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Analyzing hydrological recession behavior using plant phenology

ESS 511 Master's Thesis

Author
Hannes Tobler
13-754-999

Supervised by
Dr. Maria Staudinger

Faculty representative
Prof. Dr. Jan Seibert

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Department of Geography, University of Zurich

University of Zurich[UZH]

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Author: Hannes Tobler [13-754-999]
Master of Earth System Science
(hannes.tobler@uzh.ch)

Supervisor: Dr. Maria Staudinger

Prof. Jan Seibert

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Abstract

Hydrological droughts can have various effects on our daily lives (e.g. drinking water supplies, irrigation, transportation, hydropower, and aquatic ecosystem services) and occur in all regions albeit in varying degrees of severity. Research on recession behavior therefore was and always will be close to the real socio-cultural, economic, and environmental problems. Base flow represents the delayed portion of flow that comes from groundwater or other types of long-term storage in periods with no recharge. The recession curve of this delayed portion of flow reveals an individual and characteristic behavior. That behavior is dictated by geophysical properties and other influences in the catchment. One of them is the seasonal changing impact of vegetation. In this thesis, the influence of the active and the dormant plant season on recession behavior is analyzed with both time varying and location-specific plant phenological data. The research areas are two small Swiss catchments: The Allenbach catchment in the Bernes Alps and the Murg catchment in the eastern Swiss midlands. Visible differences in the log-log recession scatterplots and the calculated recession constant values of base flow recession were used to assess recession behavior. The annual subdivision into seven phenological season with annually changing (flexible) on- and offset dates provided an accurate insight of changing recession behavior. The discovered tendency of higher recession rates during the active season of vegetation is consistent with literature by Federer (1973), Trainer & Watkins (1974), and Czikowsky & Fitzjarrald (2004). In addition, several differences in hydrological characteristics between the alpine and the low altitude catchment and between different division approaches into the active and the dormant season have been detected. Plant phenology reveals limitations in the autumn season. Therefore, research with abiotic or animal related phenological data could improve the assessment of the autumn transition season and therefore enable improved recession behavior analyses.

Keywords: catchment hydrology, base flow, low flow, interflow, recession behavior, recession constant, master recession, plant phenology, phenological season, evapotranspiration

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Table of abbreviations

E	=	evapotranspiration
S	=	storage
P	=	precipitation
Q	=	discharge
R_C	=	recession constant
FOEN	=	Federal Office for the Environment
masl	=	meters above sea level
SWE	=	Snow water equivalent

1. Introduction

The interest in low flow recession behavior in modern times can be traced back to at least the 1840s and the survey *De la pluie et de l'influence des forets sur la cours d'eau* conducted by the French hydrologist M. Dausse in 1842 (Hall, 1968). Dausse and his colleagues in the intellectual circle of postrevolutionary France were concerned about the increasing problems related to stream pollution and their consequences, especially during drought periods. Artificial ponds were not considered to be productive because they also suffered from pollution. At that time, France was experiencing a phase of high and obvious deforestation (Bren, 2016). Dausse, as an early member of the "forest sponge" school, considered the best solution was to concentrate efforts into the investigation, development, and protection of the streams' sources (Hall, 1968).

Dausse's school viewed the forest as analogous to a sponge, and this is sometimes also referred to as the "Law of Dausse." According to this law, rain falls in greater abundance over forested areas because the air over forests is colder and more humid compared to the air over open land. Dausse believed that summer runoff (the draining water from a catchment) was both heightened and more evenly distributed from catchments with intact forests compared to the deforested catchments. Over time, this message was codified into "trees bring rain" (Bren, 2016). The "forest sponge" idea has, therefore, significantly affected public perceptions "forest generate runoff" up to the present time. Satellite data have recently confirmed that the air over forests is indeed colder compared to agricultural land. However, the link to higher amounts of precipitation is difficult to verify, hence, future research utilizing increasingly high resolution technologies is planned (Bren, 2016).

Even if the "Law of Dausse" is now regarded as a half-truth and rather oversimplified, Dausse recognized a relationship between the biosphere and the hydrosphere early on. In addition, his propositions that during periods with no accretion all stream flow comes from storage and that forests represent important low flow generators established a common foundation for future hydrologists. Since that time, the study of low flow has come a long way, developed by hydrologists all over the world. At times, these hydrologists worked in close contact with each other, while at other times they had no knowledge of the progress each was making (Hall, 1968). The long period of time that this subject has been under investigation can be distinguished by the variety of names that exist for this phenomenon. Low flow, groundwater flow, dry-weather flow, sustained flow, drought flow, and base flow are just a handful of the different terms (Brutsaert & Nieber, 1977; Brutsaert & Sugita, 2008; Hall, 1968). In the following, I use the term "base flow" to represent this phenomenon.

1.1 Motivation

As in the case of Dausse, research on base flow behavior was and always will be close to the real sociocultural, economic, and environmental problems of the time and region. Hydrological droughts can have various effects on very different aspects of our daily lives: for example, drinking water supplies, irrigation, transportation, hydropower, the cooling of nuclear power plants, reservoir storage design, aquatic ecosystem services, and water quantity and quality for recreation as well as wildlife conservation (Ghosh et al., 2016; Smakhtin, 2001; Staudinger et al., 2011; Tallaksen, 1995). Hydrological droughts occur in all regions albeit in varying degrees of severity (Staudinger et al., 2011).

Accurate assessments of recession behavior promise manifold opportunities in various domains (e.g. irrigation strategy, site preservation, and inland water transport). Discharge represents the only measurement that is aggregated for the entire catchment. Therefore, it can provide an enhanced understanding of related physical characteristics such as evapotranspiration (E), aquifer parameters, storage size quantifications, and soil properties at the catchment scale (Ghosh et al., 2016; Kirchner, 2009; Krakauer & Temimi, 2011).

I suspect that, for many people, the practical use of this scientific field is more easily recognizable than it is for other domains. In addition, base flow science is concerned with perhaps one of the most important resources for our future world, scarce water. As a result of the fears of an uncontrolled climate change pathway and the associated more frequent and severe drought events, the importance of base

flow research has recently increased once again. As an earth system scientist, I am extremely interested in the interactions of different spheres. Conducting research into the interdependence of plants (biosphere) and the water cycle (hydrosphere) was, therefore, an obvious study option.
Hereinafter, the introduction is dedicated to explaining important terms and interrelations between hydrological recession behavior and plant phenology. Afterwards, the research question, the two research areas, and methods will be introduced in detail, followed by the presentation of the results in Chapter 5 & 6. Finally, the results will be discussed and concluded with a brief outlook for potential future research questions.

1.2 Catchment hydrology

Hydrological analysis on a catchment scale often begins with the conservation of mass equation:

Equation 1 $$\frac{dS}{dt} = P - E - Q,$$

where $\frac{dS}{dt}$ represents the change of the water volume stored (S) in the catchment over time. Precipitation (P) is assumed to be the only water input into the system, and E and Q are the rates of E and discharge, respectively, and are the only water fluxes out of the catchment area. All of these components – S, P, E, and Q – are functions over time and understood to be averaged over the entire catchment. In addition, P and E are point measurements, which than are interpolated and extrapolated for the entire catchment area. For this reason, these calculation steps are often the source of errors since both quantities vary considerably in space and time. The same is true of storage measurements, for example, by piezometer wells and soil moisture probes. They are highly localized and orders of magnitude smaller than the catchment they are attempting to represent. Discharge is the only variable in the equation that can be measured at one point but represents the processes of the entire catchment (Kirchner, 2009).
During rain events, there is normally more influx than outflux into the system (P > E + Q). Consequently, the storage fills up. During times with no recharge, the gradual depletion of the storage ($\frac{dS}{dt}$) can be the only source of water for Q and E, therefore, Q and E depend on the level of S during rainless periods (Kirchner, 2009). Realistically, however, there is not one storage area in a catchment but rather a plurality of them. Some of these storage areas change their levels quickly, while others react in a delayed manner. When it starts to rain, the first raindrops are normally intercepted by vegetation or percolate into the top layer of soil and compensate for soil moisture deficits. During an abundant rain event, all the storage areas that respond rapidly (soil, surfaces) are brimming, and overland flow as well as interflow contribute significantly to discharge. At that point, only the more slowly reacting groundwater bodies will absorb some more of the rain. Effective rainfall is the portion of rain that contributes to discharge, while the rest is so-called lost rainfall. Lost rainfall fills up the remaining storage areas or evaporates on the wet surfaces. The portion of effective rainfall reaches the stream channel quickly and can be detected at the gauging station. As the rain event proceeds, the proportion of effective rain increases and the portion of lost rain decreases. After a series of heavy rain events, all the storage areas are finally filled and additional rain will contribute directly to discharge as quick overland flow and interflow (Shaw M. Elizabeth, 1994).
Eventually peak discharge ($\frac{dQ}{dt} = 0$) is reached, this typically happens at the end of the rainfall event. However, the timing of peak discharge is also related to the distance from the gauging station to the area of intense rain. At the point of peak discharge, the recession of the stream discharge begins because ($\frac{dS}{dt}$ + P < E + Q) is now true (Kirchner, 2009). Pure overland flow finishes relatively soon after it stops raining. Beyond this point, water originates largely from water temporarily stored in the soil. That so-called inter-, or subsurface flow dominates the recession in the first days after peak discharge (Shaw M. Elizabeth, 1994; Staudinger et al., 2011). Overland flow and interflow are often summarized as quick flow and are composed of the effective rainfall. After a certain time, the quick flow converges to zero

and the base flow dominates runoff again (Shaw M. Elizabeth, 1994). Consequently, the associated recession behavior after a rain event of a certain magnitude passes through at least two stages, and every stage has its own characteristic recession rate (Smakhtin, 2001). The last phase of the recession curve is called base flow, therefore, base flow characteristics can only be studied during dry weather conditions (Ghosh et al., 2016; Hall, 1968). Distinguishing between surface flow, interflow, and base flow is difficult because there are no general rules on how to ascertain the boundaries between them. However, different techniques to distinguish baseflow from the rest of the recession curve have been extensively reviewed by Hall (1968), Tallaksen (1995), and Smakhtin (2001).

