributed assessment of the stream sensitivity, distributed models are needed.

- a) The procedure evaluates the ability of the water resource (here the stream) to fulfil a specified service. The first step of the sensitivity assessment is thus to define precisely the service of interest and to set a quantitative criterion. This threshold then allows determining whether the resource is sensitive (i.e. the service cannot be guaranteed) or not sensitive (the service is guaranteed). Multiple indicators can also be defined but in this case the procedure has to be repeated for each criterion. Stream related services can for instance be minimal ecological fluxes, for which a threshold is defined.
- b) Prior to estimating the sensitivity of a resource, the analysis of historical data is a straightforward way of “pre-identifying” sensitive water-related services. If the water resource has failed to fulfil the in (a) defined service, for instance during especially dry years (e.g. 2003, 2011 or 2015 in Switzerland) and no measures have been applied to avoid it in the meantime, the service is identified as sensitive.
- c) If no “failure” cases have been observed and no changes to the resource or to its use (e.g. extraction for irrigation, river restoration, changing climatic conditions) have been carried out or are expected, the water related service is probably not sensitive. If these conditions are not met or if no historical data is available, the procedure has to be continued.
- d) This step, based on data availability, determines the choice of the approach (i.e. quantitative or qualitative). If discharge and meteorological time series are available, a modelling approach can be used to quantitatively assess the ability of the water resource to guarantee the service. For this, the time series should cover various years, be composed of dry periods and be of high temporal resolution (at least daily data).

Assessment of streamflow sensitivity to dry periods

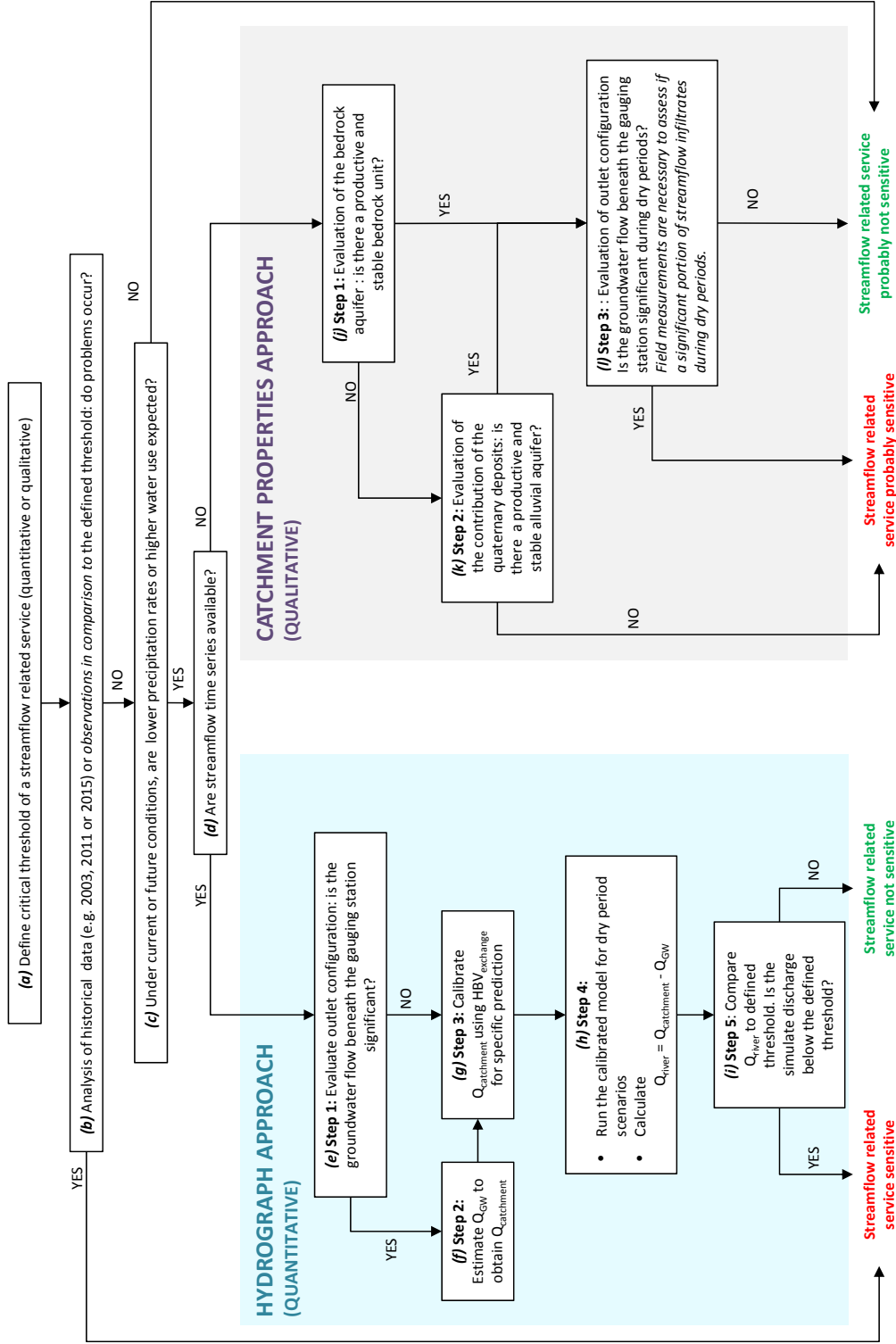


Figure 4. 1: Guideline to assess the sensitivity of streamflow to dry periods. The procedure more exactly determines whether a specific service related to the river is sensitive to dry spells.

Quantitative approach (if “yes” to (d))

- e) Before modelling streamflow, the configuration of the outlet must be considered: if the gauging station is located on impervious geological material, i.e. the measured streamflow encompasses the total catchment outflow, the discharge time series can be used for modelling without pre-processing.
- f) Significant amount of water can flow beneath the gauging station when it sits on top of permeable deposits. In this case, the groundwater flux Q_{GW} flowing in the aquifer section at the outlet location has to be estimated using hydrogeological methods. Ideally, the groundwater flow should be measured various times to the groundwater dynamics. The subsurface flow is then added to the measured streamflow Q_{river} to obtain the total catchment discharge $Q_{catchment}$.
- g) The streamflow behaviour under changed meteorological conditions can be modelled using, for instance, a hydrological model like HBV (Seibert and Vis (2012)). This model has been used in the framework of the Low flow Project and a special version was developed to better simulate low-flow conditions. The calibration of the model should be adjusted to low flows.
- h) Once the model is adequately calibrated, meteorological scenarios can be applied to simulate the river dynamics under changing climatic conditions. Uncertainties should be quantified. If discharge values have been corrected in (f) for subsurface flow, the final streamflow is obtained by subtracting Q_{GW} to the simulated $Q_{catchment}$. This is made under the assumption that changes in the groundwater regime under the meteorological scenario are insignificant.
- i) The simulated Q_{river} can be compared to the criterion defined in (a) considering the model uncertainties. Based on this comparison, a quantitative assessment of the sensitivity of the water related service is possible.

Qualitative approach (if “no” to (d))

If no adequate time series are available to proceed with the modelling approach, the estimation of the sensitivity is based on a qualitative assessment of the geology and the topography of the catchment. This method is the direct result of Chapters 2 and 3.

- j) Bedrock productivity, i.e. its capacity to sustain low flows, is mainly governed by its hydraulic conductivity and thus dependent on the lithologies present in the catchment that can be identified using geological maps. Topography also influences the productivity of bedrock, as slope gradients impact the hydraulic gradients and consequently dynamic groundwater storage. Especial flat reliefs are of concern with regards to the sensitivity to dry periods: the productivity of the bedrock, even if composed of a high proportion of permeable rock (e.g. sandstone), can be limited by

small slopes and consequently low hydraulic gradients. However, geology remains the determining factor as the permeability of bedrock spans over a great range of orders of magnitude that exceeds by far the range of slope gradients. Chapter 3 showed that the presence of sandstone is correlated to high low flows in Switzerland. We thus propose to assess the productivity of the bedrock of a specific catchment based on the presence of a relatively permeable lithology (e.g. sandstone) and the topography related to this lithology. Figure 4.2 illustrates schematically this method.

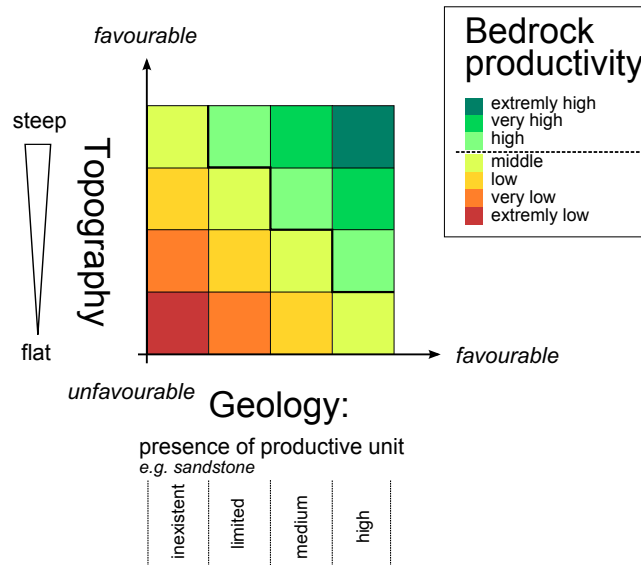


Figure 4.2: Qualitative assessment of the productivity of the bedrock based on geology and topography.

- k) In case of unproductive bedrock, alluvial aquifers might also sustain low flows, although their contribution is probably less stable and long-lasting than bedrock inflows. The productivity and dynamics of these quaternary deposits should be evaluated with hydrogeological methods. If the alluvial aquifer does not contribute notably to low flows, the water related service is probably sensitive to dry periods.
- l) In case of productive bedrock and/or alluvial aquifer, the outlet configuration should be evaluated similarly to point (e). If geological and hydrogeological maps indicate that highly permeable deposits are present under the section of interest of the river, the groundwater flow beneath the outlet is presumably important. The river-related service is consequently probably sensitive. For a more precise assessment, traditional discharge measurement can be carried out along the stream to estimate the infiltration from stream to the alluvial aquifer during dry periods.

4.2.2 Assessment of the sensitivity of an alluvial aquifer to dry periods

Figure 4.3 illustrates the methodology for the assessment of the sensitivity of a service related to an alluvial aquifer. Points (a) to (c) correspond to the first steps of the pre-

vious guideline. Groundwater related services and the corresponding thresholds are, for instance, an ecological system bound to groundwater that requires a certain groundwater head, groundwater extractions that should not exceed a certain percentage of the recharge or the groundwater contribution to stream, whose flux should respect a minimal value.

From (d) on, the procedure differs from the previous approach:

- d) To predict groundwater heads under changed recharge or consumption conditions, a numerical hydrogeological model is necessary. This modelling approach requires time series of groundwater heads as well as meteorological data that cover various years and include periods of limited recharge. Moreover, information on the bedrock and the alluvial aquifer geology and hydrogeology is necessary for the development of the numeric model. In the presence of a river, streamflow measurements can also be included in the model and the exchange fluxes between the stream and the alluvial deposits should be characterised.

Modelling approach (if “yes” to (d))

- e) The model is calibrated using the available data. An uncertainty analysis is to be carried out. When only head data is available, simulated values of groundwater discharge and exchange rates with the river are highly uncertain.
- f) Meteorological or recharge scenarios can be applied to the model, including potential changes in pumping rates, and the spatial distribution of heads are simulated.
- g) Under consideration of model uncertainties, the simulated heads or fluxes can be compared to the threshold value defined in (a). Based on this comparison, a quantitative assessment of the sensitivity of the groundwater related service is possible.

Water balance approach (if “yes” to (h))

- h) If the data required for the modelling approach are unavailable, a water balance can still provide valuable information on groundwater storage. The necessary data for a water balance are heads measurements, as well as hydrogeological characteristics of the alluvial aquifer (porosity, hydraulic conductivity, saturated volume). Based on this approach, the time during which an aquifer can sustain a certain extracting flux can be estimated, for instance. However, the water balance does not permit any insight on the spatial distribution of heads.
- i) The water balance is calculated by quantifying all the relevant water fluxes entering and exiting the aquifer system, e.g. recharge, inflows from the bedrock and the river, exfiltration to the river, pumping rates, etc. For a conservative estimation, the recharge can be defined as zero. Based on these fluxes, the time until the stored volume of water falls under a critical value can be estimated, for instance.

- j) If the discharge rate of the aquifer is high, the groundwater resource is probably sensitive. If the discharge rate is moderate, local problems can also occur as this approach does not inform on the spatial distribution of heads.

Catchment properties approach (if no heads or fluxes data available)

- k) In the absence of data, a qualitative approach based on catchment properties is proposed. As is done in the surface water guideline, the productivity of the bedrock should be assessed. Here, the geological investigation focuses on the bedrock lithologies that are drained by the alluvial aquifer, i.e. the units surrounding the quaternary deposits that are not drained by a river. The illustration in Figure 4.2 can again be used as basis for the estimation of bedrock productivity.
- l) In case of unproductive bedrock, the alluvial aquifer is potentially sensitive, as it is not sustained by stable inflows from the bedrock. However, the dynamics of the alluvial aquifer can be estimated using hydrogeological methods for a more accurate sensitivity assessment. If the productivity of both the bedrock and the alluvial aquifer is limited, the groundwater resource is potentially sensitive.

Assessment of alluvial aquifer sensitivity to dry periods

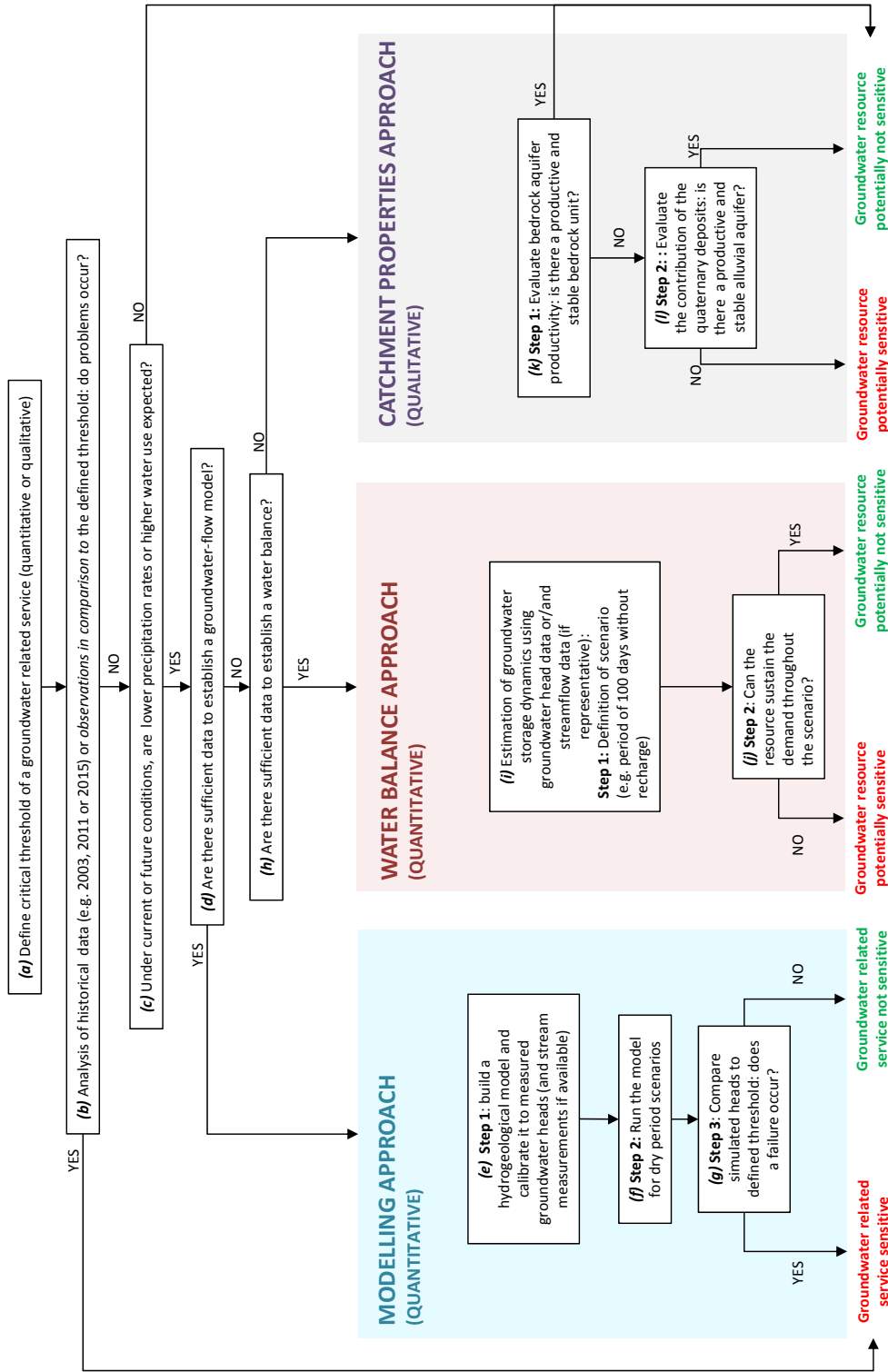


Figure 4.3: Guideline to assess the sensitivity of an alluvial aquifer to dry periods. The procedure more exactly determines whether a specific service related to the aquifer is sensitive to dry spells.

Chapter 5

Conclusion

For water resources management, it is crucial to identify the regions susceptible to be impacted by dry meteorological conditions. This requires a thorough understanding of the behaviour of rivers and aquifers under dry conditions. The characterisation of low-flow dynamics is, however, still limited. Most studies in this field investigate and model low flows with a surface perspective and thus a simplistic consideration of groundwater processes. As rivers are fed by subsurface storage in the absence of rain, the main mechanisms of low-flow generation are consequently often disregarded.