1.3 The recession curve on the hydrograph

The hydrograph is constructed with continuous Q values, recorded at the gauging station of the catchment over time. Hydrographs are graphical visualizations of Q time series measured at fixed time intervals. Hence, hydrographs are integrations of temporal and spatial variations in water input, transfer and storage processes. For this reason, the magnitude and shape of the hydrograph reveals information concerning hydrological processes and characteristics within the catchment (Hannah et al., 2000). By focusing on the declining part of the hydrograph one investigates recession behavior.

The associated curve of the recession on a hydrograph is called a recession curve and shows the characteristic decay of Q after a rain event (Krakauer & Temimi, 2011; Smakhtin, 2001). Graphical analyses of different flow components have been applied by many hydrologists and are well established (Tallaksen, 1995). The different flow paths of water with different associated residence times yield varying rates and, therefore, different slopes during a recession event. To account for the different pathways, the recession can be separated into the linear components of the different types of flows (surface, inter-, and base flow). Another way of identifying the sources and pathways of runoff can also be derived from chemical parameters and environmental isotopes (Tallaksen, 1995).

Recession behavior and, consequently, the shape of the recession curve depend primarily on the geological properties of the catchment. In addition, the variability in initial conditions of the storage areas will also result in different shapes among recession curves (Rupp & Selker, 2006). However, there are other factors (natural or artificial) that also affect the shape. All these influences together yield a unique recession curve for every specific catchment (M. Stoelzle et al., 2013). The recession curve may also often change throughout the year because of higher water use during summer from vegetation and humans, for example (Federer, 1973).

1.3.1 The master recession curve

The master recession curve represents a special instance of the recession curve. Master recessions have traditionally been constructed with graphical methods (Tallaksen, 1995). The master recession curve is defined as an envelope of recession curves of various individual recession events (Smakhtin, 2001). The three most commonly used methods are the matching strip method, the tabulating method, and the correlation method, and these have been described, among others, by Hall (1968) and Tallaksen (1995).

In the matching strip method, transparent overlays of all the recession curves are superimposed to obtain a master recession curve (Smakhtin, 2001). Hall (1968) theorized that this method is the easiest and quickest but is not very objective.

The tabulating method is similar to the matching strip method, but the recession periods are tabulated to the mean Q value from the individual record (Hall, 1968). Smakhtin (2001) claimed that the correlation method is likely to be the most objective approach. The current Q value is plotted against the Q value *n* days ago for all the base flow recession days. Typical numbers for *n* range between one and five days. With a large number of individual recessions, the envelope of the master recession curve can be defined in the region of their highest density (Smakhtin, 2001). The recession constant can be easy calculated from the linear recession equation. However, Hall (1968) stated that nonlinear curves cannot be handled so easily and, therefore, problems arise in practical use. The recession constant estimation from all three graphical methods remains rather subjective and some hydrologists have suggested that master recession curves do not provide an adequate representation of recession behavior (Smakhtin, 2001).

1.3.2 The recession constant

As mentioned in the previous section, the recession constant (R_C) can be estimated from the slope of the master recession curve (Smakhtin, 2001). The recession constant is, therefore, always a summary of many individual recession events. The recession constant represents an important and powerful hydrologic characteristic. If one has an accurate assessment of the recession constant, other hydrological quantities can be determined (Brutsaert & Nieber, 1977). The recession constant can be calculated directly from Q data in various ways; Equation 3 has been widely used by hydrologists in recent decades.

1.4 Base flow hydrology

In the literature, the definition of base flow provided by Hall (1968) is widely accepted and used by many hydrologists (Brutsaert & Nieber, 1977; Tallaksen, 1995). Hall described base flow as the delayed portion of flow that comes from groundwater or other types of long-term storage in periods with no recharge (Hall, 1968). Base flow is sometimes only considered to be groundwater depletion, but portions of melting glaciers, deep soil layers, marshes, river banks, and surface discharge from lakes can also form part of base flow (Smakhtin, 2001; M. Stoelzle et al., 2013). Base flow continues to decrease as long as there is no process that recharges its storage (mostly rain). However, because of the delayed response of aquifers to overland processes, the baseflow component of the hydrograph often continues to decrease even if a rain event is happening. Only if the event is productive enough for water to percolate down to the water table does the base flow division curve begin to rise. This rise then also lasts longer even when the quick flow is already beginning to decrease (Shaw M. Elizabeth, 1994).

Because the water in the stream channel travels orders of magnitude faster than through the aquifer or the other storage areas, the integral of the base flow is assumed to represent all upstream storage outflows. Assuming the base flow originates only from aquifers and the alteration of E is small (e.g., during night time), one can directly form conclusions about the geological nature of the catchment by analyzing the characteristics of the base flow at the gauging station (Brutsaert & Nieber, 1977). Conversely, by assuming the geological properties are constants, one can form conclusions about the diurnal or seasonal effects of plants on the quantity of E.

Base flow has numerous characteristics, which can be analyzed with discharge data measured at regular time intervals. The variability of annual base flow events, duration, magnitudes, the relative contributions of base flow or the rate of recession during rainless weather conditions are just a few of these characteristics (Smakhtin, 2001). In many catchments, base flow is a seasonal phenomenon. A drought, in contrast, is a natural event that arises from a rain deficit over an extended time period. However, human activity can also contribute to it. Hydrologists use different terms to describe drought, such as, meteorological or atmospheric, hydrological, agricultural, or socioeconomic droughts (Smakhtin, 2001). Base flow researchers study the hydrological dimension of drought events. Studying this dimension means that base flow conditions do not presume that there is a drought, but during a drought base flow conditions are a very common feature.

While the upper limit of the base flow is difficult to distinguish, the lower limit of the base flow is self-explanatory. If Q reaches zero, base flow is by force also at an end. Base flow hydrology typically differentiates between perennial and ephemeral streams. Perennial streams are normally active the entire year, whereas ephemeral streams normally dry up during a certain time of the year (Ghosh et al., 2016).

1.4.1 Base flow recession behavior

The basic mathematical equation governing water flow in an aquifer was introduced by Boussineq (1877). The nonlinear equation describes the depletion of a homogenous, unconfined rectangular aquifer without other disruptive factors and is difficult to solve precisely (Brutsaert & Nieber, 1977; Hall, 1968; Tallaksen, 1995). Boussineq linearized his equation by applying the "Dupuit assumptions." The Dupuit assumptions hold that groundwater discharge is proportional to the aquifer thickness, that groundwater flows horizontally, and that it is hydrostatical. By neglecting the effect of capillary forces above the groundwater table, the aquifer can be called a "Dupuit-Boussineq aquifer" (Brutsaert & Nieber, 1977). The linearized solution, first suggested by Boussineq (1877, 1903a), appears in the form of the heat diffusion equation and is used by many base flow recession researchers either in the original form [Equation 2] or in one of the two alternative forms [Equation 2a, 2b] (Brutsaert & Nieber, 1977; Hall, 1968).

Equation 2 $$\boldsymbol{Q = Q_0 \exp(-\alpha t)}$$
Equation 2a $$\boldsymbol{Q = Q_0 * R_c * t}$$
Equation 2b $$\boldsymbol{Q = Q_0 (10)^{-\beta t}},$$

where the recession constant R_c is equal to exp ($-\alpha$). Since its inception, many alternative processes to the primary Boussineq equation have emerged. Today, base flow recession is mathematically described by various recession equations (Smakhtin, 2001). The equations can be separated into two main groups: linear and nonlinear solutions (Tallaksen, 1995). Some hydrologists (e.g., Maillet, 1905) also assumed two components of base flow: one that declines nonlinearly and the other that has a constant behavior (Hall, 1968).
One of the most frequently cited equations for base flow recession analysis in the last few decades was initially presented by Brutsaert and Nieber (1977) and is also based on the Boussineq equation (Rupp & Selker, 2006; M. Stoelzle et al., 2013). This classical method analyzes the time rate of change in Q as a function of Q itself. To eliminate time as a reference, the negative decline in discharge (-dQ/dt) from two consecutive recession days is plotted versus the mean Q of the same time step ($Q = (Q_{t-1} + Q)/2$), suggesting the following power-law relationship:

Equation 3 $$\boldsymbol{-\frac{dQ}{dt} = a * Q^b},$$

where b is a constant and a is a function of the hydraulic properties of the aquifer. The unitless exponent b allows storage-outflow relationships that are linear ($b = 1$) and nonlinear ($b \neq 1$; (Rupp & Selker, 2006; M. Stoelzle et al., 2013). The value of the exponent b changes substantially from the initial recession to the late recession (Brutsaert & Nieber, 1977; Ghosh et al., 2016; Krakauer & Temimi, 2011; Palmroth et al., 2010). The values for b are physically reasonable from 3 in the early stage down to 1 in the late recession stage (long-term behavior; (Brutsaert & Nieber, 1977). The difference (-dQ/dt) and Q normally span over many orders of magnitude, therefore, the recession plots should be shown on a log-log scale. Logarithmic graphs of log(-dQ/dt) versus log(Q) show an approximately linear relationship with slope b and intercept a (Rupp & Selker, 2006). Many hydrological characteristics can be analyzed by recession plots of this power-law relationship (Brutsaert & Sugita, 2008; Ghosh et al., 2016). However, the description of catchment-specific base flow recession behavior remains challenging. First, one has to decide on the base flow extraction methods and second, a method that fits the power-law relationship has to be chosen (M. Stoelzle et al., 2013).