To cope with these limitations, two complementary approaches are developed in this PhD thesis, which both improve the understanding of catchment dynamics by the comprehensive consideration of groundwater processes. The coupled simulation of subsurface and surface processes using an integrated physically based model (Chapter 2), as well as the association of detailed (hydro)geological descriptors and streamflow indicators (Chapter 3), substantially support the characterisation of the mechanisms that control catchment dynamics and more particularly low flows. The results emphasise the importance of taking into account groundwater processes, and the hydrogeological and topographical characteristics governing them, more explicitly in hydrological studies.

The identification of the relative importance, for catchment dynamics, of the large scale geological setting (bedrock lithologies) and the local alluvial quaternary deposits illustrates that the various aquifers present in a catchment should be considered. Besides, these groundwater reservoirs can be characterised by diverse storage and release dynamics that should be accounted for in catchment science. Flow rates are for instance substantially superior in permeable valley fillings than in the bedrock. The contribution of alluvial and bedrock aquifers might consequently be relevant for streamflow over different time scales. The slower releasing mechanisms related to the bedrock, for example, will likely sustain streamflow even after prolonged dry periods, whereas the alluvial storage might be more important for shorter-term dry spells.

The relevance for low-flow generation of the two units is sometimes neglected because bedrock lithologies are often characterised by relatively low permeabilities, and because alluvial deposits have a limited spatial extent. The results of the present work show, however, that their contributions to low flows can be essential: the small extent of alluvial aquifers can be compensated by high flow rates, whereas the large spatial extent of bedrock lithologies can compensate for their relatively low permeabilities. What is of relevance for catchment dynamics, and especially low flows, is the capacity of a geological unit to store and release water, which is determined by its hydrogeological properties (mainly its permeability), its topographical gradient and its extent.

5.1 Implications for practice

Rivers and groundwater resources are often managed by distinct authorities and thus considered separately. By showing the importance of groundwater for catchment dynamics and more particularly for low flows, the results of this thesis call for a more integrated approach in water resources management. The authorities (Confederation, Cantons) should promote the consideration of all surface and subsurface components of the hydrological cycle, the potential anthropogenic impacts on these elements and their evolution in time.

The guidelines for the assessment of the sensitivity of water resources to dry periods, developed in the framework of the “Low flow” project and presented in Chapter 4 of this thesis, integrate the groundwater and surface water components of the hydrological cycle and propose a catchment-scale approach for water resources management. The two guidelines consist in a step-by-step procedure, in which the water manager is oriented to one or an other approach according to the water resource of interest and the data availability. This flexible structure allows for a wide applicability of the proposed assessment method.

The entry point of the guideline is the definition of the water-related service of interest (e.g. ecological flow in a river, pumping rate in an aquifer, etc). A threshold has to be set, which determines whether the water service is guaranteed or not, such as a minimal river discharge or pumping rate. A thorough definition of the boundaries of the hydrological system is crucial: all hydrological components (rivers, bedrock or alluvial aquifers, etc) connected to the investigated resource have to be considered. The entire catchment, both in terms of surface and subsurface flow, contributing to the river, the alluvial aquifer or the spring of interest, should thus be considered.

The guidelines then offer a series of questions related to the the investigated water resource and its use, as well as the data availability describing this resource. Based on the different answers, approaches for the assessment of the sensitivity of the resource to dry periods are proposed. For well characterised systems (available discharge and groundwater head time series), a precise quantification of the sensitivity can be carried out. When scarce data is available, the sensitivity assessment is based on the catchment properties. In this

case, only a qualitative estimation of the ability of the resource to fulfil the defined service is possible.

To sum up, these guidelines define essential questions regarding the ability of a water resource to fulfil specific needs, describe the types of useful data and detail the tools that can be used depending on data availability. Moreover, they can serve as a basis for developing monitoring strategies for the better characterisation of both streamflow and groundwater dynamics. Ideas for data acquisition derived from the present study are detailed in following section.

5.1.1 Suggestions for data acquisition

This study has highlighted the relevance of specific physiographic properties for catchment and low-flow dynamics. On this basis, suggestions on the type of data that would serve process understanding in catchment science are made. For water resources management, it is crucial to better quantify the ability of various lithologies to store and release water. Their connection to the stream, which influences how they sustain the river during dry periods, needs to be assessed. Furthermore, the exchange mechanisms between the various hydrogeological units should be better characterised. These elements can benefit from the following types of measurements: the hydrogeological properties of the various lithologies, groundwater heads at various locations, and river discharge to infer hydrogeological characteristics.

This PhD thesis highlights the importance of the bedrock aquifer for low flows, especially determined by its hydraulic conductivity. Measuring it is however very difficult and bound to substantial uncertainties. As a result, the hydrogeological properties of the Molasse lithologies, for instance, are not well characterised. Investigations of the bedrock, as an important groundwater reservoir, should be promoted. For the Swiss Plateau, a hydrogeological classification of the various geological formations composing the Molasse would be highly beneficial for the assessment of water resources. To this end, the permeability, the extent and the topographical gradients of the various lithologies should be characterised.

Quaternary alluvial aquifers have also been identified as relevant for low flows. Although these hydrogeological units are in general well characterised in Switzerland (hydraulic conductivity, 2D extent, etc.), the 3D architecture of these aquifers should be further explored. Their heterogeneity should be assessed: e.g. the presence of impervious layers that limit the actual alluvial volume contributing to the river (such as clayey deposits), or large-scale variations of permeability and porosity in depth or along the longitudinal profile of the aquifer. For the assessment of catchment dynamics, a detailed characterisation of the quaternary deposits under the river gauging station, if present, is necessary.

To better characterise the exchanges between the bedrock and the alluvial aquifers, hydrochemical and isotope sampling can be useful. These interactions could also potentially benefit from groundwater head measurements. An optimal setting to investigate this would

be a catchment of simple bedrock geology (a unique lithology) with a valley composed of quaternary deposits.

As suggested by our findings, low flows reflect the hydrogeological properties of specific geological units. Instead of measuring these characteristics, hydrogeological properties can potentially be inferred from discharge measurements. To better characterise the contribution of certain lithologies, the stream monitoring of geologically uniform catchments lacking alluvial deposits can be of great use. The influence of various topographical settings on catchment dynamics could for instance be assessed based on the comparison of discharge time series measured in a selection of small catchments.

5.2 Implications for further research

These findings highlight the need to incorporate hydrogeological conditions more in detail in hydrological science and especially for the assessment of low flows. They consequently call for a revision of the classification and the characterisation framework of catchments based on their physical properties, widely used in the domain. The consideration of geology in this field is often not explicit or non-existent. For a better characterisation of catchments, geology should be assessed by distinguishing the different lithologies and identifying their hydrogeological productivity. In this procedure, both the local alluvial aquifers and the larger scale geological environment need to be investigated.

The results of the synthetic models also point out directions on how to consider topography in the framework of catchment classification. They highlight the crucial role of the hillslope in governing groundwater dynamics in the bedrock, as well as the dependency on the valley slope of the alluvial contribution to low flows. The topographical feature relevant for catchment dynamics thus corresponds to the slope of the most productive hydrogeological unit. This suggests that the potential of using average slope indices in the context of catchment classification for low-flow assessment might be limited.

These considerations are also valid for hydrological modelling, especially if intended for simulating low flows or improving process understanding of catchment controls on streamflow dynamics. As discussed previously, groundwater processes can greatly impact catchment dynamics, can be highly different from one geological unit to the other, and feedback mechanisms can occur between the distinct aquifers. Moreover, topographical and hydrogeological characteristics influence catchment dynamics in a complex, combined way. Lumped conceptual models, which are widely used in hydrology, rarely allow considering these mechanisms because of their limited conceptualisation of the subsurface and the catchment geometry. These models often assume a shallow rapid aquifer that feeds a deeper slow aquifer, which then contributes to the stream. This scheme does not permit, for instance, the shallower aquifer (e.g. alluvial aquifer) to be recharged by the surrounding bedrock aquifer. This mechanism, revealed by the synthetic approach, can however be of high significance for catchment dynamics. Moreover, the commonly used hydrolo-

gical models do not allow infiltration from the stream to the groundwater compartment. As shown in Chapter 3, the presence of highly permeable alluvial deposits under the river can affect the water balance of the catchment, as well as streamflows. Especially for low-flow simulation, these processes should be accounted for in hydrological models. Our results consequently suggest that the classical hydrological models are inappropriate for low-flow modelling and for the purpose of understanding storage processes in a catchment.

From this PhD thesis, new research perspectives can be drawn for the fields of catchment controls on streamflow dynamics, low-flow hydrology and hydrogeology.

- The relationship between geology and catchment dynamics should be further explored. The approach proposed in Chapter 3 could be applied to a wider spectrum of catchments (different meteorological conditions or geological environment). More sophisticated statistical methods relating geological properties and streamflow might provide additional insights on their correlations.
- In order to better identify which lithological units are relevant for streamflow/ low-flow generation, and to better quantify their contributions, field data such as isotope and hydrochemical samplings of the river and of groundwater springs might be useful. The integration of groundwater head data could also be beneficial. These processes might be further explored using detailed hydrogeological models of existing catchments. The difference in dynamics of storage and releasing processes, which characterise geological units of distinct hydrogeological properties, should especially be assessed.
- Both the fields of hydrology and hydrogeology would benefit from a better characterisation of the exchange mechanisms between aquifers of distinct hydrogeological behaviour, such as the alluvial and the bedrock aquifer. These processes could be explored using for instance detailed numerical models or field data (groundwater heads, isotope and hydrochemical sampling).
- The topographical controls on groundwater dynamics and thus their impact on low flows, identified with the synthetic models but hard to distinguish with observed data, should be better characterised. Advanced spatial data analysis might be employed to obtain more accurate topographical descriptors, describing for instance the topographical setting of each relevant hydrogeological unit.
- The clear relationship between the BPI and low flows suggest that analytical solutions to the flow problem in such synthetic settings might be conceivable. A similar approach to Chapter 2, based for instance on synthetic models of simpler geometry (e.g. a hillslope model), could be developed to relate the catchment outflow to precipitation and physical characteristics based on the laws of fluid dynamics.

Bibliography

- C. Andermann, L. Longuevergne, S. Bonnet, A. Crave, P. Davy, and R. Gloaguen. Impact of transient groundwater storage on the discharge of Himalayan rivers. *Nature Geoscience*, 5(2):127–132, 2012. ISSN 17520894. doi: 10.1038/ngeo1356.
- Aquanty. HydroGeoSphere Reference Manual. 2015.
- Arbeitsgemeinschaft Grundwasserforschung Luthern- und Wiggertal. Grundwasserforschung im Luthern- und Wiggertal, Schlussbericht der Untersuchungsperiode 1977 bis 1983. Technical report, Amt für Gewässerschutz, Kanton Luzern, Luzern, 1978.
- Arbeitsgruppe Low flow. Niedrigwasser und Grundwasser: Synthesebericht. Technical report, Im Auftrag vom BAFU: Jan Seibert and Maria Staudinger (Uni. Zurich), Kerstin Stahl, Markus Weiler and Michael Stoelzle (Uni. Freiburg), Philip Brunner, Daniel Hunkeler, Stefanie Wirth, Fabien Cochand and Claire Carlier (Uni. Neuchâtel), 2018.
- W. Balderer. Hydrogeologie der Schweiz, Vorlesungsskript Ingenieurgeologie, Geologisches Institut ETH Zurich, 1997.
- A. Betterle, M. Schirmer, and G. Botter. Characterizing the spatial correlation of daily streamflows. *Water Resources Research*, 53(2):1646–1663, 2017. ISSN 19447973. doi: 10.1002/2016WR019195.
- K. J. Beven and M. J. Kirkby. A physically based, variable contributing area model of basin hydrology. *Hydrological Sciences Bulletin*, 24(1):43–69, mar 1979. ISSN 0303-6936. doi: 10.1080/02626667909491834.
- C. Birkel, C. Soulsby, and D. Tetzlaff. Developing a consistent process-based conceptualization of catchment functioning using measurements of internal state variables. *Water Resources Research*, 50(4):3481–3501, 2014. ISSN 19447973. doi: 10.1002/2013WR014925.
- J. P. Bloomfield, D. J. Allen, and K. J. Griffiths. Examining geological controls on baseflow index (BFI) using regression analysis: An illustration from the Thames Basin, UK. *Journal of Hydrology*, 373(1-2):164–176, 2009. ISSN 00221694. doi: 10.1016/j.jhydrol.2009.04.025.

BIBLIOGRAPHY

- G. Blöschl, M. Sivapalan, T. Wagener, A. Savenije, and H. Viglione, editors. *Runoff prediction in ungauged basins: Synthesis across processes, places and scales*. Cambridge University Press, 2013. ISBN 9781139235761.
- G. Botter, F. Peratoner, A. Porporato, I. Rodriguez-Iturbe, and A. Rinaldo. Signatures of large-scale soil moisture dynamics on streamflow statistics across U.S. climate regimes. *Water Resources Research*, 43(11):1–10, 2007a. ISSN 00431397. doi: 10.1029/2007WR006162.
- G. Botter, A. Porporato, I. Rodriguez-Iturbe, and A. Rinaldo. Basin-scale soil moisture dynamics and the probabilistic characterization of carrier hydrologic flows: Slow, leaching-prone components of the hydrologic response. *Water Resources Research*, 43(2):1–14, 2007b. ISSN 00431397. doi: 10.1029/2006WR005043.
- S. Broda, M. Larocque, C. Paniconi, and H. Haitjema. A low-dimensional hillslope-based catchment model for layered groundwater flow. *Hydrological Processes*, 26(18):2814–2826, 2012. ISSN 08856087. doi: 10.1002/hyp.8319.
- P. Brunner and C. T. Simmons. HydroGeoSphere: A Fully Integrated, Physically Based Hydrological Model. *Ground Water*, 50(2):170–176, mar 2012. ISSN 0017467X. doi: 10.1111/j.1745-6584.2011.00882.x.
- J. M. Buttle. Dynamic storage : a potential metric of inter-basin differences in storage properties. 4653(July):4644–4653, 2016. doi: 10.1002/hyp.10931.
- A. Castellarin, R. M. Vogel, and A. Brath. A stochastic index flow model of flow duration curves. *Water Resources Research*, 40(3):1–10, 2004. ISSN 00431397. doi: 10.1029/2003WR002524.
- A. Castellarin, G. Camorani, and A. Brath. Predicting annual and long-term flow-duration curves in ungauged basins. *Advances in Water Resources*, 30(4):937–953, apr 2007. ISSN 03091708. doi: 10.1016/j.advwatres.2006.08.006.
- CH2011. Swiss Climate Change Scenarios CH2011. Technical report, 2011. URL www.ch2011.ch.
- L. Cheng, M. Yaeger, A. Viglione, E. Coopersmith, S. Ye, and M. Sivapalan. Exploring the physical controls of regional patterns of flow duration curves – Part 1: Insights from statistical analyses. *Hydrology and Earth System Sciences*, 16(11):4435–4446, 2012. ISSN 10275606. doi: 10.5194/hess-16-4435-2012.
- E. Coopersmith, M. A. Yaeger, S. Ye, L. Cheng, and M. Sivapalan. Exploring the physical controls of regional patterns of flow duration curves – Part 3: A catchment classification system based on regime curve indicators. *Hydrology and Earth System Sciences*, 16(11):4467–4482, nov 2012. ISSN 1607-7938. doi: 10.5194/hess-16-4467-2012.

- A. Dassargues, J.-C. Marechal, G. Carabin, and O. Sels. On the necessity to use three-dimensional groundwater models for describing impact of drought conditions on streamflow regimes. *IAHS publication*, 225(255):165–170, 1999. ISSN 01447815.
- A. M. De Felice, W. Dragoni, and G. Giglio. Comparison of basin hydrological characteristics using only one lumped parameter: preliminary note, in: *Methods of hydrological basin comparison*, edited by: Robinson, M. Technical report, Insitute of Hydrology, Wallingford, 1993.
- G. W. Diepolder, R. Pamer, and G. team. Transnational 3D modeling, geopotential evaluation and active fault assessment in the Alpine Foreland Basins – the project GeoMol. *Rendiconti Online Societa Geologica Italiana*, 25:64–67, 2013. ISSN 20358008. doi: 10.3301/ROL.2013.05.
- B. Doulatyari, A. Betterle, S. Basso, B. Biswal, M. Schirmer, and G. Botter. Predicting streamflow distributions and flow duration curves from landscape and climate. *Advances in Water Resources*, 83:285–298, 2015. ISSN 03091708. doi: 10.1016/j.advwatres.2015.06.013.
- A. M. Fischer, D. E. Keller, M. A. Liniger, J. Rajczak, C. Schär, and C. Appenzeller. Projected changes in precipitation intensity and frequency in Switzerland: A multi-model perspective. *International Journal of Climatology*, 35(11):3204–3219, 2015. ISSN 10970088. doi: 10.1002/joc.4162.
- FOEN. *Annuaire hydrologique de la Suisse*, 2011. Technical report, Federal Office for the Environment, Berne, 2011.
- FOEN. *Impacts des changements climatiques sur les eaux et les ressources en eau*. Technical report, Federal Office for the Environment, Berne, 2012.
- FOEN. *Hitze und Trockenheit im Sommer 2015 Auswirkungen auf Mensch und Umwelt*. Technical report, Federal Office for the Environment, Berne, 2016.
- R. Freeze and J. A. Cherry. *Groundwater*. Prentice-Hall, Englewood Cliffs, NJ, page 604 pp., 1979.
- C. Frei. Interpolation of temperature in a mountainous region using nonlinear profiles and non-Euclidean distances. *International Journal of Climatology*, 34(5):1585–1605, 2014. ISSN 08998418. doi: 10.1002/joc.3786.
- P. Gander. *Geologie und Hydrogeologie der Oberen Süsswassermolasse, Dokumentation des aktuellen Kenntnisstandes*. Arbeitsbericht NAB 04-04. Technical report, Nagra, Wettingen, 2004.

BIBLIOGRAPHY

- D. Ganora, P. Claps, F. Laio, and A. Viglione. An approach to estimate nonparametric flow duration curves in ungauged basins. *Water Resources Research*, 45(10):1–10, 2009. ISSN 00431397. doi: 10.1029/2008WR007472.
- T. Gleeson and A. H. Manning. Regional groundwater flow in mountainous terrain: Three-dimensional simulations of topographic and hydrogeologic controls. *Water Resources Research*, 44(10):1–16, oct 2008. ISSN 00431397. doi: 10.1029/2008WR006848.
- H. M. Haitjema and S. Mitchell-Bruker. Are water tables a subdued replica of the topography? *Ground Water*, 43(6):781–786, 2005. ISSN 0017467X. doi: 10.1111/j.1745-6584.2005.00090.x.
- V. C. Hale, J. J. McDonnell, M. K. Stewart, D. K. Solomon, J. Doolittle, G. G. Ice, and R. T. Pack. Effect of bedrock permeability on stream base flow mean transit time scaling relationships: 2. Process study of storage and release. *Water Resources Research*, 52(2): 1375–1397, feb 2016. ISSN 00431397. doi: 10.1002/2015WR017660.
- Y. He, A. Bárdossy, and E. Zehe. A review of regionalisation for continuous streamflow simulation. *Hydrology and Earth System Sciences*, 15(11):3539–3553, 2011. ISSN 10275606. doi: 10.5194/hess-15-3539-2011.
- M. G. R. Holmes, A. R. Young, A. Gustard, and R. Grew. A region of influence approach to predicting flow duration curves within ungauged catchments. *Hydrology and Earth System Sciences*, 6(4):721–731, 2002. ISSN 16077938. doi: 10.5194/hess-6-721-2002.
- M. Hrachowitz, H. H. Savenije, G. Blöschl, J. J. McDonnell, M. Sivapalan, J. W. Pomeroy, B. Arheimer, T. Blume, M. P. Clark, U. Ehret, F. Fenicia, J. E. Freer, A. Gelfan, H. V. Gupta, D. A. Hughes, R. W. Hut, A. Montanari, S. Pande, D. Tetzlaff, P. A. Troch, S. Uhlenbrook, T. Wagener, H. C. Winsemius, R. A. Woods, E. Zehe, and C. Cudennec. A decade of Predictions in Ungauged Basins (PUB)-a review. *Hydrological Sciences Journal*, 58(6):1198–1255, 2013. ISSN 02626667. doi: 10.1080/02626667.2013.803183.
- Institute of Hydrology. Low Flow Studies (1–4). Technical report, Wallingford, UK, 1980.
- IPCC. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Technical report, IPCC, Geneva, 2014.
- A. Jefferson, A. Nolin, S. Lewis, and C. Tague. Hydrogeologic controls on streamflow sensitivity to climate variation. *Hydrological Processes*, 22(22):4371–4385, oct 2008. ISSN 08856087. doi: 10.1002/hyp.7041.
- K. G. Jencso and B. L. McGlynn. Hierarchical controls on runoff generation: Topographically driven hydrologic connectivity, geology, and vegetation. *Water Resources Research*, 47(11):1–16, 2011. ISSN 00431397. doi: 10.1029/2011WR010666.

- D. Käser and D. Hunkeler. Contribution of alluvial groundwater to the outflow of mountainous catchments. *Water Resources Research*, 52(2):680–697, 2016. ISSN 19447973. doi: 10.1002/2014WR016730.
- B. Keller. Hydrogeologie des schweizerischen Molasse-Beckens: Aktueller Wissensstand und weiterführende Betrachtungen. *Eclogae geol. Helv.*, 85:611–651, 1992.
- J. W. Kirchner. Catchments as simple dynamical systems: Catchment characterization, rainfall-runoff modeling, and doing hydrology backward. *Water Resources Research*, 45(2):1–34, feb 2009. ISSN 00431397. doi: 10.1029/2008WR006912.
- C. N. Kroll and P. Song. Impact of multicollinearity on small sample hydrologic regression models. *Water Resources Research*, 49(6):3756–3769, 2013. ISSN 00431397. doi: 10.1002/wrcr.20315.
- C. Kroll, J. Luz, B. Allen, and R. M. Vogel. Developing a Watershed Characteristics Database to Improve Low Streamflow Prediction. *Journal of Hydrologic Engineering*, 9(2):116–125, 2004. ISSN 1084-0699. doi: 10.1061/(ASCE)1084-0699(2004)9:2(116).
- G. Laaha and G. Blöschl. Low flow estimates from short stream flow records - A comparison of methods. *Journal of Hydrology*, 306(1-4):264–286, 2005. ISSN 00221694. doi: 10.1016/j.jhydrol.2004.09.012.
- Leitungsgruppe NFP 61. Gesamtsynthese des Nationalen Forschungsprogramms NFP 61, Nachhaltige Wassernutzung in der Schweiz. Technical report, FNS, Berne, 2015.
- A. H. Matonse and C. N. Kroll. Applying hillslope-storage models to improve low flow estimates with limited streamflow data at a watershed scale. *Journal of Hydrology*, 494:20–31, 2013. ISSN 00221694. doi: 10.1016/j.jhydrol.2013.04.032.
- T. D. Mayer and S. W. Naman. Streamflow response to climate as influenced by geology and elevation. *Journal of the American Water Resources Association*, 47(4):724–738, 2011. ISSN 1093474X. doi: 10.1111/j.1752-1688.2011.00537.x.
- J. P. Mcnamara, D. Tetzlaff, K. Bishop, C. Soulsby, M. Seyfried, N. E. Peters, B. T. Aulenbach, and R. Hooper. Storage as a Metric of Catchment Comparison. *Hydrological Processes*, 25(21):3364–3371, 2011. ISSN 08856087. doi: 10.1002/hyp.8113.
- M. F. Müller, D. N. Dralle, and S. E. Thompson. Analytical model for flow duration curves in seasonally dry climates. *Water Resources Research*, 50(7):5510–5531, 2014. ISSN 19447973. doi: 10.1002/2014WR015301.
- F. Naef, M. Margreth, and M. Florianic. Festlegung von Restwassermengen: Q347, eine entscheidende, aber schwer zu fassende Größe. *Wasser Energie Luft*, Heft 4(107. Jahrgang):277–284, 2015.

BIBLIOGRAPHY

- F. Nippgen, B. L. McGlynn, L. A. Marshall, and R. E. Emanuel. Landscape structure and climate influences on hydrologic response. *Water Resources Research*, 47(12):1–17, 2011. ISSN 00431397. doi: 10.1029/2011WR011161.
- L. Oudin, V. Andréassian, C. Perrin, C. Michel, and N. Le Moine. Spatial proximity, physical similarity, regression and ungaged catchments: A comparison of regionalization approaches based on 913 French catchments. *Water Resources Research*, 44(3):1–15, 2008. ISSN 00431397. doi: 10.1029/2007WR006240.
- D. Partington, P. Brunner, C. T. Simmons, A. D. Werner, R. Therrien, H. R. Maier, and G. C. Dandy. Evaluation of outputs from automated baseflow separation methods against simulated baseflow from a physically based, surface water-groundwater flow model. *Journal of Hydrology*, 458-459:28–39, aug 2012. ISSN 00221694. doi: 10.1016/j.jhydrol.2012.06.029.
- E. Peters, P. J. Torfs, H. A. van Lanen, and G. Bier. Propagation of drought through groundwater - A new approach using linear reservoir theory. *Hydrological Processes*, 17(15): 3023–3040, 2003. ISSN 08856087. doi: 10.1002/hyp.1274.
- E. Peters, H. A. Van Lanen, P. J. Torfs, and G. Bier. Drought in groundwater - Drought distribution and performance indicators. *Journal of Hydrology*, 306(1-4):302–317, 2005. ISSN 00221694. doi: 10.1016/j.jhydrol.2004.09.014.
- O. A. Pfiffner. Evolution of the north Alpine foreland basin in the Central Alps. *Spec. Publs int. Ass. Sediment.*, 8(August):219–228, 1986. doi: 10.1002/9781444303810.ch11.
- L. Pfister, N. Martínez-Carreras, C. Hissler, J. Klaus, G. E. Carrer, M. K. Stewart, and J. J. McDonnell. Bedrock geology controls on catchment storage, mixing, and release: A comparative analysis of 16 nested catchments. *Hydrological Processes*, 31(10):1828–1845, 2017. ISSN 10991085. doi: 10.1002/hyp.11134.
- K. Price. Effects of watershed topography, soils, land use, and climate on baseflow hydrology in humid regions: A review. *Progress in Physical Geography*, 35(4):465–492, 2011. ISSN 0309-1333. doi: 10.1177/0309133311402714.
- A. Pugliese, A. Castellarin, and A. Brath. Geostatistical prediction of flow-duration curves in an index-flow framework. *Hydrology and Earth System Sciences*, 18(9):3801–3816, 2014. ISSN 16077938. doi: 10.5194/hess-18-3801-2014.
- QGIS Development Team. QGIS Geographic Information System. Open Source Geospatial Foundation Project., 2014. URL <http://www.qgis.org/>.
- R Core Team. R: A Language and Environment for Statistical Computing, 2017. URL <https://www.r-project.org/>.

- T. Razavi and P. Coulibaly. Streamflow Prediction in Ungauged Basins: Review of Regionalization Methods. *Journal of Hydrologic Engineering*, 18(8):958–975, 2013. ISSN 1084-0699. doi: 10.1061/(ASCE)HE.1943-5584.0000690.
- M. Rebetez, H. Mayer, O. Dupont, D. Schindler, J. P. Kropp, A. Menzel, M. Rebetez, H. Mayer, O. Dupont, D. Schindler, and K. Gartner. Heat and drought 2003 in Europe : a climate synthesis To cite this version : HAL Id : hal-00884013 Heat and drought 2003 in Europe : a climate synthesis. 2006.
- E. Sauquet and C. Catalogne. Comparison of catchment grouping methods for flow duration curve estimation at ungauged sites in France. *Hydrology and Earth System Sciences*, 15(8):2421–2435, 2011. ISSN 10275606. doi: 10.5194/hess-15-2421-2011.
- J. Seibert and M. J. Vis. Teaching hydrological modeling with a user-friendly catchment-runoff-model software package. *Hydrology and Earth System Sciences*, 16(9):3315–3325, 2012. ISSN 10275606. doi: 10.5194/hess-16-3315-2012.
- V. U. Smakhtnin. Low flow hydrology: A review. *Journal of Hydrology*, 240:147–186, 2001.
- C. Spence. On the relation between dynamic storage and runoff: A discussion on thresholds, efficiency, and function. *Water Resources Research*, 43(12):1–11, 2007. ISSN 00431397. doi: 10.1029/2006WR005645.
- M. Staudinger, K. Stahl, J. Seibert, M. P. Clark, and L. M. Tallaksen. Comparison of hydrological model structures based on recession and low flow simulations. *Hydrology and Earth System Sciences*, 15(11):3447–3459, nov 2011. ISSN 1607-7938. doi: 10.5194/hess-15-3447-2011.
- M. Staudinger, M. Stoelzle, S. Seeger, J. Seibert, M. Weiler, and K. Stahl. Catchment water storage variation with elevation. *Hydrological Processes*, 31(11):2000–2015, 2017. ISSN 10991085. doi: 10.1002/hyp.11158.
- M. Stoelzle, M. Weiler, K. Stahl, A. Morhard, and T. Schuetz. Is there a superior conceptual groundwater model structure for baseflow simulation? *Hydrological Processes*, 29(6):1301–1313, 2015. ISSN 10991085. doi: 10.1002/hyp.10251.
- C. Tague and G. E. Grant. A geological framework for interpreting the low-flow regimes of Cascade streams, Willamette River Basin, Oregon. *Water Resources Research*, 40(4):1–9, 2004. ISSN 00431397. doi: 10.1029/2003WR002629.
- Tecplot Inc. Tecplot User ’s Manual, 2013.
- P. A. Troch, A. Berne, P. Bogaart, C. Harman, A. G. J. Hilberts, S. W. Lyon, C. Paniconi, V. R. N. Pauwels, D. E. Rupp, J. S. Selker, A. J. Teuling, R. Uijlenhoet, and N. E. C.

BIBLIOGRAPHY

- Verhoest. The importance of hydraulic groundwater theory in catchment hydrology: The legacy of Wilfried Brutsaert and Jean-Yves Parlange. *Water Resources Research*, 49(9): 5099–5116, 2013. ISSN 00431397. doi: 10.1002/wrcr.20407.
- T. Uchida, S. Miyata, and Y. Asano. Effects of the lateral and vertical expansion of the water flowpath in bedrock on temporal changes in hillslope discharge. *Geophysical Research Letters*, 35(15):2–6, 2008. ISSN 00948276. doi: 10.1029/2008GL034566.
- A. F. Van Loon and G. Laaha. Hydrological drought severity explained by climate and catchment characteristics. *Journal of Hydrology*, 526:3–14, 2015. ISSN 00221694. doi: 10.1016/j.jhydrol.2014.10.059.
- A. F. Van Loon. Hydrological drought explained. *Wiley Interdisciplinary Reviews: Water*, 2(4):359–392, 2015. ISSN 20491948. doi: 10.1002/wat2.1085.
- T. Vansteenkiste, M. Tavakoli, V. Ntegeka, F. De Smedt, O. Batelaan, F. Pereira, and P. Willems. Intercomparison of hydrological model structures and calibration approaches in climate scenario impact projections. *Journal of Hydrology*, 519(PA):743–755, 2014. ISSN 00221694. doi: 10.1016/j.jhydrol.2014.07.062.
- H. Waber, M. Heidinger, , G. Lorenz, and D. Traber. Hydrochemie und Isotopenhydrogeologie von Tiefengrundwässern in der Nordschweiz und im angrenzenden Süddeutschland. Arbeitsbericht NAB 13-63. Technical report, Nagra, Wettingen, 2014.
- R. C. Ward and M. Robinson. *Principles of Hydrology*. Maidenhead : McGraw-Hill. McGraw Hill , Maidenhead, 1990. ISBN 0077072049.
- R. Weingartner and H. Anschwanden. Abflussregimes als grundlage zur abschätzung von mittelwerten des abflusses. In *Hydrologischer atlas der Schweiz*. (Hydrologischer Atlas der Schweiz - Tafel 5.2)), 1992.
- L. A. Welch and D. M. Allen. Consistency of groundwater flow patterns in mountainous topography: Implications for valley bottom water replenishment and for defining groundwater flow boundaries. *Water Resources Research*, 48(5):1–17, 2012. ISSN 00431397. doi: 10.1029/2011WR010901.
- L. A. Welch and D. M. Allen. Hydraulic conductivity characteristics in mountains and implications for conceptualizing bedrock groundwater flow. *Hydrogeology Journal*, 22(5):1003–1026, 2014. ISSN 1431-2174. doi: 10.1007/s10040-014-1121-5.
- L. A. Welch, D. M. M. Allen, and H. (Ilja) van Meerveld. Topographic Controls on Deep Groundwater Contributions to Mountain Headwater Streams and Sensitivity to Available Recharge. *Canadian Water Resources Journal*, 37(4):349–371, 2012. ISSN 0701-1784. doi: 10.4296/cwtj2011-907.

- M. Yaeger, E. Coopersmith, S. Ye, L. Cheng, A. Viglione, and M. Sivapalan. Exploring the physical controls of regional patterns of flow duration curves – Part 4: A synthesis of empirical analysis, process modeling and catchment classification. *Hydrology and Earth System Sciences*, 16(11):4483–4498, 2012. ISSN 10275606. doi: 10.5194/hess-16-4483-2012.
- S. Ye, M. Yaeger, E. Coopersmith, L. Cheng, and M. Sivapalan. Exploring the physical controls of regional patterns of flow duration curves Part 2: Role of seasonality, the regime curve, and associated process controls. *Hydrology and Earth System Sciences*, 16(11):4447–4465, 2012. ISSN 10275606. doi: 10.5194/hess-16-4447-2012.