1.5 Base flow extraction methods

Extracting the base flow recession from a continuous flow record has proved to be difficult and includes subjective decisions from the researcher (Tallaksen, 1995). Stoelzle et al. (2013) found that the most consistent ranking of similarity in recession characteristics was ascertained within the same extraction method. The model-fitting method was found to be less critical than the extraction methods (M. Stoelzle et al., 2013). This finding means that choosing extraction procedures will always have a significant impact on recession constant results. This makes it all the more remarkable that base flow separation techniques are described as being arbitrary (Smakhtin, 2001; M. Stoelzle et al., 2013). There are many ways to extract the base flow recession from a continuous flow record, and I presume that the same techniques do not produce equally good solutions in different catchments.

The only widely accepted but obvious rule is that streamflow does not rise during a recession period (Tallaksen, 1995). The start of the base flow recession segment can take the form of a constant or a variable, which can include one or more condition terms (Tallaksen, 1995). A constant is a fixed value defined before the analysis. The mean annual runoff or median flow, for example, can be set as an upper fixed threshold to base flow (Smakhtin, 2001). The Q value a certain time after rainfall or peak discharge is an example of a variable starting value. The Q value at the starting point will then differ for each event (Tallaksen, 1995). Another widely used criterion is the length that a base flow event must have. Similarly to the declaration of the starting point, this criterion can be a constant or a variable. Tallaksen (1995) stated that a minimum length of four to 10 days is usually chosen. However, the minimum duration also has to be based on the climatic conditions in the catchment area (Tallaksen, 1995). Other extraction criteria are the amount of rain from a previous event, rainfall during a recession event, or the maximum decline rates of Q (Ghosh et al., 2016; Vogel & Kroll, 1992). All the listed extraction criteria can be used alone or in combination (Tallaksen, 1995). However, the rich selection of extraction methods and the rather subjective choice of threshold values within each method can lead to results that are difficult to compare (Stoelzle, Stahl and Weiler, 2013).

1.6 Influencing processes on base flow hydrology

Catchments represent a series of interlinked reservoirs. Recharge on a catchment scale is highly dependent on precipitation, but storage and depletion are often complex functions of physiographic characteristics. During dry conditions, the processes that influence base flow are usually in close range to the stream channel. Conversely, the influences on hydrological processes during periods with high Q are often distributed over the entire catchment area (Smakhtin, 2001). The factors and processes of base flow can be divided into two groups: those that pose gains and those that pose losses to the base flow. In addition, I have also distinguished between natural and anthropogenic influences.

1.6.1 Natural influences on base flow

Some of the natural factors that influence base flow hydrology are hydraulic characteristics and the size of the aquifers, the rate and frequency of recharge and distribution, the infiltration characteristics of the soils, the distribution of vegetation types, topography, and climate (Smakhtin, 2001).

Most natural gains originate from releases of groundwater storage areas into the stream channel. To maintain a sustainable flow of water to the stream, the aquifer must be recharged with adequate amounts of water during wet periods, the size and hydraulic properties must be sufficient to maintain flows during the entire length of the dry period, and the water table must be shallow enough to intersect with the stream. Natural springs are another source of water, especially in mountainous regions. The volume of this outflow depends on the size and density of the fractures. Springs can provide water even if the water table is well below the stream level. It is clear that catchment geology greatly influences the base flow generating mechanism (Smakhtin, 2001).

Meyer et al. (2011) linked the range of unequal relative portions of base flow across the Swiss Plateau region to the variability of local geological conditions. Further, the relatively large portion of base flow found in the Jura regions can be explained by the influence of the karstic aquifers of the Jura mountain range (Kohn et al., 2019). Other base flow gains are derived from wetted channel bank soils, marshes, and alluvial valley fills. Strictly speaking, such gains are not really from groundwater bodies, but they often outlast dry periods and contribute to base flow, especially in humid climates. Furthermore, in mountainous regions a substantial amount of the base flow may originate from snow and glaciers. Only when the specific components of base flow are clearly distinguished can a better understanding of the individual processes and factors of base flow occur (Kohn et al., 2019; Michael Stoelzle et al., 2015). Storage depletion from glaciers and lakes are good examples of factors that compensate for fluctuations during base flow conditions and, thus, conceal the true magnitude of groundwater flow. In semi-arid environments, a distinction between groundwater depletion and other base flow factors is usually easier to make (Smakhtin, 2001).

In contrast, the most important factors and processes responsible for base flow losses are direct evaporation from all open waterbodies and wetlands, bed losses, losses to the dry soils surrounding the stream banks (enhanced by evaporation caused by riparian vegetation), and groundwater recharge where the phreatic groundwater table lies below the channel surface and the water of the stream seeps through the river banks (Smakhtin, 2001). Apart from information from a few well studied catchments, the relative importance of the "transmission losses" often remains unknown and is, therefore, part of ongoing base flow research (Smakhtin, 2001).
In cold regions, there are additional losses of base flow that are not well understood or quantified yet. Losses from ice cover formation and the phase changes of permafrost moisture can lead to intense winter base flow events in mountainous streams. In addition, winter precipitation is stored in the snow cover and does not contribute to Q until spring or mild winter temperatures. Because of the wide variety of geological, climatic, and topographical conditions, determining the gains and losses to base flow is sometimes very difficult and the literature on it is rather limited (Smakhtin, 2001).

1.6.2 Anthropogenic influences on base flow

Wherever people settle they need some sort of water supply. Groundwater abstraction affects the level of the groundwater table, which can have far-reaching consequents. The disruption of the hydraulic gradients and the shortening of the channel intersecting with the phreatic surface can lead to the substantial environmental degradation of aquatic habitats further downstream. Artificial drainage for agriculture and building reduces the storage capacity of the valley bottom and, therefore, enhances the magnitude of flood and base flow events. Artificial changes to vegetation as well as farming on riparian soils modifies the level of E and, hence, alters the base flow losses (Smakhtin, 2001).
Afforestation is another factor that can greatly influence the hydrology of a catchment. Contrary to the assumptions of the "forest sponge" theory in the 19th century, afforestation was identified as significantly reducing not only total flow but also base flow. In fact, afforestation reduces base flow volumes to a greater degree than those of annual flow (Smakhtin, 2001). The processes that are responsible for that effect are increased interception and transpiration losses due to more leaf area and the buildup of biomass, and the disturbance of the soil structure and properties in the course of site preparation. However, the influence from afforestation on base flow also changes in conjunction with the different stages of the forest cycle (tree planting, growth, clearing). Studies showed that after clear felling the total flow and the base flow increased (Smakhtin, 2001). In catchments with large populations, the effect of floor sealing influences the rate of storage accumulation during rainfall events and, consequently, decreases the rate of Q from groundwater into streams during dry periods (Smakhtin, 2001).
The factors and processes listed so far represent the indirect influence of human activities on base flow. However, direct river abstraction for industry, agriculture, or municipal purposes must not be overlooked. Water withdrawals have a pronounced effect during dry weather conditions and lead to the increased frequency of low river flow. Effluents from industrial, municipal, and agricultural areas usually significantly affect the water quality of a river and, therefore, present a possible danger for ecosystems as well as limiting availability for downstream users (Smakhtin, 2001). Finally, the construction of dams of any kind can either increase or decrease base flow. Large river dams are likely to exert the greatest direct influence on the base flow regimes of streams, which many researchers have been able to confirm. Given the variety of anthropogenic influences on base flow, it becomes even more complicated to study the impact of individual natural influences (Smakhtin, 2001).

1.7 The role of evapotranspiration in the hydrological cycle

E marks the phase transition from liquid water to vapor. A distinction is made between "evaporation" and "transpiration." Evaporation describes the phase transition of water from "dead" surfaces or interceptional losses from living surfaces, while transpiration is the evaporation "through" living surfaces (e.g., plant transpiration; Spreafico and Weingartner, 2005).
Equation 1 indicates that E is an important factor in catchment hydrology. However, E plays an crucial role in the hydrological cycle in general but also as a link between the surface energy balance equation

and the hydrological cycle (Czikowsky & Fitzjarrald, 2004). In Switzerland, approximately one-third of all precipitation evaporates back into the atmosphere via E (Schädler, 1985). E is an interesting quantity for hydrologists because it can have a high magnitude throughout the year. At the beginning of the growing season, the land cover characteristics can change dramatically in as little as one to two weeks (Czikowsky & Fitzjarrald, 2004). Evaporation is significantly higher during growing season when plants are photosynthetically active than it is during the dormant season (Menzel et al., 1997).

A distinction can also be made between potential and real evaporation. Potential evaporation is controlled by the moisture deficit in the air, the wind, and the air pressure. The real evaporation rate is also mainly dependent on surface cover and on water availability. Concrete surfaces dry up quickly and evaporation is very soon diminished. However, plant-covered surfaces compensate for the regression in evaporation with transpiration. Forests transpire more than grasslands if the soil contains sufficient water content (Spreafico & Weingartner, 2005). The real evaporation in Switzerland is approximately 80% of the potential evaporation (Menzel, 1999).