Appendix A

Parameters and main outputs of the synthetic models (Chapter 2)

APPENDIX A. SYNTHETIC MODELS

Table A.1: Parameters and main outputs of synthetic models (group 1), part 1

Models	K_{bedrock} [m/s]	K_{alluvial} [m/s]	RS [-]	HS [-]	p_{bedrock} [-]	Prec.	aspect-ratio [mxm]	Q95 [mm/d]	Q50 [mm/d]	Q95/Q50 [-]	Dyn. V [mm]
sim_pap1tr	1.E-08	1.E-08	0.005	0.05	0.1	HUT	2000x6000	0.03	0.59	0.06	4.10
sim_pap5tr	1.E-08	1.E-08	0.03	0.05	0.1	HUT	2000x6000	0.03	0.59	0.06	3.93
sim_pap9tr	1.E-08	1.E-08	0.09	0.05	0.1	HUT	2000x6000	0.03	0.56	0.06	3.61
sim_pap13tr	1.E-08	1.E-08	0.15	0.05	0.1	HUT	2000x6000	0.03	0.54	0.07	3.50
sim_pap2tr	1.E-08	1.E-08	0.005	0.18	0.1	HUT	2000x6000	0.04	0.57	0.08	4.05
sim_pap6tr	1.E-08	1.E-08	0.03	0.18	0.1	HUT	2000x6000	0.04	0.58	0.08	3.93
sim_pap10tr	1.E-08	1.E-08	0.09	0.18	0.1	HUT	2000x6000	0.04	0.55	0.08	3.56
sim_pap14tr	1.E-08	1.E-08	0.15	0.18	0.1	HUT	2000x6000	0.04	0.51	0.09	3.37
sim_pap3tr	1.E-08	1.E-08	0.005	0.35	0.1	HUT	2000x6000	0.07	0.58	0.14	4.58
sim_pap7tr	1.E-08	1.E-08	0.03	0.35	0.1	HUT	2000x6000	0.07	0.59	0.13	4.50
sim_pap11tr	1.E-08	1.E-08	0.09	0.35	0.1	HUT	2000x6000	0.07	0.55	0.14	4.18
sim_pap15tr	1.E-08	1.E-08	0.15	0.35	0.1	HUT	2000x6000	0.07	0.54	0.15	3.99
sim_pap4tr	1.E-08	1.E-08	0.005	0.5	0.1	HUT	2000x6000	0.11	0.61	0.20	5.66
sim_pap8tr	1.E-08	1.E-08	0.03	0.5	0.1	HUT	2000x6000	0.11	0.60	0.20	5.67
sim_pap12tr	1.E-08	1.E-08	0.09	0.5	0.1	HUT	2000x6000	0.11	0.59	0.21	5.35
sim_pap16tr	1.E-08	1.E-08	0.15	0.5	0.1	HUT	2000x6000	0.11	0.57	0.22	5.39
sim_dim33tr	1.E-07	1.E-07	0.005	0.05	0.1	HUT	2000x6000	0.05	0.61	0.10	4.49
sim_dim1tr	1.E-07	1.E-07	0.03	0.05	0.1	HUT	2000x6000	0.05	0.59	0.10	4.42
sim_pap65tr	1.E-07	1.E-07	0.09	0.05	0.1	HUT	2000x6000	0.06	0.57	0.12	4.25
sim_dim17tr	1.E-07	1.E-07	0.15	0.05	0.1	HUT	2000x6000	0.07	0.55	0.14	4.39
sim_dim34tr	1.E-07	1.E-07	0.005	0.18	0.1	HUT	2000x6000	0.22	0.71	0.33	17.82
sim_dim2tr	1.E-07	1.E-07	0.03	0.18	0.1	HUT	2000x6000	0.22	0.71	0.33	16.69
sim_pap66tr	1.E-07	1.E-07	0.09	0.18	0.1	HUT	2000x6000	0.22	0.69	0.36	17.38
sim_dim18tr	1.E-07	1.E-07	0.15	0.18	0.1	HUT	2000x6000	0.23	0.69	0.38	18.43
sim_dim35tr	1.E-07	1.E-07	0.005	0.35	0.1	HUT	2000x6000	0.54	0.94	0.60	63.74
sim_dim3tr	1.E-07	1.E-07	0.03	0.35	0.1	HUT	2000x6000	0.54	0.93	0.60	61.81
sim_pap67tr	1.E-07	1.E-07	0.09	0.35	0.1	HUT	2000x6000	0.55	0.90	0.63	60.03
sim_dim19tr	1.E-07	1.E-07	0.15	0.35	0.1	HUT	2000x6000	0.56	0.90	0.64	62.97
sim_dim36tr	1.E-07	1.E-07	0.005	0.5	0.1	HUT	2000x6000	0.79	1.10	0.73	117.71
sim_dim4tr	1.E-07	1.E-07	0.03	0.5	0.1	HUT	2000x6000	0.80	1.09	0.75	105.86
sim_pap68tr	1.E-07	1.E-07	0.09	0.5	0.1	HUT	2000x6000	0.80	1.08	0.76	103.76
sim_dim20tr	1.E-07	1.E-07	0.15	0.5	0.1	HUT	2000x6000	0.81	1.07	0.77	105.78
sim_dim37tr	1.E-06	1.E-06	0.005	0.05	0.1	HUT	2000x6000	0.28	0.77	0.39	23.61
sim_dim5tr	1.E-06	1.E-06	0.03	0.05	0.1	HUT	2000x6000	0.30	0.75	0.43	24.06
sim_pap69tr	1.E-06	1.E-06	0.09	0.05	0.1	HUT	2000x6000	0.35	0.77	0.49	28.49
sim_dim21tr	1.E-06	1.E-06	0.15	0.05	0.1	HUT	2000x6000	0.40	0.80	0.52	34.54
sim_dim38tr	1.E-06	1.E-06	0.005	0.18	0.1	HUT	2000x6000	1.10	1.33	0.83	150.03
sim_dim6tr	1.E-06	1.E-06	0.03	0.18	0.1	HUT	2000x6000	1.11	1.31	0.85	138.48
sim_pap70tr	1.E-06	1.E-06	0.09	0.18	0.1	HUT	2000x6000	1.13	1.30	0.87	137.96
sim_dim22tr	1.E-06	1.E-06	0.15	0.18	0.1	HUT	2000x6000	1.15	1.31	0.88	141.83
sim_dim39tr	1.E-06	1.E-06	0.005	0.35	0.1	HUT	2000x6000	1.43	1.55	0.93	197.43
sim_dim7tr	1.E-06	1.E-06	0.03	0.35	0.1	HUT	2000x6000	1.44	1.54	0.93	203.46
sim_pap71tr	1.E-06	1.E-06	0.09	0.35	0.1	HUT	2000x6000	1.43	1.53	0.94	195.96
sim_dim23tr	1.E-06	1.E-06	0.15	0.35	0.1	HUT	2000x6000	1.44	1.53	0.94	190.69
sim_dim40tr	1.E-06	1.E-06	0.005	0.5	0.1	HUT	2000x6000	1.53	1.57	0.97	212.51
sim_dim8tr	1.E-06	1.E-06	0.03	0.5	0.1	HUT	2000x6000	1.52	1.57	0.97	202.60
sim_pap72tr	1.E-06	1.E-06	0.09	0.5	0.1	HUT	2000x6000	1.51	1.57	0.96	197.38
sim_dim24tr	1.E-06	1.E-06	0.15	0.5	0.1	HUT	2000x6000	1.51	1.57	0.96	192.28
sim_dim41tr	1.E-05	1.E-05	0.005	0.05	0.1	HUT	2000x6000	1.37	1.55	0.88	163.90
sim_dim9tr	1.E-05	1.E-05	0.03	0.05	0.1	HUT	2000x6000	1.34	1.54	0.87	172.61
sim_pap73tr	1.E-05	1.E-05	0.09	0.05	0.1	HUT	2000x6000	1.40	1.56	0.90	182.46
sim_dim25tr	1.E-05	1.E-05	0.15	0.05	0.1	HUT	2000x6000	1.47	1.60	0.92	200.60

APPENDIX A. SYNTHETIC MODELS

Table A.2: Parameters and main outputs of synthetic models (group 1), part 2

Models	K_{edrock} [m/s]	$K_{lluvial}$ [m/s]	RS [-]	HS [-]	$p_{bedro\ k}$ [-]	Prec.	aspect-ratio [m/m]	Q95 [mm/d]	Q50 [mm/d]	Q95/Q50 [-]	Dyn. V [mm]
sim_dim42tr	1.E-05	1.E-05	0.005	0.18	0.1	HUT	2000x6000	1.54	1.66	0.93	199.31
sim_dim10tr	1.E-05	1.E-05	0.03	0.18	0.1	HUT	2000x6000	1.51	1.63	0.93	207.18
sim_pap74tr	1.E-05	1.E-05	0.09	0.18	0.1	HUT	2000x6000	1.53	1.62	0.94	206.69
sim_dim26tr	1.E-05	1.E-05	0.15	0.18	0.1	HUT	2000x6000	1.55	1.63	0.95	217.42
sim_dim43tr	1.E-05	1.E-05	0.005	0.35	0.1	HUT	2000x6000	1.55	1.64	0.94	195.48
sim_dim11tr	1.E-05	1.E-05	0.03	0.35	0.1	HUT	2000x6000	1.54	1.63	0.94	212.72
sim_pap75tr	1.E-05	1.E-05	0.09	0.35	0.1	HUT	2000x6000	1.56	1.63	0.95	212.29
sim_dim27tr	1.E-05	1.E-05	0.15	0.35	0.1	HUT	2000x6000	1.58	1.64	0.97	220.54
sim_dim44tr	1.E-05	1.E-05	0.005	0.5	0.1	HUT	2000x6000	1.56	1.63	0.96	202.27
sim_dim12tr	1.E-05	1.E-05	0.03	0.5	0.1	HUT	2000x6000	1.55	1.62	0.95	213.89
sim_pap76tr	1.E-05	1.E-05	0.09	0.5	0.1	HUT	2000x6000	1.58	1.64	0.96	211.81
sim_dim28tr	1.E-05	1.E-05	0.15	0.5	0.1	HUT	2000x6000	1.60	1.64	0.97	219.58
sim_pap49tr	1.E-08	1.E-04	0.005	0.05	0.1	HUT	2000x6000	0.26	1.09	0.24	15.20
sim_pap53tr	1.E-08	1.E-04	0.03	0.05	0.1	HUT	2000x6000	0.25	1.10	0.24	15.86
sim_pap57tr	1.E-08	1.E-04	0.09	0.05	0.1	HUT	2000x6000	0.31	1.15	0.28	18.47
sim_pap61tr	1.E-08	1.E-04	0.15	0.05	0.1	HUT	2000x6000	0.35	1.15	0.32	24.15
sim_pap50tr	1.E-08	1.E-04	0.005	0.18	0.1	HUT	2000x6000	0.26	1.06	0.26	15.30
sim_pap54tr	1.E-08	1.E-04	0.03	0.18	0.1	HUT	2000x6000	0.25	1.05	0.25	15.70
sim_pap58tr	1.E-08	1.E-04	0.09	0.18	0.1	HUT	2000x6000	0.31	1.09	0.30	19.33
sim_pap62tr	1.E-08	1.E-04	0.15	0.18	0.1	HUT	2000x6000	0.36	1.11	0.34	23.10
sim_pap51tr	1.E-08	1.E-04	0.005	0.35	0.1	HUT	2000x6000	0.29	1.06	0.29	15.53
sim_pap55tr	1.E-08	1.E-04	0.03	0.35	0.1	HUT	2000x6000	0.28	1.07	0.28	16.14
sim_pap59tr	1.E-08	1.E-04	0.09	0.35	0.1	HUT	2000x6000	0.34	1.07	0.33	19.28
sim_pap63tr	1.E-08	1.E-04	0.15	0.35	0.1	HUT	2000x6000	0.39	1.11	0.36	23.56
sim_pap52tr	1.E-08	1.E-04	0.005	0.5	0.1	HUT	2000x6000	0.32	1.09	0.31	16.52
sim_pap56tr	1.E-08	1.E-04	0.03	0.5	0.1	HUT	2000x6000	0.32	1.09	0.31	17.00
sim_pap60tr	1.E-08	1.E-04	0.09	0.5	0.1	HUT	2000x6000	0.37	1.09	0.35	20.54
sim_pap64tr	1.E-08	1.E-04	0.15	0.5	0.1	HUT	2000x6000	0.42	1.12	0.39	24.61
sim_aq73tr	1.E-07	1.E-04	0.005	0.05	0.1	HUT	2000x6000	0.27	1.05	0.27	15.68
sim_aq49tr	1.E-07	1.E-04	0.03	0.05	0.1	HUT	2000x6000	0.27	1.10	0.26	16.40
sim_pap101tr	1.E-07	1.E-04	0.09	0.05	0.1	HUT	2000x6000	0.33	1.16	0.30	18.85
sim_aq61tr	1.E-07	1.E-04	0.15	0.05	0.1	HUT	2000x6000	0.38	1.17	0.34	23.76
sim_aq74tr	1.E-07	1.E-04	0.005	0.18	0.1	HUT	2000x6000	0.42	1.15	0.38	26.22
sim_aq50tr	1.E-07	1.E-04	0.03	0.18	0.1	HUT	2000x6000	0.43	1.12	0.40	26.61
sim_p p102tr	1.E-07	1.E-04	0.09	0.18	0.1	HUT	2000x6000	0.47	1.15	0.42	33.22
sim_aq62tr	1.E-07	1.E-04	0.15	0.18	0.1	HUT	2000x6000	0.52	1.18	0.46	39.12
sim_aq75tr	1.E-07	1.E-04	0.005	0.35	0.1	HUT	2000x6000	0.68	1.32	0.53	75.31
sim_aq51tr	1.E-07	1.E-04	0.03	0.35	0.1	HUT	2000x6000	0.68	1.35	0.51	68.93
sim_pap103tr	1.E-07	1.E-04	0.09	0.35	0.1	HUT	2000x6000	0.72	1.33	0.55	71.51
sim_aq63tr	1.E-07	1.E-04	0.15	0.35	0.1	HUT	2000x6000	0.76	1.36	0.58	75.47
sim_aq76tr	1.E-07	1.E-04	0.005	0.5	0.1	HUT	2000x6000	0.90	1.45	0.63	129.77
sim_q52tr	1.E-07	1.E-04	0.03	0.5	0.1	HUT	2000x6000	0.91	1.45	0.63	116.00
sim_pap104tr	1.E-07	1.E-04	0.09	0.5	0.1	HUT	2000x6000	0.94	1.43	0.66	108.74
sim_aq64tr	1.E-07	1.E-04	0.15	0.5	0.1	HUT	2000x6000	0.98	1.46	0.68	116.92
sim_aq77tr	1.E-06	1.E-04	0.005	0.05	0.1	HUT	2000x6000	0.46	1.15	0.42	32.52
sim_aq53tr	1.E-06	1.E-04	0.03	0.05	0.1	HUT	2000x6000	0.48	1.22	0.41	35.13
sim_pap105tr	1.E-06	1.E-04	0.09	0.05	0.1	HUT	2000x6000	0.56	1.27	0.45	40.22
sim_aq65tr	1.E-06	1.E-04	0.15	0.05	0.1	HUT	2000x6000	0.63	1.29	0.50	45.88
sim_aq78tr	1.E-06	1.E-04	0.005	0.18	0.1	HUT	2000x6000	1.17	1.55	0.76	148.56
sim_aq54tr	1.E-06	1.E-04	0.03	0.18	0.1	HUT	2000x6000	1.16	1.53	0.76	145.98
sim_pap106tr	1.E-06	1.E-04	0.09	0.18	0.1	HUT	2000x6000	1.20	1.54	0.78	145.55
sim_aq66tr	1.E-06	1.E-04	0.15	0.18	0.1	HUT	2000x6000	1.23	1.55	0.80	148.39