The classical method for estimating E for a catchment is based on the conservation of mass equation (Palmroth et al., 2010). However, with modern evaporation models and satellite data, E can also be estimated more directly. Generally, E decreases with elevation. Even if the potential evaporation increases sharply from an altitude of 2000 m upwards, the real evaporation is low because of shallow soils and high gradients that prevent water storage on the surface (Spreafico & Weingartner, 2005).

1.7.1 Long-term trend of evapotranspiration

Although the seasonal vegetation effect on soil and groundwater reduction is usually large, over a longer time scale an approximate balance exists between groundwater recharge and depletion. Therefore, the difference between P and Q must be balanced by E (Palmroth et al., 2010). With that assumption and long time series of Q and P data, one can analyze long-term trends of evaporation. As early as 1985, Schädler (1985) stated that E in Switzerland regularly and slightly increased during the 20th century. As a consequence, Q values were significantly lower during the second phase of this investigation period, while P values remained the same (Schädler, 1985). A similar trend was found in the period from 1901 to 1960 in the state of Bavaria (Menzel et al., 1997). Human influences are an obvious explanation but also the influence of climate change. However, higher temperatures are just one possible explanation. As a result, no simple relationship between the values should be inferred yet (Spreafico & Weingartner, 2005).

On a global scale, the long-term development of E is reversed. Palmroth et al. (2010) stated that a series of studies have suggested that despite the use of increasing upstream water by humans, continental and global Q increased in a manner inconsistent with the changes in P. The drivers of this trend are not clear yet. Reduced near-surface windspeeds, the decreasing drying power of the atmosphere, increased efficiency in water use by plants because of elevated CO_2 levels, or global deforestation trends could all be explanations and, hence, form part of the ongoing research (Brutsaert & Sugita, 2008; Palmroth et al., 2010).

1.8 The role of evapotranspiration on recession behavior

The influence of E as a result of seasonal plant phenology changes on recession behavior has been proven in different studies (Czikowsky & Fitzjarrald, 2004; Federer, 1973; Trainer & Watkins, 1974). During the growing season, the recession rates increase because of enhanced water absorption from vegetation (Federer, 1973). The smaller the influence of P and Q during base flow conditions, the more important E becomes. A sensitivity analysis by Krakauer and Temimi (2011) showed that recession times vary with different levels of Q. The inclusion of E resulted in a 40% lower recession timescale. During high flow events, the effect of E on the recession time was considerably smaller (Krakauer & Temimi, 2011). This result means that the different influences of E on recession should be more detectable during base flow conditions than during surface or interflow conditions.

Federer (1973) showed the differences in recession constants during summer in the Hubbard Brook research area (U.S. East Coast). He stated that the recession rates corresponded with the onset of tree

transpiration in June and with leaf coloring in October. The increased recession rates during summer were observed at many different flow rates but were pronounced at base flow conditions. Unfortunately, some flow rates were only supported by a small amount of data.
At another site, vegetation was cleared and an herbicide was applied aerially to prevent regrowth within the entire catchment. The forest floor remained physically undisturbed. Although evaporation increased during summer because of higher temperatures and radiation, transpiration was practically zero and, therefore, a dormant condition could be simulated. The results supported the assumption that tree transpiration during the growing season increases the recession rates. The man-made "dormant" catchment had lower recession rates throughout the summer season compared to a nearby untreated catchment. Therefore, Federer (1973) concluded that transpiration mainly accounts for the rapid recession during summer. However, the recession at Hubbard Brook did not originate from groundwater but is most likely to have been derived from the interflow. The interflow in the soil was removed by active vegetation and then transpired and, hence, did not contribute to Q at the gauging station (Federer, 1973).

1.9 Vegetation period assessments based on plant phenological datasets

Phenology is the science of observations in nature and changes in the seasonal rhythm. The recording of recurring natural phenomena, especially in relation to weather, is the main concern of phenology. However, there are different targets in phenology. The research roughly distinguishes between biotic and abiotic (e.g., snow, ice, fog, or frost occurrences) observations. Biotic observation is further divided into animal and plant phenology. Usually, the results are specified by the dates on which a characteristic feature has been observed. Plant phenology has been practiced by humans for millennia. Modern plant phenology is considered to have a greater level of objectivity compared to historical plant phenology because modern network observations are based on instructions (e.g., how to count) and phase definitions.
The active period or vegetation period is the time in which a plant grows and unfolds. The vegetation period differs depending on the growth type of the plant. Annual plants have just one vegetation period, from germination until death. However, perennial plants are characterized by recurring vegetation periods and the associated phenological changes (e.g., leaf unfolding in spring and leaf drop in autumn). Phenological recording in autumn is more difficult than that in spring because there are greater differences between individual plants in leaf coloring and drop than in leaf unfolding and flowering in spring. This is because the physiological effects on plants of previous summer and autumn weather conditions are more complex in autumn than in spring (Jeanneret et al., 2011).
The period of the year when a perennial plant does not grow is called the dormant period. In a healthy plant, colder and longer nights lead to more growth-inhibiting hormones. In the moderate latitudes, the "complete rest" usually occurs during November and December. One disadvantage of plant phenology is often missing winter observations. If no abiotic observations are considered, the plant phenology circle is more often just a half-yearly circle. Ultimately, it is not trivial to illustrate the course of the seasons with a relevant graphic even if several types of representation are in use (e.g., "phenological clocks" Fig. 3; Jeanneret, Rutishauser and Brügger, 2011).
Temperatures are certainly an important control factor for the phenological phases of plants. However, many more control factors exist (e.g., pollution, pests, competition, genotype, water availability, weather of the last vegetation period etc.). Consequently, a plant is definitely more than just a thermometer (Jeanneret et al., 2011). Most tree species in a temperate climate do not depend primarily on temperature for their on- and offset dates. They are sensitive to light, that is, to the length of the day. This sensitivity protects the trees from reacting to dangerous temperature fluctuations at the wrong time. This genetic control remains even if the tree is planted in a subtropical climate (Körner & Basler, 2010).

1.9.1 Date method

The date method is the standard method in phenology, which means that the exact date of the start or end of a particular phenological phase is recorded. The same phenological phenomenon can have two different dates if, for example, the first flower on the tree (start of flowering) and full blossoming (flowering) are recorded separately (Jeanneret et al., 2011). Phenological data are, therefore, usually accurate in terms of the date.

2. Research question

2.1 Research gap

To date, little research has been conducted on assessing the difference between base flow recession behavior during the active and the dormant vegetation seasons, especially with multiple phenological indicators. Recession behavior is often analyzed for the entire year, despite the recognition that E influences the recession characteristics by different degrees over the year, especially during base flow conditions. Vegetation has also often been viewed as one item, despite the staggered character of the awakening of vegetation during spring. Czikowsky and Fitzjarrald (2004) examined different hydrological measures (precipitation - runoff method, recession time constant, and diurnal amplitude) to assess vegetation onset dates. They discovered a considerable time gap existed between recession behavior and other possible onset indicators (energy balance, geographical, or phenological measures). However, an assessment of the time gap or possible explanations for it were left for future research (Czikowsky & Fitzjarrald, 2004). Therefore, the time lag between leaf appearance and increased recession constants is has yet to be investigated properly.

2.2 Research question and main objective

The main objective of this thesis is to estimate precise recession behavior by incorporating plant phenological data sets. The thesis is built on the assumption that recession and base flow recession are enhanced during the growing season of catchment vegetation (Federer, 1973). Focus is on grouping isochronal indicators of plant phenology together to receive robust start and end dates for the dormant and active vegetation period with a yearly preciseness to the day. The idea behind this approach is to account for the variability of phenological appearances and, thus, differing E values across the years. With this precise time assessment, a better distinction between the active to dormant seasons is expected. In addition, a clearer graduation of base flow recession behavior throughout the transition period may be possible. Considering the main objective, the research seeks to answer the following question:

Does the incorporation of both time varying and location-specific plant phenological data improve the understanding of hydrological processes during recession events?

If the plant phenological data sets do not improve the assessment of base flow recession behavior, then fixed start and end dates represent adequate estimations of the reality. This would suggest that fixed dates have a sufficient level of precision and the annually changing start and end dates of vegetation due to the variability of weather conditions yield no further gains. In that case, the additional preparation of annually changing start and end dates for plant indicator groups could be neglected without losing data accuracy.

2.3 Research hypothesis

H_0: The incorporation of annual plant phenological data has a visible effect on recession behavior and intensifies the difference between winter and summer base flow recession.

H_1: The incorporation of annual plant phenological data has no clear visible effect on recession behavior and even diminishes differences between winter and summer base flow recession.

A broader hypothesis concerns differences in geological and climatical properties as well as differing human influences on catchments. Consequently, (base) flow recession behavior is expected to show differences too.

2.4 Sub questions

During the literature research, further questions arose, which I am also motivated to answer but on a smaller scale. In general, the aim is to find additional indicators to divide the hydrological year into the plant active and dormant season. Subsequently, the divisions from the additional indicators can be compared to the divisions with the phenological groups. That could be a prime gain for catchments that for example do not have any phenological data available.