APPENDIX A. SYNTHETIC MODELS

Table A.3: Parameters and main outputs of synthetic models (group 1), part 3

Models	K_{edrock} [m/s]	$K_{lluvial}$ [m/s]	RS [-]	HS [-]	$p_{bedrock}$ [-]	Prec.	aspect-ratio [m \times m]	Q95 [mm/d]	Q50 [mm/d]	Q95/Q50 [-]	Dyn. V [mm]
sim_aq79tr	1.E-06	1.E-04	0.005	0.35	0.1	HUT	2000x6000	1.47	1.65	0.90	199.00
sim_aq55tr	1.E-06	1.E-04	0.03	0.35	0.1	HUT	2000x6000	1.48	1.64	0.90	189.23
sim_pap107tr	1.E-06	1.E-04	0.09	0.35	0.1	HUT	2000x6000	1.49	1.65	0.91	189.40
sim_aq67tr	1.E-06	1.E-04	0.15	0.35	0.1	HUT	2000x6000	1.51	1.66	0.91	195.81
sim_aq80tr	1.E-06	1.E-04	0.005	0.5	0.1	HUT	2000x6000	1.57	1.67	0.94	204.56
sim_aq56tr	1.E-06	1.E-04	0.03	0.5	0.1	HUT	2000x6000	1.58	1.68	0.94	218.54
sim_pap108tr	1.E-06	1.E-04	0.09	0.5	0.1	HUT	2000x6000	1.58	1.68	0.94	210.88
sim_aq68tr	1.E-06	1.E-04	0.15	0.5	0.1	HUT	2000x6000	1.59	1.68	0.95	206.34
sim_aq81tr	1.E-05	1.E-04	0.005	0.05	0.1	HUT	2000x6000	1.45	1.61	0.90	180.36
sim_aq57tr	1.E-05	1.E-04	0.03	0.05	0.1	HUT	2000x6000	1.45	1.63	0.89	174.93
sim_pap109tr	1.E-05	1.E-04	0.09	0.05	0.1	HUT	2000x6000	1.48	1.64	0.91	183.00
sim_aq69tr	1.E-05	1.E-04	0.15	0.05	0.1	HUT	2000x6000	1.53	1.64	0.93	204.63
sim_aq82tr	1.E-05	1.E-04	0.005	0.18	0.1	HUT	2000x6000	1.53	1.66	0.92	210.09
sim_aq58tr	1.E-05	1.E-04	0.03	0.18	0.1	HUT	2000x6000	1.54	1.66	0.93	218.90
sim_pap110tr	1.E-05	1.E-04	0.09	0.18	0.1	HUT	2000x6000	1.57	1.66	0.94	214.29
sim_aq70tr	1.E-05	1.E-04	0.15	0.18	0.1	HUT	2000x6000	1.59	1.66	0.96	221.21
sim_aq83tr	1.E-05	1.E-04	0.005	0.35	0.1	HUT	2000x6000	1.55	1.65	0.94	209.48
sim_aq59tr	1.E-05	1.E-04	0.03	0.35	0.1	HUT	2000x6000	1.57	1.66	0.94	221.87
sim_pap111tr	1.E-05	1.E-04	0.09	0.35	0.1	HUT	2000x6000	1.60	1.67	0.96	215.90
sim_aq71tr	1.E-05	1.E-04	0.15	0.35	0.1	HUT	2000x6000	1.62	1.67	0.97	218.89
sim_aq84tr	1.E-05	1.E-04	0.005	0.5	0.1	HUT	2000x6000	1.57	1.66	0.95	219.83
sim_aq60tr	1.E-05	1.E-04	0.03	0.5	0.1	HUT	2000x6000	1.58	1.66	0.95	217.25
sim_pap112tr	1.E-05	1.E-04	0.09	0.5	0.1	HUT	2000x6000	1.61	1.67	0.96	214.97
sim_aq72tr	1.E-05	1.E-04	0.15	0.5	0.1	HUT	2000x6000	1.63	1.68	0.98	218.32
sim_pap33tr	1.E-08	1.E-03	0.005	0.05	0.1	HUT	2000x6000	0.11	0.93	0.13	14.55
sim_pap37tr	1.E-08	1.E-03	0.03	0.05	0.1	HUT	2000x6000	0.39	0.98	0.43	33.07
sim_pap41tr	1.E-08	1.E-03	0.09	0.05	0.1	HUT	2000x6000	1.06	1.29	0.82	87.81
sim_pap45tr	1.E-08	1.E-03	0.15	0.05	0.1	HUT	2000x6000	0.95	1.50	0.65	101.56
sim_pap34tr	1.E-08	1.E-03	0.005	0.18	0.1	HUT	2000x6000	0.12	0.91	0.14	14.48
sim_pap38tr	1.E-08	1.E-03	0.03	0.18	0.1	HUT	2000x6000	0.40	0.99	0.43	32.99
sim_pap42tr	1.E-08	1.E-03	0.09	0.18	0.1	HUT	2000x6000	1.09	1.30	0.84	88.02
sim_pap46tr	1.E-08	1.E-03	0.15	0.18	0.1	HUT	2000x6000	1.14	1.57	0.74	120.56
sim_pap35tr	1.E-08	1.E-03	0.005	0.35	0.1	HUT	2000x6000	0.14	0.95	0.16	15.13
sim_pap39tr	1.E-08	1.E-03	0.03	0.35	0.1	HUT	2000x6000	0.42	1.01	0.44	33.51
sim_pap43tr	1.E-08	1.E-03	0.09	0.35	0.1	HUT	2000x6000	1.10	1.31	0.84	88.85
sim_pap47tr	1.E-08	1.E-03	0.15	0.35	0.1	HUT	2000x6000	1.16	1.56	0.76	122.06
sim_pap36tr	1.E-08	1.E-03	0.005	0.5	0.1	HUT	2000x6000	0.17	0.97	0.19	15.64
sim_pap40tr	1.E-08	1.E-03	0.03	0.5	0.1	HUT	2000x6000	0.45	1.01	0.47	34.84
sim_pap44tr	1.E-08	1.E-03	0.09	0.5	0.1	HUT	2000x6000	1.11	1.33	0.84	88.01
sim_pap48tr	1.E-08	1.E-03	0.15	0.5	0.1	HUT	2000x6000	1.19	1.57	0.77	123.91
sim_aq33tr	1.E-07	1.E-03	0.005	0.05	0.1	HUT	2000x6000	0.13	0.95	0.15	15.27
sim_aq1tr	1.E-07	1.E-03	0.03	0.05	0.1	HUT	2000x6000	0.41	0.94	0.45	35.19
sim_p_p89tr	1.E-07	1.E-03	0.09	0.05	0.1	HUT	2000x6000	1.03	1.27	0.81	96.93
sim_aq17tr	1.E-07	1.E-03	0.15	0.05	0.1	HUT	2000x6000	0.95	1.46	0.67	95.38
sim_aq34tr	1.E-07	1.E-03	0.005	0.18	0.1	HUT	2000x6000	0.27	1.02	0.28	25.92
sim_aq2tr	1.E-07	1.E-03	0.03	0.18	0.1	HUT	2000x6000	0.52	1.09	0.50	45.07
sim_pap90tr	1.E-07	1.E-03	0.09	0.18	0.1	HUT	2000x6000	1.13	1.37	0.83	99.34
sim_aq18tr	1.E-07	1.E-03	0.15	0.18	0.1	HUT	2000x6000	1.14	1.55	0.75	117.39
sim_aq35tr	1.E-07	1.E-03	0.005	0.35	0.1	HUT	2000x6000	0.57	1.22	0.49	67.36
sim_aq3tr	1.E-07	1.E-03	0.03	0.35	0.1	HUT	2000x6000	0.77	1.25	0.63	76.38
sim_p_p91tr	1.E-07	1.E-03	0.09	0.35	0.1	HUT	2000x6000	1.22	1.47	0.84	115.65
sim_aq19tr	1.E-07	1.E-03	0.15	0.35	0.1	HUT	2000x6000	1.33	1.64	0.82	141.71

APPENDIX A. SYNTHETIC MODELS

Table A.4: Parameters and main outputs of synthetic models (group 1), part 4

Models	K_{bedrock} [m/s]	K_{alluvial} [m/s]	RS [-]	HS [-]	p_{bedrock} [-]	Prec.	aspect-ratio [m x m]	Q95 [mm/d]	Q50 [mm/d]	Q95/Q50 [-]	Dyn. V [mm]
sim_aq36tr	1.E-07	1.E-03	0.005	0.5	0.1	HUT	2000x6000	0.82	1.34	0.62	113.76
sim_aq4tr	1.E-07	1.E-03	0.03	0.5	0.1	HUT	2000x6000	0.97	1.35	0.73	119.47
sim_pap92tr	1.E-07	1.E-03	0.09	0.5	0.1	HUT	2000x6000	1.31	1.53	0.86	146.60
sim_aq20tr	1.E-07	1.E-03	0.15	0.5	0.1	HUT	2000x6000	NA	NA	NA	NA
sim_aq37tr	1.E-06	1.E-03	0.005	0.05	0.1	HUT	2000x6000	0.33	1.08	0.32	32.63
sim_aq5tr	1.E-06	1.E-03	0.03	0.05	0.1	HUT	2000x6000	0.58	1.09	0.55	52.25
sim_pap93tr	1.E-06	1.E-03	0.09	0.05	0.1	HUT	2000x6000	1.14	1.34	0.86	107.91
sim_aq21tr	1.E-06	1.E-03	0.15	0.05	0.1	HUT	2000x6000	1.11	1.51	0.75	109.47
sim_aq38tr	1.E-06	1.E-03	0.005	0.18	0.1	HUT	2000x6000	1.13	1.50	0.76	148.47
sim_aq6tr	1.E-06	1.E-03	0.03	0.18	0.1	HUT	2000x6000	1.22	1.50	0.82	146.20
sim_pap94tr	1.E-06	1.E-03	0.09	0.18	0.1	HUT	2000x6000	1.41	1.57	0.90	178.13
sim_aq22tr	1.E-06	1.E-03	0.15	0.18	0.1	HUT	2000x6000	1.49	1.65	0.91	193.02
sim_aq39tr	1.E-06	1.E-03	0.005	0.35	0.1	HUT	2000x6000	1.45	1.63	0.89	193.31
sim_aq7tr	1.E-06	1.E-03	0.03	0.35	0.1	HUT	2000x6000	1.50	1.63	0.92	203.88
sim_pap95tr	1.E-06	1.E-03	0.09	0.35	0.1	HUT	2000x6000	1.59	1.67	0.95	200.59
sim_aq23tr	1.E-06	1.E-03	0.15	0.35	0.1	HUT	2000x6000	NA	NA	NA	NA
sim_aq40tr	1.E-06	1.E-03	0.005	0.5	0.1	HUT	2000x6000	1.57	1.67	0.94	213.43
sim_aq8tr	1.E-06	1.E-03	0.03	0.5	0.1	HUT	2000x6000	1.59	1.68	0.95	224.70
sim_pap96tr	1.E-06	1.E-03	0.09	0.5	0.1	HUT	2000x6000	1.64	1.70	0.96	233.00
sim_aq24tr	1.E-06	1.E-03	0.15	0.5	0.1	HUT	2000x6000	1.67	1.71	0.97	229.68
sim_aq41tr	1.E-05	1.E-03	0.005	0.05	0.1	HUT	2000x6000	1.44	1.64	0.88	185.11
sim_aq9tr	1.E-05	1.E-03	0.03	0.05	0.1	HUT	2000x6000	1.49	1.66	0.90	187.09
sim_pap97tr	1.E-05	1.E-03	0.09	0.05	0.1	HUT	2000x6000	1.61	1.69	0.95	217.41
sim_aq25tr	1.E-05	1.E-03	0.15	0.05	0.1	HUT	2000x6000	1.60	1.68	0.95	228.40
sim_aq42tr	1.E-05	1.E-03	0.005	0.18	0.1	HUT	2000x6000	1.52	1.66	0.91	207.33
sim_aq10tr	1.E-05	1.E-03	0.03	0.18	0.1	HUT	2000x6000	1.57	1.67	0.94	219.65
sim_pap98tr	1.E-05	1.E-03	0.09	0.18	0.1	HUT	2000x6000	1.64	1.69	0.97	233.20
sim_aq26tr	1.E-05	1.E-03	0.15	0.18	0.1	HUT	2000x6000	1.66	1.71	0.97	234.17
sim_aq43tr	1.E-05	1.E-03	0.005	0.35	0.1	HUT	2000x6000	1.55	1.66	0.93	209.82
sim_aq11tr	1.E-05	1.E-03	0.03	0.35	0.1	HUT	2000x6000	1.59	1.67	0.95	214.26
sim_pap99tr	1.E-05	1.E-03	0.09	0.35	0.1	HUT	2000x6000	1.66	1.70	0.98	226.52
sim_aq27tr	1.E-05	1.E-03	0.15	0.35	0.1	HUT	2000x6000	1.67	1.70	0.98	228.72
sim_aq44tr	1.E-05	1.E-03	0.005	0.5	0.1	HUT	2000x6000	1.56	1.65	0.94	205.60
sim_aq12tr	1.E-05	1.E-03	0.03	0.5	0.1	HUT	2000x6000	1.60	1.67	0.95	215.62
sim_pap100tr	1.E-05	1.E-03	0.09	0.5	0.1	HUT	2000x6000	1.67	1.70	0.98	227.93
sim_aq28tr	1.E-05	1.E-03	0.15	0.5	0.1	HUT	2000x6000	1.68	1.71	0.99	225.38
sim_pap17tr	1.E-08	1.E-02	0.005	0.05	0.1	HUT	2000x6000	0.62	1.00	0.64	37.41
sim_pap21tr	1.E-08	1.E-02	0.03	0.05	0.1	HUT	2000x6000	0.96	1.71	0.59	104.44
sim_pap25tr	1.E-08	1.E-02	0.09	0.05	0.1	HUT	2000x6000	0.79	1.64	0.50	69.17
sim_pap29tr	1.E-08	1.E-02	0.15	0.05	0.1	HUT	2000x6000	0.60	1.52	0.40	51.37
sim_pap18tr	1.E-08	1.E-02	0.005	0.18	0.1	HUT	2000x6000	0.62	1.01	0.63	35.46
sim_pap22tr	1.E-08	1.E-02	0.03	0.18	0.1	HUT	2000x6000	0.99	1.68	0.61	104.27
sim_pap26tr	1.E-08	1.E-02	0.09	0.18	0.1	HUT	2000x6000	0.82	1.59	0.55	75.62
sim_pap30tr	1.E-08	1.E-02	0.15	0.18	0.1	HUT	2000x6000	0.65	1.56	0.43	64.71
sim_pap19tr	1.E-08	1.E-02	0.005	0.35	0.1	HUT	2000x6000	0.63	1.02	0.64	36.05
sim_pap23tr	1.E-08	1.E-02	0.03	0.35	0.1	HUT	2000x6000	1.04	1.69	0.63	110.09
sim_pap27tr	1.E-08	1.E-02	0.09	0.35	0.1	HUT	2000x6000	0.83	1.61	0.55	78.92
sim_pap31tr	1.E-08	1.E-02	0.15	0.35	0.1	HUT	2000x6000	0.65	1.54	0.43	67.28
sim_pap20tr	1.E-08	1.E-02	0.005	0.5	0.1	HUT	2000x6000	0.65	1.03	0.65	37.29
sim_pap24tr	1.E-08	1.E-02	0.03	0.5	0.1	HUT	2000x6000	1.05	1.70	0.64	111.26
sim_pap28tr	1.E-08	1.E-02	0.09	0.5	0.1	HUT	2000x6000	0.84	1.61	0.56	76.52
sim_pap32tr	1.E-08	1.E-02	0.15	0.5	0.1	HUT	2000x6000	0.65	1.52	0.44	72.38

APPENDIX A. SYNTHETIC MODELS

Table A.5: Parameters and main outputs of synthetic models (group 1), part 5

Models	K_{bedrock} [m/s]	K_{alluvial} [m/s]	RS [-]	HS [-]	ρ_{bedrock} [-]	Prec.	aspect-ratio [mxm]	Q95 [mm/d]	Q50 [mm/d]	Q95/Q50 [-]	Dyn. V [mm]
sim_pap113tr	1.E-07	1.E-02	0.005	0.05	0.1	HUT	2000x6000	0.62	1.01	0.63	36.62
sim_pap125tr	1.E-07	1.E-02	0.03	0.05	0.1	HUT	2000x6000	1.00	1.70	0.61	102.99
sim_pap77tr	1.E-07	1.E-02	0.09	0.05	0.1	HUT	2000x6000	0.78	1.67	0.50	66.20
sim_pap137tr	1.E-07	1.E-02	0.15	0.05	0.1	HUT	2000x6000	0.63	1.53	0.41	53.43
sim_pap114tr	1.E-07	1.E-02	0.005	0.18	0.1	HUT	2000x6000	0.69	1.07	0.66	42.60
sim_pap126tr	1.E-07	1.E-02	0.03	0.18	0.1	HUT	2000x6000	1.08	1.72	0.65	109.35
sim_pap78tr	1.E-07	1.E-02	0.09	0.18	0.1	HUT	2000x6000	0.89	1.62	0.58	75.47
sim_pap138tr	1.E-07	1.E-02	0.15	0.18	0.1	HUT	2000x6000	0.75	1.58	0.48	66.91
sim_pap115tr	1.E-07	1.E-02	0.005	0.35	0.1	HUT	2000x6000	0.87	1.22	0.72	74.95
sim_pap127tr	1.E-07	1.E-02	0.03	0.35	0.1	HUT	2000x6000	1.23	1.71	0.74	132.58
sim_pap79tr	1.E-07	1.E-02	0.09	0.35	0.1	HUT	2000x6000	1.05	1.66	0.65	95.31
sim_pap139tr	1.E-07	1.E-02	0.15	0.35	0.1	HUT	2000x6000	1.07	1.60	0.68	99.80
sim_pap116tr	1.E-07	1.E-02	0.005	0.5	0.1	HUT	2000x6000	1.04	1.35	0.78	121.77
sim_pap128tr	1.E-07	1.E-02	0.03	0.5	0.1	HUT	2000x6000	1.36	1.72	0.80	157.63
sim_pap80tr	1.E-07	1.E-02	0.09	0.5	0.1	HUT	2000x6000	1.18	1.67	0.71	131.80
sim_pap140tr	1.E-07	1.E-02	0.15	0.5	0.1	HUT	2000x6000	1.19	1.63	0.74	132.70
sim_pap117tr	1.E-06	1.E-02	0.005	0.05	0.1	HUT	2000x6000	0.72	1.10	0.67	50.03
sim_pap129tr	1.E-06	1.E-02	0.03	0.05	0.1	HUT	2000x6000	1.11	1.66	0.69	112.87
sim_pap81tr	1.E-06	1.E-02	0.09	0.05	0.1	HUT	2000x6000	0.98	1.58	0.64	77.32
sim_pap141tr	1.E-06	1.E-02	0.15	0.05	0.1	HUT	2000x6000	0.93	1.62	0.59	68.49
sim_pap118tr	1.E-06	1.E-02	0.005	0.18	0.1	HUT	2000x6000	1.24	1.49	0.84	151.32
sim_pap130tr	1.E-06	1.E-02	0.03	0.18	0.1	HUT	2000x6000	1.50	1.72	0.88	176.25
sim_pap82tr	1.E-06	1.E-02	0.09	0.18	0.1	HUT	2000x6000	1.43	1.70	0.85	162.85
sim_pap142tr	1.E-06	1.E-02	0.15	0.18	0.1	HUT	2000x6000	0.75	0.85	0.88	NA
sim_pap119tr	1.E-06	1.E-02	0.005	0.35	0.1	HUT	2000x6000	1.51	1.64	0.92	211.69
sim_pap131tr	1.E-06	1.E-02	0.03	0.35	0.1	HUT	2000x6000	1.66	1.72	0.96	232.72
sim_pap83tr	1.E-06	1.E-02	0.09	0.35	0.1	HUT	2000x6000	1.64	1.72	0.95	227.72
sim_pap143tr	1.E-06	1.E-02	0.15	0.35	0.1	HUT	2000x6000	1.64	1.72	0.95	227.26
sim_pap120tr	1.E-06	1.E-02	0.005	0.5	0.1	HUT	2000x6000	1.60	1.68	0.95	231.35
sim_pap132tr	1.E-06	1.E-02	0.03	0.5	0.1	HUT	2000x6000	1.67	1.72	0.97	241.02
sim_pap84tr	1.E-06	1.E-02	0.09	0.5	0.1	HUT	2000x6000	1.66	1.72	0.97	237.44
sim_pap144tr	1.E-06	1.E-02	0.15	0.5	0.1	HUT	2000x6000	1.66	1.72	0.96	237.28
sim_pap121tr	1.E-05	1.E-02	0.005	0.05	0.1	HUT	2000x6000	1.53	1.70	0.90	184.63
sim_pap133tr	1.E-05	1.E-02	0.03	0.05	0.1	HUT	2000x6000	1.64	1.75	0.94	211.72
sim_pap85tr	1.E-05	1.E-02	0.09	0.05	0.1	HUT	2000x6000	1.62	1.75	0.93	210.65
sim_pap145tr	1.E-05	1.E-02	0.15	0.05	0.1	HUT	2000x6000	1.63	1.75	0.93	213.11
sim_pap122tr	1.E-05	1.E-02	0.005	0.18	0.1	HUT	2000x6000	1.59	1.72	0.93	207.80
sim_pap134tr	1.E-05	1.E-02	0.03	0.18	0.1	HUT	2000x6000	1.68	1.75	0.96	225.10
sim_pap86tr	1.E-05	1.E-02	0.09	0.18	0.1	HUT	2000x6000	1.67	1.75	0.96	221.52
sim_pap146tr	1.E-05	1.E-02	0.15	0.18	0.1	HUT	2000x6000	1.67	1.75	0.96	221.75
sim_pap123tr	1.E-05	1.E-02	0.005	0.35	0.1	HUT	2000x6000	1.61	1.70	0.95	222.18
sim_pap135tr	1.E-05	1.E-02	0.03	0.35	0.1	HUT	2000x6000	1.69	1.74	0.97	235.88
sim_pap87tr	1.E-05	1.E-02	0.09	0.35	0.1	HUT	2000x6000	1.68	1.74	0.97	233.12
sim_pap147tr	1.E-05	1.E-02	0.15	0.35	0.1	HUT	2000x6000	1.69	1.74	0.97	235.92
sim_pap124tr	1.E-05	1.E-02	0.005	0.5	0.1	HUT	2000x6000	1.61	1.69	0.95	226.98
sim_pap136tr	1.E-05	1.E-02	0.03	0.5	0.1	HUT	2000x6000	1.70	1.73	0.98	241.56
sim_pap88tr	1.E-05	1.E-02	0.09	0.5	0.1	HUT	2000x6000	1.69	1.73	0.97	238.73
sim_pap148tr	1.E-05	1.E-02	0.15	0.5	0.1	HUT	2000x6000	1.69	1.73	0.98	241.14

APPENDIX A. SYNTHETIC MODELS

Table A.6: Parameters and main outputs of synthetic models (group 2), part 1

Models	K_{edrock} [m/s]	K_{lluvial} [m/s]	RS [-]	HS [-]	ρ_{bedrock} [-]	Prec.	aspect-ratio [mxm]	Q95 [mm/d]	Q50 [mm/d]	Q95/Q50 [-]	Dyn. V [mm]
sim_dim49tr	4.E-07	4.E-07	0.03	0.05	0.1	HUT	2000x6000	0.14	0.65	0.24	9.76
sim_dim50tr	4.E-07	4.E-07	0.03	0.18	0.1	HUT	2000x6000	0.69	1.02	0.69	83.93
sim_dim51tr	4.E-07	4.E-07	0.03	0.35	0.1	HUT	2000x6000	1.13	1.30	0.87	153.05
sim_dim52tr	4.E-07	4.E-07	0.03	0.5	0.1	HUT	2000x6000	1.29	1.42	0.91	188.63
sim_dim53tr	7.E-07	7.E-07	0.03	0.05	0.1	HUT	2000x6000	0.23	0.70	0.35	15.50
sim_dim54tr	7.E-07	7.E-07	0.03	0.18	0.1	HUT	2000x6000	0.94	1.19	0.79	118.31
sim_dim55tr	7.E-07	7.E-07	0.03	0.35	0.1	HUT	2000x6000	1.30	1.43	0.91	185.70
sim_dim56tr	7.E-07	7.E-07	0.03	0.5	0.1	HUT	2000x6000	1.44	1.54	0.94	214.20
sim_dim57tr	4.E-06	4.E-06	0.03	0.05	0.1	HUT	2000x6000	0.88	1.17	0.77	98.85
sim_dim58tr	4.E-06	4.E-06	0.03	0.18	0.1	HUT	2000x6000	1.50	1.60	0.93	203.94
sim_dim59tr	4.E-06	4.E-06	0.03	0.35	0.1	HUT	2000x6000	1.55	1.62	0.95	211.18
sim_dim60tr	4.E-06	4.E-06	0.03	0.5	0.1	HUT	2000x6000	1.55	1.62	0.96	212.74
sim_dim13tr	1.E-04	1.E-04	0.03	0.05	0.1	HUT	2000x6000	1.53	1.65	0.93	215.99
sim_dim14tr	1.E-04	1.E-04	0.03	0.18	0.1	HUT	2000x6000	1.59	1.66	0.96	241.78
sim_dim15tr	1.E-04	1.E-04	0.03	0.35	0.1	HUT	2000x6000	1.61	1.66	0.97	250.32
sim_dim16tr	1.E-04	1.E-04	0.03	0.5	0.1	HUT	2000x6000	1.64	1.68	0.97	244.25
sim_dim_CIM1tr	1.E-07	1.E-07	0.03	0.05	0.1	CIM	2000x6000	0.04	0.28	0.16	8.62
sim_dim_CIM2tr	1.E-07	1.E-07	0.03	0.18	0.1	CIM	2000x6000	0.21	0.42	0.54	29.13
sim_dim_CIM3tr	1.E-07	1.E-07	0.03	0.35	0.1	CIM	2000x6000	0.57	0.70	0.81	112.22
sim_dim_CIM4tr	1.E-07	1.E-07	0.03	0.5	0.1	CIM	2000x6000	0.87	0.98	0.89	185.14
sim_dim_CIM5tr	1.E-06	1.E-06	0.03	0.05	0.1	CIM	2000x6000	0.29	0.50	0.60	40.00
sim_dim_CIM6tr	1.E-06	1.E-06	0.03	0.18	0.1	CIM	2000x6000	1.26	1.40	0.90	266.09
sim_dim_CIM7tr	1.E-06	1.E-06	0.03	0.35	0.1	CIM	2000x6000	1.78	1.86	0.96	446.20
sim_dim_CIM8tr	1.E-06	1.E-06	0.03	0.5	0.1	CIM	2000x6000	1.88	1.97	0.95	442.97
sim_dim_CIM9tr	1.E-05	1.E-05	0.03	0.05	0.1	CIM	2000x6000	1.51	1.77	0.85	309.88
sim_dim_CIM10tr	1.E-05	1.E-05	0.03	0.18	0.1	CIM	2000x6000	1.91	2.08	0.92	470.96
sim_dim_CIM11tr	1.E-05	1.E-05	0.03	0.35	0.1	CIM	2000x6000	1.98	2.07	0.95	469.00
sim_dim_CIM12tr	1.E-05	1.E-05	0.03	0.5	0.1	CIM	2000x6000	2.00	2.09	0.96	492.61
sim_dim_CIM13tr	1.E-04	1.E-04	0.03	0.05	0.1	CIM	2000x6000	1.78	2.06	0.86	448.82
sim_dim_CIM14tr	1.E-04	1.E-04	0.03	0.18	0.1	CIM	2000x6000	2.01	2.15	0.93	454.28
sim_dim_CIM15tr	1.E-04	1.E-04	0.03	0.35	0.1	CIM	2000x6000	2.07	2.17	0.95	487.58
sim_dim_CIM16tr	1.E-04	1.E-04	0.03	0.5	0.1	CIM	2000x6000	2.12	2.19	0.97	480.53
sim_dim_CIM17tr	4.E-07	4.E-07	0.03	0.05	0.1	CIM	2000x6000	0.12	0.36	0.38	17.12
sim_dim_CIM18tr	4.E-07	4.E-07	0.03	0.18	0.1	CIM	2000x6000	0.72	0.88	0.82	135.58
sim_dim_CIM19tr	4.E-07	4.E-07	0.03	0.35	0.1	CIM	2000x6000	1.38	1.47	0.94	301.68
sim_dim_CIM20tr	4.E-07	4.E-07	0.03	0.5	0.1	CIM	2000x6000	1.65	1.76	0.94	436.73
sim_dim_CIM21tr	7.E-07	7.E-07	0.03	0.05	0.1	CIM	2000x6000	0.21	0.43	0.51	27.96
sim_dim_CIM22tr	7.E-07	7.E-07	0.03	0.18	0.1	CIM	2000x6000	1.05	1.18	0.89	212.11
sim_dim_CIM23tr	7.E-07	7.E-07	0.03	0.35	0.1	CIM	2000x6000	1.64	1.78	0.92	451.77
sim_dim_CIM24tr	7.E-07	7.E-07	0.03	0.5	0.1	CIM	2000x6000	1.86	1.97	0.95	522.75
sim_dim_CIM25tr	4.E-06	4.E-06	0.03	0.05	0.1	CIM	2000x6000	0.89	1.10	0.81	163.96
sim_dim_CIM26tr	4.E-06	4.E-06	0.03	0.18	0.1	CIM	2000x6000	1.89	2.02	0.93	412.79
sim_dim_CIM27tr	4.E-06	4.E-06	0.03	0.35	0.1	CIM	2000x6000	1.98	2.10	0.95	454.05
sim_dim_CIM28tr	4.E-06	4.E-06	0.03	0.5	0.1	CIM	2000x6000	2.02	2.09	0.96	463.39
sim_dim_CIM29tr	7.E-06	7.E-06	0.03	0.05	0.1	CIM	2000x6000	1.26	1.51	0.83	264.38
sim_dim_CIM30tr	7.E-06	7.E-06	0.03	0.18	0.1	CIM	2000x6000	1.90	2.08	0.92	433.86
sim_dim_CIM31tr	7.E-06	7.E-06	0.03	0.35	0.1	CIM	2000x6000	1.98	2.08	0.95	477.37
sim_dim_CIM32tr	7.E-06	7.E-06	0.03	0.5	0.1	CIM	2000x6000	2.01	2.08	0.96	473.36
sim_dim_AIG1tr	1.E-07	1.E-07	0.03	0.05	0.1	AIG	2000x6000	0.05	0.41	0.12	4.01
sim_dim_AIG2tr	1.E-07	1.E-07	0.03	0.18	0.1	AIG	2000x6000	0.21	0.52	0.44	19.98
sim_dim_AIG3tr	1.E-07	1.E-07	0.03	0.35	0.1	AIG	2000x6000	0.51	0.72	0.72	67.55
sim_dim_AIG4tr	1.E-07	1.E-07	0.03	0.5	0.1	AIG	2000x6000	0.73	0.86	0.85	92.10

APPENDIX A. SYNTHETIC MODELS

Table A.7: Parameters and main outputs of synthetic models (group 2), part 2

Models	K_{edrock} [m/s]	K_{lluvial} [m/s]	RS [-]	HS [-]	p_{bedrock} [-]	Prec.	aspect-ratio [mxm]	Q95 [mm/d]	Q50 [mm/d]	Q95/Q50 [-]	Dyn. V [mm]
sim_dim_AIG5tr	1.E-06	1.E-06	0.03	0.05	0.1	AIG	2000x6000	0.29	0.58	0.52	27.24
sim_dim_AIG6tr	1.E-06	1.E-06	0.03	0.18	0.1	AIG	2000x6000	0.97	1.05	0.92	131.26
sim_dim_AIG7tr	1.E-06	1.E-06	0.03	0.35	0.1	AIG	2000x6000	1.14	1.19	0.95	168.64
sim_dim_AIG8tr	1.E-06	1.E-06	0.03	0.5	0.1	AIG	2000x6000	1.22	1.26	0.97	165.56
sim_dim_AIG9tr	1.E-05	1.E-05	0.03	0.05	0.1	AIG	2000x6000	1.11	1.22	0.91	151.01
sim_dim_AIG10tr	1.E-05	1.E-05	0.03	0.18	0.1	AIG	2000x6000	1.19	1.26	0.94	194.28
sim_dim_AIG11tr	1.E-05	1.E-05	0.03	0.35	0.1	AIG	2000x6000	1.21	1.26	0.95	188.79
sim_dim_AIG12tr	1.E-05	1.E-05	0.03	0.5	0.1	AIG	2000x6000	1.21	1.27	0.96	185.94
sim_dim_AIG13tr	1.E-04	1.E-04	0.03	0.05	0.1	AIG	2000x6000	1.22	1.27	0.96	201.50
sim_dim_AIG14tr	1.E-04	1.E-04	0.03	0.18	0.1	AIG	2000x6000	1.26	1.29	0.97	229.29
sim_dim_AIG15tr	1.E-04	1.E-04	0.03	0.35	0.1	AIG	2000x6000	1.27	1.30	0.98	199.99
sim_dim_AIG16tr	1.E-04	1.E-04	0.03	0.5	0.1	AIG	2000x6000	1.28	1.30	0.98	220.66
sim_dim_AIG17tr	4.E-07	4.E-07	0.03	0.05	0.1	AIG	2000x6000	0.13	0.46	0.31	11.32
sim_dim_AIG18tr	4.E-07	4.E-07	0.03	0.18	0.1	AIG	2000x6000	0.62	0.79	0.78	83.70
sim_dim_AIG19tr	4.E-07	4.E-07	0.03	0.35	0.1	AIG	2000x6000	0.99	1.08	0.92	143.52
sim_dim_AIG20tr	4.E-07	4.E-07	0.03	0.5	0.1	AIG	2000x6000	1.12	1.18	0.95	165.33
sim_dim_AIG21tr	7.E-07	7.E-07	0.03	0.05	0.1	AIG	2000x6000	0.21	0.53	0.43	18.46
sim_dim_AIG22tr	7.E-07	7.E-07	0.03	0.18	0.1	AIG	2000x6000	0.85	0.96	0.89	113.07
sim_dim_AIG23tr	7.E-07	7.E-07	0.03	0.35	0.1	AIG	2000x6000	1.12	1.18	0.95	163.84
sim_dim_AIG24tr	7.E-07	7.E-07	0.03	0.5	0.1	AIG	2000x6000	1.14	1.19	0.96	172.11
sim_dim_AIG25tr	4.E-06	4.E-06	0.03	0.05	0.1	AIG	2000x6000	0.80	0.97	0.83	101.53
sim_dim_AIG26tr	4.E-06	4.E-06	0.03	0.18	0.1	AIG	2000x6000	1.19	1.26	0.95	171.97
sim_dim_AIG27tr	4.E-06	4.E-06	0.03	0.35	0.1	AIG	2000x6000	1.21	1.26	0.96	182.74
sim_dim_AIG28tr	4.E-06	4.E-06	0.03	0.5	0.1	AIG	2000x6000	1.22	1.26	0.97	177.55
sim_dim_AIG29tr	7.E-06	7.E-06	0.03	0.05	0.1	AIG	2000x6000	1.04	1.16	0.90	134.50
sim_dim_AIG30tr	7.E-06	7.E-06	0.03	0.18	0.1	AIG	2000x6000	1.19	1.26	0.94	173.91
sim_dim_AIG31tr	7.E-06	7.E-06	0.03	0.35	0.1	AIG	2000x6000	1.20	1.26	0.95	182.69
sim_dim_AIG32tr	7.E-06	7.E-06	0.03	0.5	0.1	AIG	2000x6000	1.21	1.26	0.96	185.79
sim_dim_STG1tr	1.E-07	1.E-07	0.03	0.05	0.1	STG	2000x6000	0.05	0.50	0.11	5.05
sim_dim_STG2tr	1.E-07	1.E-07	0.03	0.18	0.1	STG	2000x6000	0.22	0.61	0.37	21.20
sim_dim_STG3tr	1.E-07	1.E-07	0.03	0.35	0.1	STG	2000x6000	0.56	0.91	0.62	66.61
sim_dim_STG4tr	1.E-07	1.E-07	0.03	0.5	0.1	STG	2000x6000	0.83	1.09	0.77	102.20
sim_dim_STG5tr	1.E-06	1.E-06	0.03	0.05	0.1	STG	2000x6000	0.31	0.68	0.46	30.83
sim_dim_STG6tr	1.E-06	1.E-06	0.03	0.18	0.1	STG	2000x6000	1.19	1.36	0.88	185.53
sim_dim_STG7tr	1.E-06	1.E-06	0.03	0.35	0.1	STG	2000x6000	1.59	1.70	0.94	258.08
sim_dim_STG8tr	1.E-06	1.E-06	0.03	0.5	0.1	STG	2000x6000	1.63	1.71	0.95	270.42
sim_dim_STG9tr	1.E-05	1.E-05	0.03	0.05	0.1	STG	2000x6000	1.43	1.65	0.87	218.33
sim_dim_STG10tr	1.E-05	1.E-05	0.03	0.18	0.1	STG	2000x6000	1.66	1.80	0.92	260.67
sim_dim_STG11tr	1.E-05	1.E-05	0.03	0.35	0.1	STG	2000x6000	1.71	1.81	0.94	264.51
sim_dim_STG12tr	1.E-05	1.E-05	0.03	0.5	0.1	STG	2000x6000	1.72	1.81	0.95	275.69
sim_dim_STG13tr	1.E-04	1.E-04	0.03	0.05	0.1	STG	2000x6000	1.64	1.77	0.93	253.98
sim_dim_STG14tr	1.E-04	1.E-04	0.03	0.18	0.1	STG	2000x6000	1.74	1.82	0.95	269.70
sim_dim_STG15tr	1.E-04	1.E-04	0.03	0.35	0.1	STG	2000x6000	1.78	1.83	0.97	287.08
sim_dim_STG16tr	1.E-04	1.E-04	0.03	0.5	0.1	STG	2000x6000	1.79	1.84	0.98	274.46
sim_dim_STG17tr	4.E-07	4.E-07	0.03	0.05	0.1	STG	2000x6000	0.14	0.56	0.26	11.65
sim_dim_STG18tr	4.E-07	4.E-07	0.03	0.18	0.1	STG	2000x6000	0.70	0.99	0.71	98.37
sim_dim_STG19tr	4.E-07	4.E-07	0.03	0.35	0.1	STG	2000x6000	1.23	1.40	0.87	199.87
sim_dim_STG20tr	4.E-07	4.E-07	0.03	0.5	0.1	STG	2000x6000	1.41	1.54	0.92	230.58
sim_dim_STG21tr	7.E-07	7.E-07	0.03	0.05	0.1	STG	2000x6000	0.23	0.62	0.38	21.57
sim_dim_STG22tr	7.E-07	7.E-07	0.03	0.18	0.1	STG	2000x6000	1.00	1.21	0.83	143.61
sim_dim_STG23tr	7.E-07	7.E-07	0.03	0.35	0.1	STG	2000x6000	1.42	1.56	0.91	239.54
sim_dim_STG24tr	7.E-07	7.E-07	0.03	0.5	0.1	STG	2000x6000	1.60	1.70	0.94	265.79