- *How do other annually changing indicators (temperature, snow cover) compare with the plant phenological information?*
- *How do fixed meteorological and hydrological calendar dates compare to the flexible plant phenological groups?*
- *How large is the variability in the reference dates between and within the different indicator groups? Are yearly shifts consistent?*
- *By incorporating the phenological data, how accurate is the zoom into the transition periods during spring and autumn and is the information gained useful for further hydrological analysis?*
- *What are the differences between alpine and catchments on lower altitudes?*

With the main research question and the five sub questions in mind, the data are analyzed step by step in accordance with the scope of this thesis in the next chapters.

3. Data and research areas

To answer my research questions and assess the hypothesis presented in Chapter 2, I analyzed plant phenological and streamflow (Q) data series from 1992 to 2019 for two small Swiss catchments: The Allenbach catchment in the Bernes Alps and the Murg catchment in the eastern Swiss midlands.
To determine the different growing seasons, I used plant phenological data sets from the Swiss phenological network (IDAWEB) provided by MeteoSwiss (Federal Office of Meteorology and Climatology). The Q data series are daily means and are provided by the Federal Office for the Environment (FOEN). The data from 2018 and 2019 are provisional but show no visible or mean abnormalities compared to the entire data set. The meteorological parameters P and temperature are the aggregated daily means of the catchment area provided by MeteoSwiss. The stated hydrological means are from 1981 to 2010 and are also provided by MeteoSwiss. Snow cover information is provided by WSL Institute for Snow and Avalanche Research SLF.
To determine the surface properties of the catchments, data from the FOEN and from the Hydrological Atlas of Switzerland were used. Despite the differences between the two sources, I decided to use both because the data complement each other. Whenever possible, data from the FOEN were used or the values were calculated to a mean. The map sections shown are from the federal geoportal provided by swisstopo (Federal Office of Topography).

3.1 Allenbach catchment

The size of the Allenbach catchment (Fig. 1) is 28.8 km^2 and it has a nival discharge pattern. The Q data are collected at 1,297 meters above sea level (masl) from the monitoring station directly in front of the well-known village Adelboden. The source of the Allenbach is in a steep cirque on the eastern slope of the Albristhore (2,762 masl). The channel length is rather small; the Allenbach only covers about 6.3 km from the source to the monitoring station. Therefore, the Allenbach can be characterized as a steep and wild mountain stream with a mean gradient of approximately 200 m per km. The streamflow is near-natural with no known influences by dams, withdrawals, or return flow. The entire catchment is used for winter tourism with many lifts and slopes. The catchment is enclosed by many mountain peaks between 2,000 and 2,762 masl. In the lower part of the catchment, there are some farm buildings and small roads (*FOEN*, 2020).

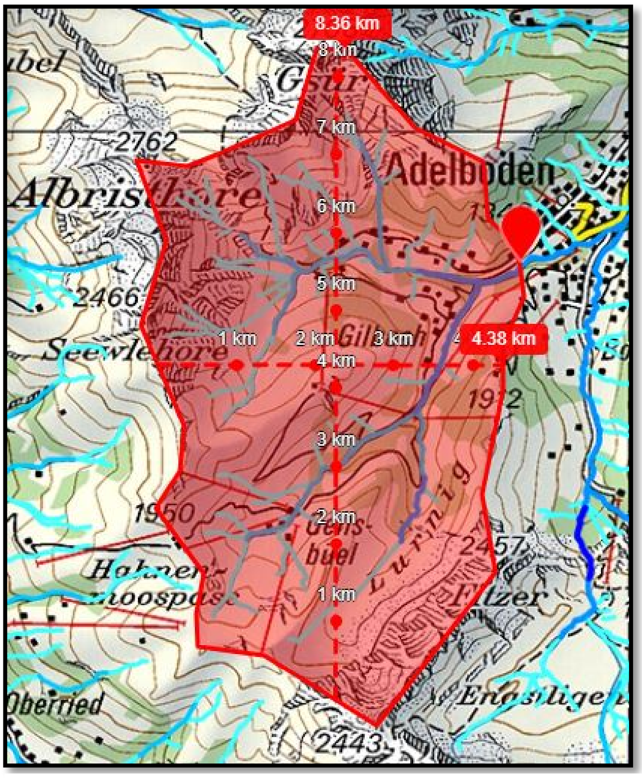

Figure 1. *Allenbach catchment (https://map.geo.admin.ch)*

3.1.1 Land cover properties

The dominating land cover class is cultivated and rambunctious alpine grassland (60%). Only 14% of the catchment is covered by forest. Three-quarters of the forest consists of purely coniferous trees and one-quarter of the forest is coniferous dominated mixed forest. Approximately 5% of the catchment is covered by shrubbery. In the Allenbach catchment, 21% of the surface is considered to be vegetation-free (consolidated rocks, loose rocks, roads, buildings, and unidentified areas). These vegetation-free areas are found mostly at the highest elevations of the catchment (*FOEN*, 2020; *Hydrological Atlas of Switzerland*, 2020).

3.1.2 Geological and soil properties

The catchment is situated mostly and in equal parts in the geological formation of the Niesen-Decke and Ultrahelvetikum. Due to the high proportion of clay in the prevailing rocks, the permeability is generally low. The geology underneath the catchment consists of 48% unconsolidated rocks with varying levels of permeability and 52% solid bedrock that is partly jointed. The most common soil types in the catchment are Regosol (28%), Gleysol (21%), Rendzina (19%), and Lithosol (11%). Because the soils are relatively young, they are rather shallow. The water retention ability of the soils ranges from extremely weak to moderate. The permeability of the soils is classified as strongly inhibited (4%), inhibited (33%), slightly inhibited (11%), and normal (30%; *FOEN*, 2020).

3.1.3 Hydrological characteristics

There are no glaciers or lakes in the catchment. The annual P at the gauging station is 1,642 mm. The highest amount of P occurs during summer (544 mm). The lowest amount of P is expected during autumn (350 mm). The spring (393 mm) and winter (384 mm) seasons have quite similar amounts of P.
There is no information about the mean snow water equivalent (SWE) available for this catchment. However, SWE information is provided at the monitoring station two km further down the stream. The mean SWE on 1st February was 190 mm, on 1st March it was 271 mm, on 1st April it was 283 mm, and on 1st May it was 215 mm (MeteoSwiss, 2020).

3.2 Murg catchment

The size of the Murg catchment (Fig. 2) is 80.2 km^2 and it has a pluvial discharge pattern. The Q data are collected at 466 masl from the monitoring station at Wängi. The Murg has its source in the Bechtenwald at an elevation of approximately 960 masl. The Bechtenwald forest is on the northeastern and eastern slopes of the Regelsberg (1,036 masl) and Schlattberg (1,022 masl), which are the two highest points of elevation in the catchment. The channel length is 19.4 km with a mean gradient of 25.5 m per km. The upper part of the catchment is dotted with farms with surrounding pasture- and croplands and forests on the slopes of the hills. In the lower part of the catchment, the stream flows through a patchwork of populated areas, small forests, and agricultural land and is influenced by two known points of water abstraction and one point of return flow. The two most populous communities in the catchment area are Münchwilen (TG) with approximately 5,600 inhabitants and Sirnach (TG) with approximately 7,800 inhabitants (*FOEN*, 2020).

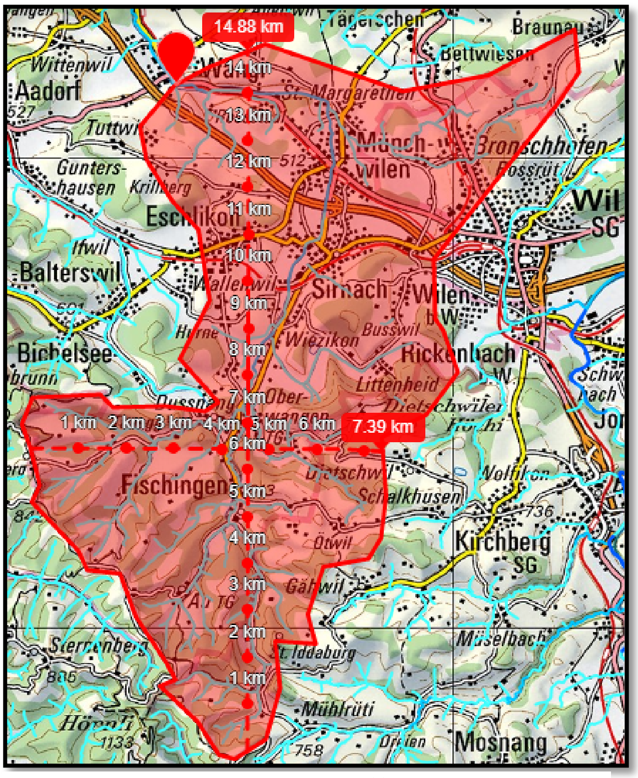

Figure 2. *Murg catchment (https://map.geo.admin.ch)*

3.2.1 Land cover properties

Agricultural fields and grassland are the dominating land cover class (53%). Approximately 34% of the catchment is covered by forest and fruit-growing plantations. One-fourth of the forests consist of deciduous trees and three-quarters are coniferous trees. The shrubbery class is rather insignificant; only 3% of the catchment is covered by different kind of bushes. In the Murg catchment, 10% of the surface is considered to be vegetation-free (mostly buildings and streets) and is located mostly within the populated areas (*FOEN*, 2020; *Hydrological Atlas of Switzerland*, 2020).