APPENDIX A. SYNTHETIC MODELS

Table A.8: Parameters and main outputs of synthetic models (group 2), part 3

Models	K_{edrock} [m/s]	$K_{lluvial}$ [m/s]	RS [-]	HS [-]	$p_{bedro\ k}$ [-]	Prec.	aspect-ratio [m \times m]	Q95 [mm/d]	Q50 [mm/d]	Q95/Q50 [-]	Dyn. V [mm]
sim_dim_STG25tr	4.E-06	4.E-06	0.03	0.05	0.1	STG	2000x6000	0.90	1.16	0.78	124.85
sim_dim_STG26tr	4.E-06	4.E-06	0.03	0.18	0.1	STG	2000x6000	1.64	1.77	0.93	254.71
sim_dim_STG27tr	4.E-06	4.E-06	0.03	0.35	0.1	STG	2000x6000	1.70	1.80	0.94	284.94
sim_dim_STG28tr	4.E-06	4.E-06	0.03	0.5	0.1	STG	2000x6000	1.72	1.80	0.96	285.19
sim_dim_STG29tr	7.E-06	7.E-06	0.03	0.05	0.1	STG	2000x6000	1.24	1.46	0.85	176.28
sim_dim_STG30tr	7.E-06	7.E-06	0.03	0.18	0.1	STG	2000x6000	1.66	1.80	0.92	265.69
sim_dim_STG31tr	7.E-06	7.E-06	0.03	0.35	0.1	STG	2000x6000	1.71	1.80	0.95	272.18
sim_dim_STG32tr	7.E-06	7.E-06	0.03	0.5	0.1	STG	2000x6000	1.72	1.81	0.96	269.42
sim_dimLP1tr	1.E-07	1.E-07	0.03	0.05	0.05	HUT	2000x6000	0.05	0.59	0.10	4.42
sim_dimLP2tr	1.E-07	1.E-07	0.03	0.18	0.05	HUT	2000x6000	0.22	0.71	0.33	15.21
sim_dimLP3tr	1.E-07	1.E-07	0.03	0.35	0.05	HUT	2000x6000	0.54	0.96	0.58	62.46
sim_dimLP4tr	1.E-07	1.E-07	0.03	0.5	0.05	HUT	2000x6000	0.80	1.12	0.73	96.09
sim_dimLP5tr	1.E-06	1.E-06	0.03	0.05	0.05	HUT	2000x6000	0.30	0.75	0.43	20.58
sim_dimLP6tr	1.E-06	1.E-06	0.03	0.18	0.05	HUT	2000x6000	1.09	1.34	0.82	136.87
sim_dimLP7tr	1.E-06	1.E-06	0.03	0.35	0.05	HUT	2000x6000	1.42	1.54	0.92	181.14
sim_dimLP8tr	1.E-06	1.E-06	0.03	0.5	0.05	HUT	2000x6000	1.50	1.56	0.96	209.24
sim_dimLP9tr	1.E-05	1.E-05	0.03	0.05	0.05	HUT	2000x6000	1.27	1.51	0.84	163.17
sim_dimLP10tr	1.E-05	1.E-05	0.03	0.18	0.05	HUT	2000x6000	1.42	1.58	0.90	202.43
sim_dimLP11tr	1.E-05	1.E-05	0.03	0.35	0.05	HUT	2000x6000	1.47	1.59	0.93	222.87
sim_dimLP12tr	1.E-05	1.E-05	0.03	0.5	0.05	HUT	2000x6000	1.49	1.60	0.94	230.80
sim_dimLP13tr	1.E-04	1.E-04	0.03	0.05	0.05	HUT	2000x6000	1.43	1.61	0.89	182.07
sim_dimLP14tr	1.E-04	1.E-04	0.03	0.18	0.05	HUT	2000x6000	1.51	1.63	0.93	213.50
sim_dimLP15tr	1.E-04	1.E-04	0.03	0.35	0.05	HUT	2000x6000	1.54	1.64	0.94	237.96
sim_dimLP16tr	1.E-04	1.E-04	0.03	0.5	0.05	HUT	2000x6000	1.56	1.65	0.95	222.19
sim_dimHP1tr	1.E-07	1.E-07	0.03	0.05	0.2	HUT	2000x6000	0.05	0.59	0.10	4.42
sim_dimHP2tr	1.E-07	1.E-07	0.03	0.18	0.2	HUT	2000x6000	0.22	0.70	0.34	18.78
sim_dimHP3tr	1.E-07	1.E-07	0.03	0.35	0.2	HUT	2000x6000	0.54	0.91	0.62	66.28
sim_dimHP4tr	1.E-07	1.E-07	0.03	0.5	0.2	HUT	2000x6000	0.80	1.07	0.75	109.51
sim_dimHP5tr	1.E-06	1.E-06	0.03	0.05	0.2	HUT	2000x6000	0.31	0.75	0.43	29.27
sim_dimHP6tr	1.E-06	1.E-06	0.03	0.18	0.2	HUT	2000x6000	1.11	1.30	0.86	152.93
sim_dimHP7tr	1.E-06	1.E-06	0.03	0.35	0.2	HUT	2000x6000	1.44	1.53	0.94	215.54
sim_dimHP8tr	1.E-06	1.E-06	0.03	0.5	0.2	HUT	2000x6000	1.52	1.57	0.97	221.09
sim_dimHP9tr	1.E-05	1.E-05	0.03	0.05	0.2	HUT	2000x6000	1.40	1.56	0.90	167.34
sim_dimHP10tr	1.E-05	1.E-05	0.03	0.18	0.2	HUT	2000x6000	1.57	1.65	0.95	201.67
sim_dimHP11tr	1.E-05	1.E-05	0.03	0.35	0.2	HUT	2000x6000	1.58	1.64	0.96	208.09
sim_dimHP12tr	1.E-05	1.E-05	0.03	0.5	0.2	HUT	2000x6000	1.58	1.64	0.96	208.03
sim_dimHP13tr	1.E-04	1.E-04	0.03	0.05	0.2	HUT	2000x6000	1.60	1.69	0.95	216.52
sim_dimHP14tr	1.E-04	1.E-04	0.03	0.18	0.2	HUT	2000x6000	1.64	1.68	0.97	219.67
sim_dimHP15tr	1.E-04	1.E-04	0.03	0.35	0.2	HUT	2000x6000	1.65	1.68	0.98	222.93
sim_dimHP16tr	1.E-04	1.E-04	0.03	0.5	0.2	HUT	2000x6000	1.67	1.69	0.98	227.14
sim_wd1tr	1.E-07	1.E-07	0.03	0.05	0.1	HUT	6000x2000	0.06	0.56	0.12	4.34
sim_wd2tr	1.E-07	1.E-07	0.03	0.18	0.1	HUT	6000x2000	0.21	0.71	0.33	16.81
sim_wd3tr	1.E-07	1.E-07	0.03	0.35	0.1	HUT	6000x2000	0.54	0.92	0.60	63.35
sim_wd4tr	1.E-07	1.E-07	0.03	0.5	0.1	HUT	6000x2000	0.80	1.09	0.74	111.18
sim_wd5tr	1.E-06	1.E-06	0.03	0.05	0.1	HUT	6000x2000	0.31	0.74	0.45	28.18
sim_wd6tr	1.E-06	1.E-06	0.03	0.18	0.1	HUT	6000x2000	1.06	1.24	0.86	146.83
sim_wd7tr	1.E-06	1.E-06	0.03	0.35	0.1	HUT	6000x2000	1.43	1.51	0.95	210.57
sim_wd8tr	1.E-06	1.E-06	0.03	0.5	0.1	HUT	6000x2000	1.47	1.53	0.96	212.57
sim_wd9tr	1.E-05	1.E-05	0.03	0.05	0.1	HUT	6000x2000	1.27	1.43	0.89	158.41
sim_wd10tr	1.E-05	1.E-05	0.03	0.18	0.1	HUT	6000x2000	1.58	1.63	0.97	215.86
sim_wd11tr	1.E-05	1.E-05	0.03	0.35	0.1	HUT	6000x2000	1.59	1.63	0.98	223.19
sim_wd12tr	1.E-05	1.E-05	0.03	0.5	0.1	HUT	6000x2000	1.60	1.63	0.98	222.68

APPENDIX A. SYNTHETIC MODELS

Table A.9: Parameters and main outputs of synthetic models (group 2), part 4

Models	K_{bedrock} [m/s]	K_{alluvial} [m/s]	RS [-]	HS [-]	p_{bedrock} [-]	Prec.	aspect-ratio [m \times m]	Q95 [mm/d]	Q50 [mm/d]	Q95/Q50 [-]	Dyn. V [mm]
sim_wd13tr	1.E-04	1.E-04	0.03	0.05	0.1	HUT	6000x2000	1.60	1.67	0.96	222.46
sim_wd14tr	1.E-04	1.E-04	0.03	0.18	0.1	HUT	6000x2000	1.63	1.67	0.98	242.54
sim_wd15tr	1.E-04	1.E-04	0.03	0.35	0.1	HUT	6000x2000	1.65	1.67	0.98	230.91
sim_wd16tr	1.E-04	1.E-04	0.03	0.5	0.1	HUT	6000x2000	1.65	1.67	0.99	249.03
sim_wd17tr	4.E-07	4.E-07	0.03	0.05	0.1	HUT	6000x2000	0.15	0.64	0.25	11.30
sim_wd18tr	4.E-07	4.E-07	0.03	0.18	0.1	HUT	6000x2000	0.66	0.98	0.69	82.58
sim_wd19tr	4.E-07	4.E-07	0.03	0.35	0.1	HUT	6000x2000	1.13	1.29	0.88	161.59
sim_wd20tr	4.E-07	4.E-07	0.03	0.5	0.1	HUT	6000x2000	1.31	1.41	0.93	199.66
sim_wd21tr	7.E-07	7.E-07	0.03	0.05	0.1	HUT	6000x2000	0.23	0.69	0.37	18.73
sim_wd22tr	7.E-07	7.E-07	0.03	0.18	0.1	HUT	6000x2000	0.91	1.13	0.81	121.44
sim_wd23tr	7.E-07	7.E-07	0.03	0.35	0.1	HUT	6000x2000	1.30	1.41	0.92	197.27
sim_wd24tr	7.E-07	7.E-07	0.03	0.5	0.1	HUT	6000x2000	1.45	1.52	0.96	224.57
sim_wd25tr	4.E-06	4.E-06	0.03	0.05	0.1	HUT	6000x2000	0.86	1.13	0.77	99.85
sim_wd26tr	4.E-06	4.E-06	0.03	0.18	0.1	HUT	6000x2000	1.47	1.55	0.95	186.40
sim_wd27tr	4.E-06	4.E-06	0.03	0.35	0.1	HUT	6000x2000	1.59	1.63	0.98	208.96
sim_wd28tr	4.E-06	4.E-06	0.03	0.5	0.1	HUT	6000x2000	1.60	1.63	0.98	221.05
sim_wd29tr	7.E-06	7.E-06	0.03	0.05	0.1	HUT	6000x2000	1.12	1.32	0.86	136.52
sim_wd30tr	7.E-06	7.E-06	0.03	0.18	0.1	HUT	6000x2000	1.55	1.61	0.96	217.03
sim_wd31tr	7.E-06	7.E-06	0.03	0.35	0.1	HUT	6000x2000	1.59	1.63	0.98	220.85
sim_wd32tr	7.E-06	7.E-06	0.03	0.5	0.1	HUT	6000x2000	1.60	1.63	0.98	217.07
sim_sq1tr	1.E-07	1.E-07	0.03	0.05	0.1	HUT	3000x3000	0.05	0.57	0.11	4.17
sim_sq2tr	1.E-07	1.E-07	0.03	0.18	0.1	HUT	3000x3000	0.21	0.69	0.33	17.22
sim_sq3tr	1.E-07	1.E-07	0.03	0.35	0.1	HUT	3000x3000	0.54	0.91	0.61	62.62
sim_sq4tr	1.E-07	1.E-07	0.03	0.5	0.1	HUT	3000x3000	0.80	1.07	0.75	117.58
sim_sq5tr	1.E-06	1.E-06	0.03	0.05	0.1	HUT	3000x3000	0.30	0.73	0.43	24.73
sim_sq6tr	1.E-06	1.E-06	0.03	0.18	0.1	HUT	3000x3000	1.08	1.26	0.86	143.59
sim_sq7tr	1.E-06	1.E-06	0.03	0.35	0.1	HUT	3000x3000	1.43	1.52	0.94	188.75
sim_sq8tr	1.E-06	1.E-06	0.03	0.5	0.1	HUT	3000x3000	1.49	1.54	0.96	207.07
sim_sq9tr	1.E-05	1.E-05	0.03	0.05	0.1	HUT	3000x3000	1.30	1.48	0.88	154.04
sim_sq10tr	1.E-05	1.E-05	0.03	0.18	0.1	HUT	3000x3000	1.55	1.63	0.95	211.93
sim_sq11tr	1.E-05	1.E-05	0.03	0.35	0.1	HUT	3000x3000	1.57	1.63	0.96	216.44
sim_sq12tr	1.E-05	1.E-05	0.03	0.5	0.1	HUT	3000x3000	1.57	1.63	0.97	217.76
sim_sq13tr	1.E-04	1.E-04	0.03	0.05	0.1	HUT	3000x3000	1.57	1.66	0.95	236.65
sim_sq14tr	1.E-04	1.E-04	0.03	0.18	0.1	HUT	3000x3000	1.61	1.65	0.97	241.18
sim_sq15tr	1.E-04	1.E-04	0.03	0.35	0.1	HUT	3000x3000	1.63	1.67	0.98	255.44
sim_sq16tr	1.E-04	1.E-04	0.03	0.5	0.1	HUT	3000x3000	1.64	1.67	0.98	237.94
sim_sq17tr	4.E-07	4.E-07	0.03	0.05	0.1	HUT	3000x3000	0.14	0.63	0.25	10.35
sim_sq18tr	4.E-07	4.E-07	0.03	0.18	0.1	HUT	3000x3000	0.67	0.97	0.70	76.57
sim_sq19tr	4.E-07	4.E-07	0.03	0.35	0.1	HUT	3000x3000	1.13	1.29	0.88	163.41
sim_sq20tr	4.E-07	4.E-07	0.03	0.5	0.1	HUT	3000x3000	1.30	1.41	0.92	194.65
sim_sq21tr	7.E-07	7.E-07	0.03	0.05	0.1	HUT	3000x3000	0.22	0.67	0.36	15.15
sim_sq22tr	7.E-07	7.E-07	0.03	0.18	0.1	HUT	3000x3000	0.93	1.15	0.81	116.37
sim_sq23tr	7.E-07	7.E-07	0.03	0.35	0.1	HUT	3000x3000	1.31	1.42	0.92	188.73
sim_sq24tr	7.E-07	7.E-07	0.03	0.5	0.1	HUT	3000x3000	1.44	1.52	0.95	201.97
sim_sq25tr	4.E-06	4.E-06	0.03	0.05	0.1	HUT	3000x3000	0.84	1.13	0.75	94.06
sim_sq26tr	4.E-06	4.E-06	0.03	0.18	0.1	HUT	3000x3000	1.49	1.57	0.95	201.87
sim_sq27tr	4.E-06	4.E-06	0.03	0.35	0.1	HUT	3000x3000	1.57	1.63	0.96	215.11
sim_sq28tr	4.E-06	4.E-06	0.03	0.5	0.1	HUT	3000x3000	1.58	1.62	0.97	217.41
sim_sq29tr	7.E-06	7.E-06	0.03	0.05	0.1	HUT	3000x3000	1.14	1.35	0.84	133.24
sim_sq30tr	7.E-06	7.E-06	0.03	0.18	0.1	HUT	3000x3000	1.54	1.62	0.95	208.07
sim_sq31tr	7.E-06	7.E-06	0.03	0.35	0.1	HUT	3000x3000	1.57	1.63	0.96	215.32
sim_sq32tr	7.E-06	7.E-06	0.03	0.5	0.1	HUT	3000x3000	1.57	1.62	0.97	217.65