3.2.2 Geological and soil properties

The catchment of the Murg is situated in the geological formation of the Molasse basin and is partly covered by moraines and fluvial-glacial rubble. The catchment contains a small aquifer, which is situated in an ancient, buried stream of the Thur and is used by pumping stations. Consequently, during very long dry periods, the Murg runs dry in this zone. The most common soil in the catchment is Cambisol (70%) followed by Regosol (17%). Other soils can be found as well but only in small percentages. The water retention ability of the soils is classified as moderate (43%) to good (54%). The permeability of the soils is classified as inhibited (43%), slightly inhibited (47%), normal (4%), and overly permeable (5%; *FOEN*, 2020).

3.2.3 Hydrological characteristics

There are no glaciers or lakes in the catchment. The annual P at the gauging station is 1,354 mm. The highest amount of P usually occurs during summer (418 mm) and the lowest during winter (277 mm). The P in spring (339 mm) and autumn (316 mm) are somewhere in between these two measures. The mean SWE on 1st February was 19 mm, on 1st March it was 23 mm, and on 1st April it was 3 mm (MeteoSwiss, 2020).

4. Method

After accurately describing the two catchment areas, the first step was to select the different reference dates to subsequently divide the Q data into different periods. The Swiss phenological network of MeteoSwiss (IDAWEB) consists of 160 stations, one of which is at Adelboden (ADB). At Wängi, the gauging station of the Murg catchment, there is no phenological station. However, the closest station at Wil (WIL) is only 8.5 km in air-line distance and has approximately the same altitude. I decided that I wanted to concentrate only on the plant phenological data, which meant that no ornithological data were considered. The phenological data are accurate to the day. Therefore, all the subsequent analysis is based on the variable "day of the year," which consist of values from 1 to 365. All data were processed using the R program.

4.1 Plant phenological data

The plant phenological data limited the time frame of this research from 1992 to 2019 (28 years or 10,227 days) because most of the tree information is only available from that point in time. Forests are the most important sources of E (despite open water bodies) and, therefore, incorporating them in this study is important. The data acquisition resulted in 36 plant phenological features at ADB and 50 at WIL. The data availability was better for spring (onset) than for autumn (offset) in both catchments. A legend of all the reviewed plant features with a German translation and information on normal distribution can be found in Appendix A.

4.1.1 Evapotranspiration group approach

With the E group approach, I tried to depict the onset and offset of E for the entire catchment to obtain an active and a dormant vegetation season. The vegetation was divided into three categories: forest, shrubbery, and grassland. The forest category was further divided into broadleaf and coniferous forest. Given that E was the relevant factor, only the features "needle shoot," "leaf unfolding," "needle/leaf coloring," and "needle/leaf drop" were considered in the forest and shrubbery classes. However, the only feature of the grassland class was "flowering." Areas considered to be vegetation-free were not included in the calculations.
The relative size of the land cover categories (3.1.1 and 3.2.1) was included along with their individual relative evaporation capacities. Menzel (1999) estimated the average annual evaporation [mm] for different vegetation types and altitudes in Switzerland. Those original altitudes (600 m and 1,800 m) from Menzel (1999) were used for the calculations (for the Murg catchment values from 600 m altitude and for the Allenbach from 1,800 m altitude). The forest and shrubbery categories have the same relative evaporation capacity value because Menzel (1999) only distinguished between forest and agricultural land. The relative E capacity of forest and shrubbery is 0.61 in the Allenbach catchment and 0.57 in the Murg catchment. Accordingly, the relative E capacity of grassland is 0.39 in the Allenbach catchment and 0.43 in the Murg catchment (Menzel, 1999).
The result is an on- and offset E vector from 1992 to 2019 consisting of 28 "day of the year" values. Further information as well as the management of the missing values can be found in Appendix B.

4.1.2 Similar group approach

The similar group approach had the goal of generating as many groups with as many phenological features as possible in the specific catchment. First, all the phenological features were tested for their normal distribution and their mean value "day of the year" to gain an impression of the data and their distribution. The normal distribution was performed using the Shapiro-Wilk normality test and visually double checked. In that process, features with too many (more than five) missing values or features that were not at all normally distributed were rejected for further processing. Several times a feature was not normally distributed because of one or two outliers, and in that case, it was retained. Normality tests have little power to reject the null hypothesis (normal distribution) if the sample size is small.

Conversely, the null hypothesis is rejected easily with large sample sizes. With 28 variables, the sample size used here was neither small nor large.

Normal distribution is an important assumption for many statistical procedures. Parametric tests assume that the collected data follow a normal distribution. The normality assumption is especially critical when establishing reference intervals for variables. Using parametric tests rather than non-parametric tests is preferred because they have more power. They are more likely to detect a difference that truly exists and less likely to make a type II error (Ghasemi & Zahediasl, 2012). The type II error sometimes also called "false negative", is the acceptation of a false null hypothesis instead of using the alternative hypothesis that would describe the true state of nature.

To conduct the parametric tests, the variances must be homogenous (similar). This is referred to as variance homogeneity. In contrast, if the variances are not equal, this is referred to as variance heterogeneity. To test for the homogeneity of variances, the Levene test was applied. If the null hypothesis (homogeneity) is not rejected, a parametric test can be applied. If the null hypothesis is rejected, one must assume variance heterogeneity and use a non-parametric test (Levene, 1960). The groups consisted of all possible features (all categories); the only restriction was that one plant could not be in the same group twice with different phenological features. In that case, the feature with a more complete data set was kept. For example, the feature "hazel leaf unfolding" was canceled because the feature "hazel flowering" had fewer missing values.

To assess whether the phenological groups had equal means, they were tested with the parametric (two-sample *t*-test and one-way ANOVA) tests. However, some of the groups contained phenological features that were not normally distributed or had variance heterogeneity, hence, non-parametric (Mann-Whitney-U-Test and Welch ANOVA) tests were also used.

One benefit of groups with the same means was that data gaps for one phenological feature could be filled with data from the other features without difficulty. The second benefit was that the average on- and offset values were more robust against possible data collection errors. However, there were some phenological features that did not correspond with other features at all. I decided to include them only if they provided additional information and contained only a few values. In the case of missing values, the missing years were filled with the mean of that specific phenological feature or group. The results were many on- and offset vectors from 1992 to 2019 consisting of 28 "day of the year" values.

4.2 Additional indicators

The focus of this thesis is plant phenological data. However, other indicators were also used to obtain a more holistic assessment of recession behavior, especially base flow recession. The other indicators are described in the following subsections. All the data are accurate to the day.

4.2.1 Temperature

The vegetation period was sometimes also derived directly from the temperatures in the transition period. According to MeteoSwiss, the following thresholds are common:

- Onset: Seven consecutive days with daily mean temperatures of at least 5°C.
- Offset: Five consecutive days with daily mean temperatures below 5°C, three consecutive days with minimum temperatures below 0°C, or one day with a minimum temperature below -2°C.

This definition was provided by B. Primault from MeteoSwiss (MeteoSwiss, 2020).

For the onset days, I was able to adopt the exact definition. However, because the temporal resolution of the temperature data series is daily, I only adopted the first premise from the definition for the offset dates. The data extraction was then performed with threshold filters and a minimal run length. Unusual periods of warm weather (temperatures above 5°C for a minimum of 7 days) that started in January were excluded by hand. The Allenbach catchment experienced three such events (2007, 11 days; 2016, 7 days; 2018, 8 days), while the Murg catchment experienced four such events (2002, 7 days; 2007, 9 days; 2016, 8 days; 2018, 8 days). The final of the seven consecutive days in spring and the final of the five consecutive days in autumn were respectively determined as the on- and offset dates. This approach resulted in an on- and offset vector from 1992 to 2019 consisting of 28 "day of the year" values for both catchments.

4.2.2 Snow cover

Unfortunately, I could not find a snow depth data series that would have provided more information for the Murg catchment. However, to obtain an estimation of snow cover conditions on the mountains around Adelboden, snow depth data from the fully automated SLF weather station, Ottere, (2,020 masl) were considered. Apart from the weather station at Adelboden, there are no consistent snow data available within the catchment. The Ottere station has an approximate 6 km air-line distance to the gauging station and is approximately 7.5 km to the waterhead of the Allenbach. The exposition of the station is the same as the general exposition of the catchment and it is in the same valley. The snow depth data provide an even better estimation on "true" summer (base flow) recession behavior because the information permits an assessment of when the effect of the snow cover as a water storage can be neglected.

Daily snow depth data were only available for the Allenbach catchment from 1998 to 2019 and were noisy. Therefore, the data were processed with a three-day smoothing filter and 10 cm was subtracted (the automatic device always detected 3 to 9 cm snow depth; even if based on T and P data, the presence of snow was impossible). The reference date in spring "end of snow season" was the last day of sustained winter snow. The reference date in autumn "start of snow season" was the first day of snow occurrence that lasted a minimum of five days with the filter applied. The result is an off- and onset snow vector from 1998 to 2019 consisting of 22 "day of the year" values. Additionally, the peak snow depths of six extreme winters are shown in Table 1.

Table 1. *Extreme winter snow depths in the Allenbach catchment (1998 to 2019)*

The three winters with highest snow depth		The three winters with lowest snow depth	
Winter 1999, Day 56 (25.2)	357 cm	Winter 2010, Day 43	106 cm
Winter 2018, Day 92	296 cm	Winter 2011, Day 61	112 cm
Winter 2000, Day 53	262 cm	Winter 1998, Day 111	130 cm

4.2.3 Calendar reference dates

To compare the flexible periods, three different fixed calendar date periods were selected.

<u>Hydrological year</u>:
In Switzerland, the hydrological year starts on 1st October. The hydrological year is simply divided in half. Therefore, the winter season lasts from 1st October till 31st March and the summer season from 1st April to 30th September.

<u>Meteorological seasons</u>:
There are four meteorological seasons, and they can be analyzed separately. However, to generate halves, the spring season (1st March till 31st May) and the summer season (1st June to 31st August) can be summarized as the "active season." Following from this, the autumn season (1st September to 30th November) and the winter season (1st December to 28th or 29th February) can be summarized as the "dormant season."

<u>Supplementary phenological values from Weather Spark</u>:
After a brief web research, I discovered WeatherSpark.com. This webpage provides detailed information about typical weather conditions as well as phenological season lengths for over 145,000 sites worldwide. The website provides information from Wängi, the gauging station of the Murg catchment,

but not from Adelboden. The nearest station to Adelboden is at Gstaad (BE). Gstaad lies at an altitude of 1,050 m, which is 250 m lower than Adelboden. According to the webpage, the average active season at Gstaad lasts from 19th May (Day 139 of the year) until 30th September (Day 273 of the year). At Wängi, the active season is from 14th April (Day 104 of the year) until 31st October (Day 304 of the year).

4.3 Resulting phenological seasons and periods

All the different phenological seasons and periods of the catchments are summarized in a phenological circle, and information about the group compositions are summarized in the associated table. Additionally, the variability between years and within the groups is also shown.

4.3.1 Phenological circle for the Allenbach catchment (ADB)

At Adelboden, the onset can be divided into 12 (S_1-S_{12}) and the offset into six different periods (W_1-W_6). The entire year is divided into seven phenological seasons Fig. 4). The mean on- and offsets from all the phenological groups are shown in the phenological circle (Fig. 3). The phenological features of all groups are listed in Table 2. The figures of on- (Fig. 5) and offset days (Fig. 6) reveal the exact reference dates in each year through the research period. Finally, the figures of on- (Fig. 7) and offset groups (Fig. 8) illustrate the variability within the ADB phenological groups.

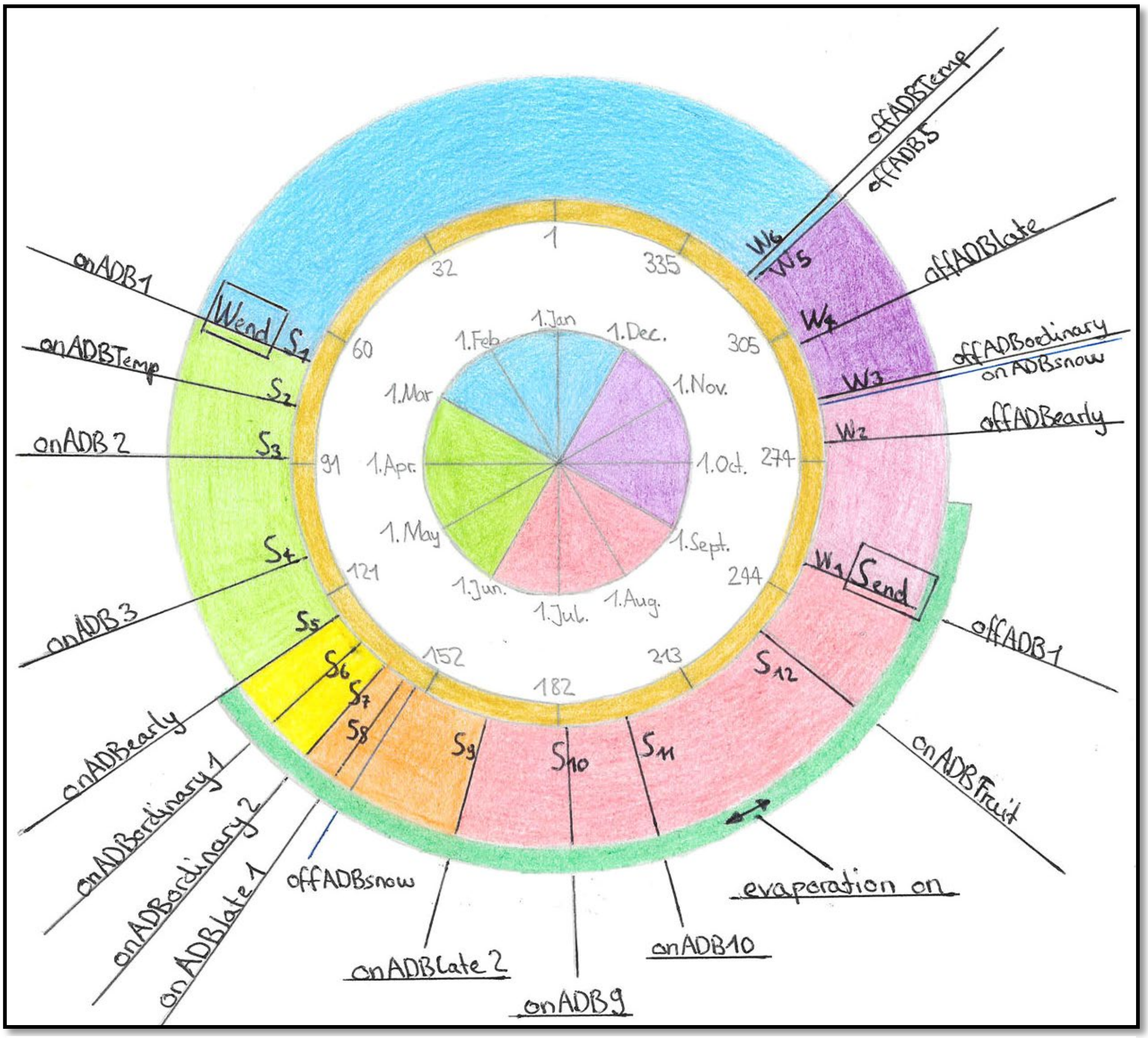

Figure 3. *Phenological circle ADB*

Figure 4. *Legend of the phenological seasons*

Table 2. *Summary of the phenological groups (ADB)*

Phenological group	n	Normally distributed	Variance homogeneity	*p*-value	Phenological feature
onADB1	1	yes	-	-	Hazel - flowering (50%)
onADB2	1	yes	-	-	Coltsfoot - flowering (50%)
onADB3	1	yes	-	-	Wood anemone - flowering (50%)
onADBearly	6	yes	yes	0.64	Larch - needle shoot (50%), Dandelion - flowering (50%), Hazel - leaf unfolding (50%), Cuckoo flower - flowering (50%), European rowan - leaf unfolding (50%), Cherry tree - flowering (50%)
onADBevaporation	13	yes	-	-	Spruce - needle shoot (50%), Larch - needle shoot (50%), Sycamore maple - leaf unfolding (50%), Beech - leaf unfolding (50%), Horse chestnut - leaf unfolding (50%), Hazel - leaf unfolding (50%), European rowan - leaf unfolding (50%), Coltsfoot - flowering (50%), Wood anemone - flowering (50%), Dandelion - flowering (50%), Cuckoo flower - flowering (50%), Field daisy - flowering (50%), Cocksfoot grass - flowering (50%)
onADBordinary1	2	yes	yes	0.75	Horse chestnut - leaf unfolding (50%), European red elder - flowering (50%)
onADBordinary2	3	yes	yes	0.32	Sycamore maple - leaf unfolding (50%), Beech - leaf unfolding (50%), Apple tree - flowering (50%)
onADBlate1	2	yes	yes	0.18	Spruce - needle shoot (50%), Field daisy - flowering (50%)
onADBlate2	2	yes	yes	0.39	Cocksfoot grass - flowering (50%), Hay harvest - start
onADB9	1	yes	-	-	European elder - flowering (50%)
onADB10	1	yes	-	-	Willow herb - flowering (50%)
onADBFruit	1	yes	-	-	European rowan - fruit maturity (50%)
offADB1	1		-	-	Autumn crocus - flowering (50%)
offADBevaporation	9	no	-	-	Larch needle - coloring (50%), Larch - needle drop (50%), Sycamore maple - leaf coloring (50%), Beech - leaf coloring (50%), Horse chestnut - leaf coloring (50%), Horse chestnut - leaf drop (50%), Autumn crocus - flowering (50%), European rowan - leaf coloring (50%), European rowan - leaf drop (50%)
offADBearly	2	yes	yes	0.15	European rowan - leaf coloring (50%), European elder - fruit maturity (50%)
offADBordinary	3	yes	yes	0.6	Horse chestnut - leaf coloring (50%), Beech - leaf coloring (50%), European rowan - leaf drop (50%)
offADBlate	2	no	yes	0.43	Horse chestnut - leaf drop (50%), Larch needle - coloring (50%)
offADB5	1	yes	-	-	Larch - needle drop (50%)