APPENDIX A. SYNTHETIC MODELS

Table A.10: Parameters and main outputs of synthetic models (group 2), part 5

Models	K_{bedrock} [m/s]	K_{alluvial} [m/s]	RS [-]	HS [-]	p_{bedrock} [-]	Prec.	aspect-ratio [m _x m]	Q95 [mm/d]	Q50 [mm/d]	Q95/Q50 [-]	Dyn. V [mm]
sim_lg1tr	1.E-07	1.E-07	0.03	0.05	0.1	HUT	1000x12000	0.07	0.67	0.12	5.91
sim_lg2tr	1.E-07	1.E-07	0.03	0.18	0.1	HUT	1000x12000	0.24	0.78	0.33	18.65
sim_lg3tr	1.E-07	1.E-07	0.03	0.35	0.1	HUT	1000x12000	0.56	0.99	0.58	65.99
sim_lg4tr	1.E-07	1.E-07	0.03	0.5	0.1	HUT	1000x12000	0.80	1.12	0.72	101.35
sim_lg5tr	1.E-06	1.E-06	0.03	0.05	0.1	HUT	1000x12000	0.41	0.88	0.49	27.55
sim_lg6tr	1.E-06	1.E-06	0.03	0.18	0.1	HUT	1000x12000	1.23	1.42	0.87	145.75
sim_lg7tr	1.E-06	1.E-06	0.03	0.35	0.1	HUT	1000x12000	1.44	1.58	0.91	185.15
sim_lg8tr	1.E-06	1.E-06	0.03	0.5	0.1	HUT	1000x12000	1.44	1.58	0.92	195.68
sim_lg9tr	1.E-05	1.E-05	0.03	0.05	0.1	HUT	1000x12000	1.26	1.58	0.80	162.20
sim_lg10tr	1.E-05	1.E-05	0.03	0.18	0.1	HUT	1000x12000	1.36	1.61	0.85	196.98
sim_lg11tr	1.E-05	1.E-05	0.03	0.35	0.1	HUT	1000x12000	1.42	1.61	0.89	207.39
sim_lg12tr	1.E-05	1.E-05	0.03	0.5	0.1	HUT	1000x12000	1.44	1.60	0.90	195.77
sim_lg13tr	1.E-04	1.E-04	0.03	0.05	0.1	HUT	1000x12000	1.29	1.57	0.83	144.16
sim_lg14tr	1.E-04	1.E-04	0.03	0.18	0.1	HUT	1000x12000	1.39	1.62	0.86	174.03
sim_lg15tr	1.E-04	1.E-04	0.03	0.35	0.1	HUT	1000x12000	1.46	1.64	0.90	208.70
sim_lg16tr	1.E-04	1.E-04	0.03	0.5	0.1	HUT	1000x12000	1.47	1.61	0.91	222.34
sim_lg17tr	4.E-07	4.E-07	0.03	0.05	0.1	HUT	1000x12000	0.19	0.72	0.29	12.33
sim_lg18tr	4.E-07	4.E-07	0.03	0.18	0.1	HUT	1000x12000	0.75	1.12	0.68	91.28
sim_lg19tr	4.E-07	4.E-07	0.03	0.35	0.1	HUT	1000x12000	1.20	1.38	0.88	144.80
sim_lg20tr	4.E-07	4.E-07	0.03	0.5	0.1	HUT	1000x12000	1.28	1.46	0.88	175.54
sim_lg21tr	7.E-07	7.E-07	0.03	0.05	0.1	HUT	1000x12000	0.30	0.80	0.41	19.03
sim_lg22tr	7.E-07	7.E-07	0.03	0.18	0.1	HUT	1000x12000	1.06	1.29	0.82	126.46
sim_lg23tr	7.E-07	7.E-07	0.03	0.35	0.1	HUT	1000x12000	1.38	1.50	0.92	170.34
sim_lg24tr	7.E-07	7.E-07	0.03	0.5	0.1	HUT	1000x12000	1.45	1.58	0.92	197.56
sim_lg25tr	4.E-06	4.E-06	0.03	0.05	0.1	HUT	1000x12000	1.13	1.40	0.81	122.05
sim_lg26tr	4.E-06	4.E-06	0.03	0.18	0.1	HUT	1000x12000	1.41	1.61	0.88	187.88
sim_lg27tr	4.E-06	4.E-06	0.03	0.35	0.1	HUT	1000x12000	1.45	1.59	0.91	200.25
sim_lg28tr	4.E-06	4.E-06	0.03	0.5	0.1	HUT	1000x12000	1.45	1.59	0.91	189.83
sim_lg29tr	7.E-06	7.E-06	0.03	0.05	0.1	HUT	1000x12000	1.31	1.62	0.81	156.68
sim_lg30tr	7.E-06	7.E-06	0.03	0.18	0.1	HUT	1000x12000	1.42	1.65	0.86	194.18
sim_lg31tr	7.E-06	7.E-06	0.03	0.35	0.1	HUT	1000x12000	1.46	1.64	0.90	203.13
sim_lg32tr	7.E-06	7.E-06	0.03	0.5	0.1	HUT	1000x12000	1.47	1.62	0.91	193.44

Appendix B

Characteristics of the 22 Swiss catchments (Chapter 3)

Table A1: 22 Swiss catchments: meteorological data

Catchment	P mean [mm/y]	ET [mm/y]	P-ET [mm/y]	ET/P [-]	ratio dry days [-]	PDC_a [-]	PDC_b [-]	PDC_k [-]
Aach	1045	578	467	1.81	0.08	60.64	-10.81	0.31
Alp	2014	369	1645	5.46	0.08	105.46	-29.40	0.23
Biber	1879	478	1400	3.93	0.07	99.08	-25.83	0.24
Broye	1205	569	637	2.12	0.08	67.33	-14.58	0.28
Glatt	1542	529	1013	2.91	0.07	81.55	-17.65	0.28
Goldach	1436	539	897	2.67	0.08	77.95	-15.86	0.29
Guerbe	1284	508	776	2.53	0.06	70.27	-15.14	0.28
Ilfis	1708	546	1163	3.13	0.07	89.77	-26.07	0.22
Langeten	1322	571	751	2.31	0.07	70.67	-16.66	0.26
Luthern	1319	582	737	2.27	0.07	69.91	-17.99	0.25
Mentue	1086	589	497	1.84	0.09	64.12	-10.75	0.33
Murg Waengi	1351	557	794	2.43	0.11	72.49	-16.36	0.27
Murg Frauenfeld	1249	566	683	2.21	0.07	67.43	-14.43	0.28
Murg Walliswil	1235	585	650	2.11	0.07	66.09	-15.98	0.26
Necker	1755	513	1242	3.42	0.07	91.26	-21.35	0.26
Rappengraben	1676	610	1066	2.75	0.08	88.31	-22.99	0.24
Rietholzbach	1545	562	983	2.75	0.08	82.13	-19.71	0.26
Sellenbodenbach	1234	571	663	2.16	0.08	78.44	-18.98	0.26
Sense	1444	491	953	2.94	0.05	66.82	-14.47	0.28
Sitter	1731	478	1253	3.62	0.06	77.24	-19.64	0.25
Sperbelgraben	1664	610	1054	2.73	0.08	88.61	-23.49	0.24
Wigger	1220	577	643	2.12	0.06	87.90	-21.99	0.25

APPENDIX B. SWISS CATCHMENTS

Table A2: 22 Swiss catchments: general, geometrical and topographical data

Catchment	Area [km ²]	Elevation [m]	Max. elev. diff. [m]	Total vol by surface [m]	Max. L to outlet [km]	Aspect ratio [-]	River network density [L^{-1}]	% 1st order stream [L^{-1}]	TWI mean [L^{-1}]	Mean slope [%]	Max. slope [%]	Smallest stream slope [%]	Main river slope [%]
Aach	47.38	467	154	61	11	0.39	2.26	44.95%	11.61	3.00	20.07	2.15	1.58
Alp	46.71	1158	1015	318	15	0.21	1.63	54.66%	9.55	15.30	75.34	16.64	2.67
Biber	31.91	1003	658	178	8	0.50	1.78	55.04%	9.87	11.20	42.59	12.46	3.19
Broye	415.93	715	1055	275	40	0.26	2.07	49.32%	10.52	6.60	63.00	7.82	2.00
Glatt	16.72	830	369	151	6	0.46	1.83	52.24%	9.44	10.30	38.49	11.24	5.01
Goldach	50.41	832	839	434	14	0.26	2.05	52.14%	9.48	10.90	54.66	13.61	8.66
Guerbe	116.15	847	1619	329	18	0.36	2.14	49.34%	10.26	12.00	69.89	12.96	1.21
Ilfis	187.45	1039	1403	354	18	0.58	1.80	56.74%	8.97	16.60	67.35	19.19	4.49
Langeten	59.92	760	488	163	10	0.60	1.92	42.15%	9.80	8.30	42.53	10.19	3.75
Luthern	104.68	750	901	256	16	0.41	1.95	52.08%	9.65	10.00	65.00	12.47	5.22
Mentue	105.30	675	478	230	20	0.26	2.09	46.45%	10.64	5.30	49.74	7.36	7.63
Murg Waengi	80.15	652	555	187	9	0.99	2.08	48.66%	10.06	8.90	58.20	11.54	2.06
Murg Frauenfeld	213.30	597	631	207	25	0.34	2.04	44.07%	10.40	7.70	58.20	8.87	2.09
Murg Walliswil	183.36	653	666	234	25	0.29	1.95	36.12%	10.13	7.80	42.53	7.30	1.94
Necker	88.10	956	913	350	17	0.30	1.81	56.88%	9.28	13.90	70.11	15.79	5.32
Rappengraben	0.61	1142	245	146	1	0.61	0.10	77.98%	8.39	18.00	40.61	21.95	15.97
Rietholzbach	3.19	793	245	111	2	0.80	1.38	72.04%	9.35	11.10	40.98	9.32	11.79
Sellenbodenbach	10.40	608	312	93	5	0.42	2.16	47.53%	10.67	4.80	35.73	6.80	2.06
Sense	351.17	1072	1626	521	25	0.56	1.84	54.80%	9.54	14.00	74.04	14.78	2.94
Sitter	261.07	1043	1850	466	18	0.81	1.83	56.96%	9.38	14.70	75.91	14.54	8.73
Sperbelgraben	0.56	1070	258	159	1	0.56	0.00	66.36%	8.45	18.50	42.13	22.62	14.22
Wigger	366.19	656	969	230	25	0.59	2.05	46.99%	10.25	8.60	65.00	10.06	0.80

APPENDIX B. SWISS CATCHMENTS

Table A3: 22 Swiss catchments: soil and land data

Catchment	% rural	% urban	% various	% forest	Depth	Wetness	Permeability	Storage capacity	Structure
	[%]	[%]	[%]	[%]					
Aach	73.88%	5.86%	0.00%	20.26%	4.39	2.30	3.53	5.17	2.42
Alp	37.42%	1.69%	1.70%	59.19%	3.19	2.34	3.07	3.63	2.94
Biber	56.68%	0.00%	0.00%	43.32%	3.26	1.97	3.11	3.71	2.42
Broye	75.02%	1.42%	0.00%	23.55%	4.49	1.56	4.39	4.78	2.24
Glatt	84.32%	10.96%	0.00%	4.73%	3.75	2.20	3.10	4.40	2.15
Goldach	68.43%	6.13%	0.00%	25.44%	4.11	2.23	3.74	4.83	2.63
Guerbe	75.44%	0.69%	0.59%	23.29%	3.99	1.77	4.25	4.29	2.59
Ilfis	35.33%	0.05%	0.78%	63.84%	3.79	1.90	4.27	3.95	3.18
Langeten	80.83%	1.28%	0.00%	17.89%	4.70	2.04	4.27	4.68	2.51
Luthern	70.23%	0.00%	0.00%	29.77%	4.56	1.86	4.66	4.51	2.49
Mentue	76.85%	0.00%	0.00%	23.15%	4.76	1.00	4.76	4.76	2.23
Murg Waengi	64.43%	6.02%	0.00%	29.55%	4.29	2.24	3.63	4.51	2.88
Murg Frauenfeld	65.91%	5.62%	0.00%	28.47%	4.39	2.29	3.75	4.61	2.79
Murg Walliswil	70.11%	3.73%	0.00%	26.16%	4.73	1.91	4.42	4.56	2.14
Necker	70.75%	0.00%	0.00%	29.25%	4.07	2.24	3.76	4.73	2.87
Rappengraben	0.00%	0.00%	0.00%	100.00%	4.00	2.00	5.00	4.00	3.00
Rietholzbach	100.00%	0.00%	0.00%	0.00%	4.00	2.71	3.00	4.71	3.00
Sellenbodenbach	83.18%	7.26%	0.00%	9.57%	4.70	2.19	3.80	4.94	2.80
Sense	64.57%	0.22%	1.31%	33.91%	3.83	1.86	4.01	3.97	2.63
Sitter	72.24%	1.42%	3.54%	22.81%	3.64	2.21	3.71	4.16	2.88
Sperbelgraben	0.00%	0.00%	0.00%	100.00%	4.00	2.00	5.00	4.00	3.00
Wigger	72.33%	1.84%	0.21%	25.62%	4.55	1.93	4.45	4.51	2.59

Table A4: 22 Swiss catchments: geological data

Catchment	% 2D prod. aq	Tot. quat. vol. by surface	Prod. quat. vol. by surface	% Prod quat. vol	Quat. slope	Bedrock K	% sandstone	% Fan	%Sub. Molasse	% Fine grained
	[%]	[m]	[m]	[%]	[%]	[m/s]	[-]	[-]	[-]	[-]
Aach	13.00%	43.67	0.38	0.62%	10.32	5.05E-08	0	0.5	0	0.5
Alp	16.00%	8.51	0.99	0.31%	14.11	1.00E-06	0	0	1	0
Biber	6.00%	11.48	0.76	0.43%	8.28	7.25E-07	0	0.25	0.7	0.05
Broye	6.00%	9.58	1.29	0.47%	10.74	1.14E-05	0.27	0.05	0.46	0.22
Glatt	0.00%	3.73	0.00	0.00%	NA	1.00E-07	0	1	0	0
Goldach	1.00%	8.70	0.28	0.07%	7.18	9.78E-06	0.3	0.45	0.25	0
Guerbe	16.00%	20.26	5.02	1.53%	13.61	2.12E-05	0.66	0	0.34	0
Ilfis	7.00%	8.10	0.96	0.27%	19.82	1.90E-07	0	0.9	0.1	0
Langeten	21.00%	8.92	2.95	1.81%	18.72	1.74E-05	0.55	0	0	0.45
Luthern	17.00%	4.09	0.66	0.26%	11.95	2.06E-05	0.65	0.2	0	0.15
Mentue	1.00%	6.06	0.00	0.00%	15.41	9.49E-06	0.3	0	0	0.7
Murg Waengi	14.00%	11.15	3.80	2.04%	11.53	1.00E-07	0	1	0	0
Murg Frauenfeld	19.00%	12.51	3.59	1.74%	10.63	1.59E-08	0	0.15	0	0.85
Murg Walliswil	22.00%	5.83	4.07	1.74%	10.59	2.23E-05	0.70	0	0.07	0.23
Necker	2.00%	5.09	0.00	0.00%	21.01	5.50E-07	0	0.5	0.5	0
Rappengraben	0.00%	7.30	0.00	0.00%	NA	1.00E-07	0	1	0	0
Rietholzbach	0.00%	3.31	0.00	0.00%	NA	1.00E-07	0	1	0	0
Sellenbodenbach	0.00%	3.44	0.01	0.01%	5.98	1.00E-09	0	0	0	1
Sense	7.00%	5.94	0.86	0.17%	15.95	2.55E-05	0.8	0	0.2	0
Sitter	2.00%	6.28	0.01	0.00%	8.94	3.86E-06	0.1	0.23	0.67	0
Sperbelgraben	0.00%	7.17	0.00	0.00%	NA	1.00E-07	0	1	0	0
Wigger	19.00%	8.94	2.02	0.88%	9.07	1.96E-05	0.62	0.08	0	0.3

APPENDIX B. SWISS CATCHMENTS

Table A5: 22 Swiss catchments: discharge statistics, average values for the period of 01.01.1993-31.12.2012

Catchments	Q mean	Q5	Q10	Q30	Q50	Q70	Q90	Q95	Q5/Qmean	Q5/Q50	Q95/Qmean	Q95/Q50	Q95/Q5	k of FDC
	[mm/d]	[mm/d]	[mm/d]	[mm/d]	[mm/d]	[mm/d]	[mm/d]	[mm/d]	-	-	-	-	-	-
Aach	1.37	4.32	2.90	1.29	0.75	0.47	0.29	0.24	3.15	5.75	0.18	0.32	0.06	0.43
Alp	4.19	13.90	9.31	3.95	2.28	1.48	0.92	0.79	3.32	6.10	0.19	0.35	0.06	0.43
Biber	3.01	10.62	6.88	2.77	1.48	0.91	0.53	0.44	3.52	7.17	0.14	0.29	0.04	0.48
Broye	1.58	4.88	3.28	1.52	0.94	0.64	0.40	0.35	3.09	5.17	0.22	0.37	0.07	0.38
Glatt	3.04	9.33	6.17	2.85	1.80	1.29	0.92	0.82	3.07	5.18	0.27	0.45	0.09	0.45
Goldach	2.44	7.73	5.24	2.42	1.40	0.86	0.50	0.41	3.17	5.51	0.17	0.29	0.05	0.36
Guerbe	1.97	4.87	3.57	2.06	1.44	1.08	0.79	0.68	2.47	3.37	0.35	0.47	0.14	0.22
Ilfis	2.47	6.79	4.84	2.55	1.64	1.12	0.76	0.66	2.74	4.14	0.27	0.40	0.10	0.29
Langeten	1.78	3.56	2.80	1.86	1.45	1.22	1.00	0.93	2.00	2.45	0.52	0.64	0.26	0.20
Luthern	1.23	3.13	2.27	1.26	0.86	0.63	0.45	0.41	2.54	3.63	0.33	0.48	0.13	0.29
Mentue	1.28	3.64	2.46	1.26	0.82	0.55	0.35	0.31	2.84	4.41	0.24	0.37	0.09	0.34
Murg Waengi	1.98	5.47	4.06	2.03	1.31	0.92	0.61	0.54	2.76	4.17	0.27	0.41	0.10	0.27
Murg Frauenfeld	1.62	4.45	3.26	1.61	1.06	0.74	0.50	0.44	2.74	4.21	0.27	0.42	0.10	0.32
Murg Walliswil	1.57	3.19	2.48	1.63	1.29	1.08	0.89	0.83	2.03	2.47	0.53	0.64	0.26	0.20
Necker	3.21	10.48	6.94	3.09	1.84	1.14	0.63	0.52	3.27	5.68	0.16	0.28	0.05	0.37
Rappengraben	2.98	10.02	6.59	2.91	1.58	0.97	0.52	0.40	3.36	6.33	0.14	0.26	0.04	0.39
Rietholzbach	2.86	10.13	6.38	2.59	1.45	0.90	0.47	0.38	3.54	6.98	0.13	0.26	0.04	0.45
Sellenbodenbach	1.81	5.64	3.74	1.57	0.95	0.60	0.37	0.29	3.12	5.94	0.16	0.31	0.05	0.48
Sense	2.10	5.94	4.12	2.15	1.43	0.99	0.67	0.59	2.83	4.15	0.28	0.41	0.10	0.28
Sitter	3.40	10.65	7.08	3.39	2.04	1.30	0.80	0.67	3.13	5.21	0.20	0.33	0.06	0.35
Sperbelgraben	2.54	7.65	5.37	2.64	1.55	1.00	0.62	0.52	3.01	4.94	0.21	0.34	0.07	0.31
Wigger	1.33	2.94	2.27	1.39	1.03	0.80	0.61	0.55	2.22	2.87	0.42	0.54	0.19	0.22