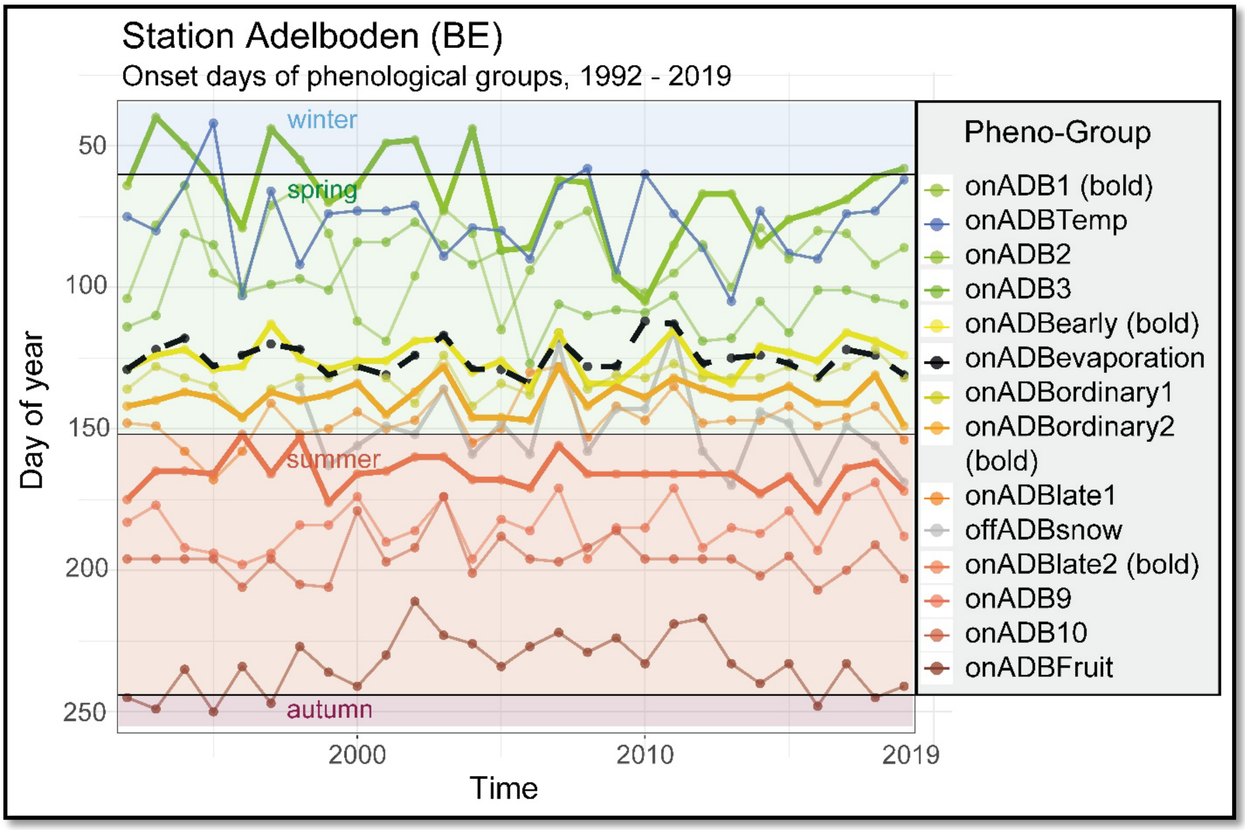

Figure 5. *Onset days through the years (ADB)*
Note, the stated background seasons are meteorological seasons.

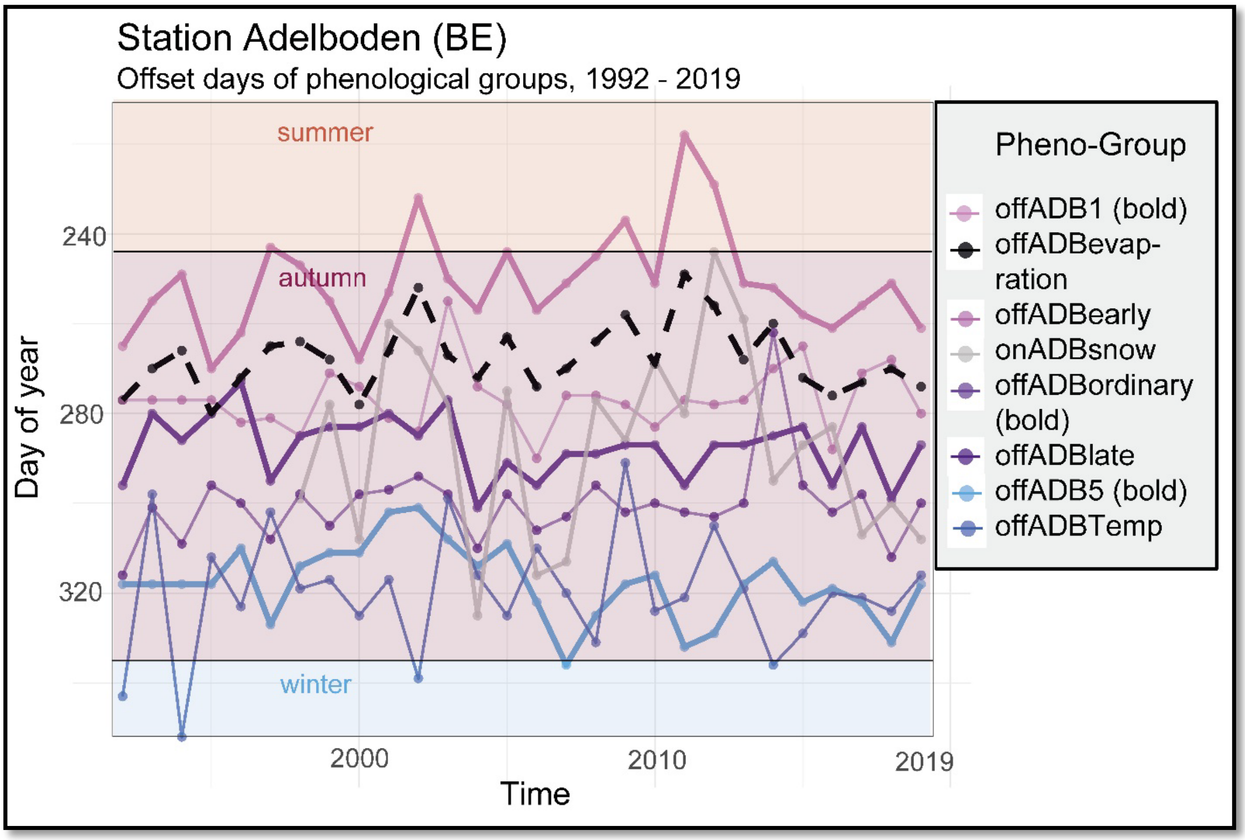

Figure 6. *Offset days through the years (ADB)*
Note, the stated background seasons are meteorological seasons.

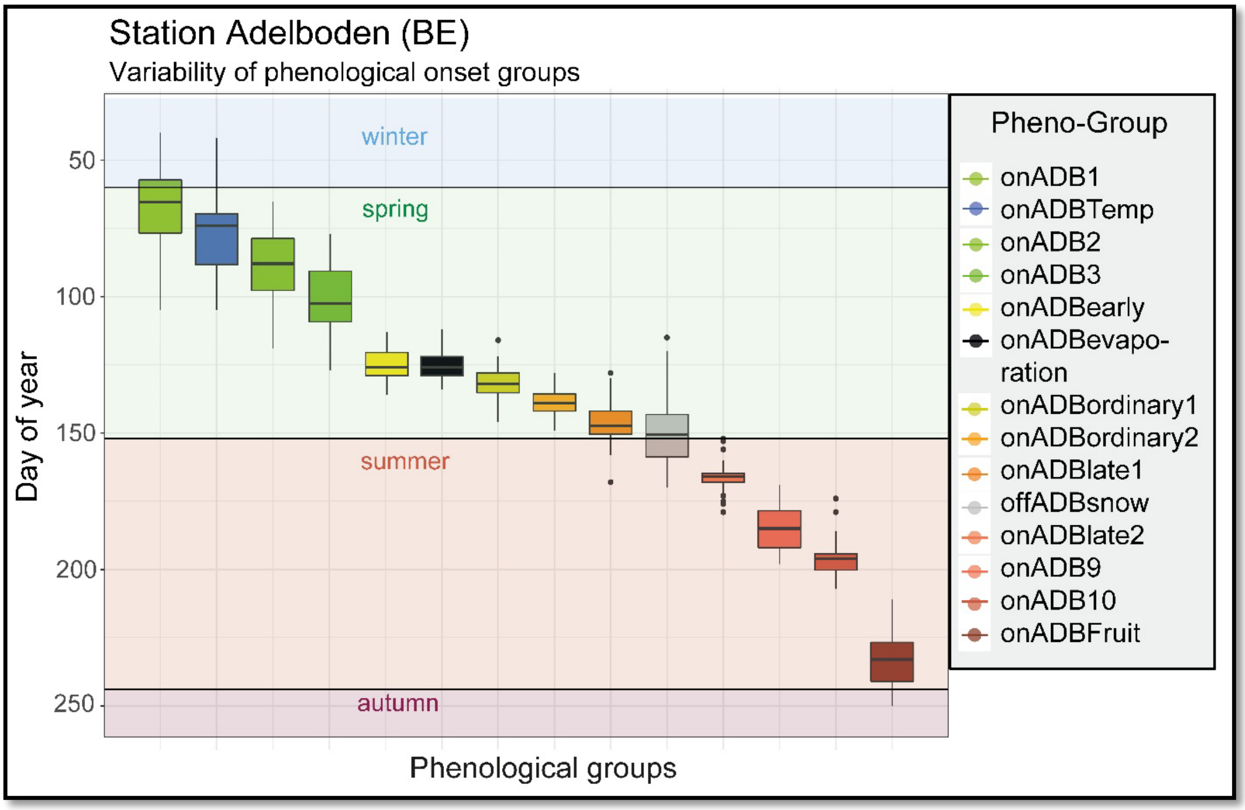

Figure 7. *Variability within phenological onset groups (ADB)*
Note, the stated background seasons are meteorological seasons.

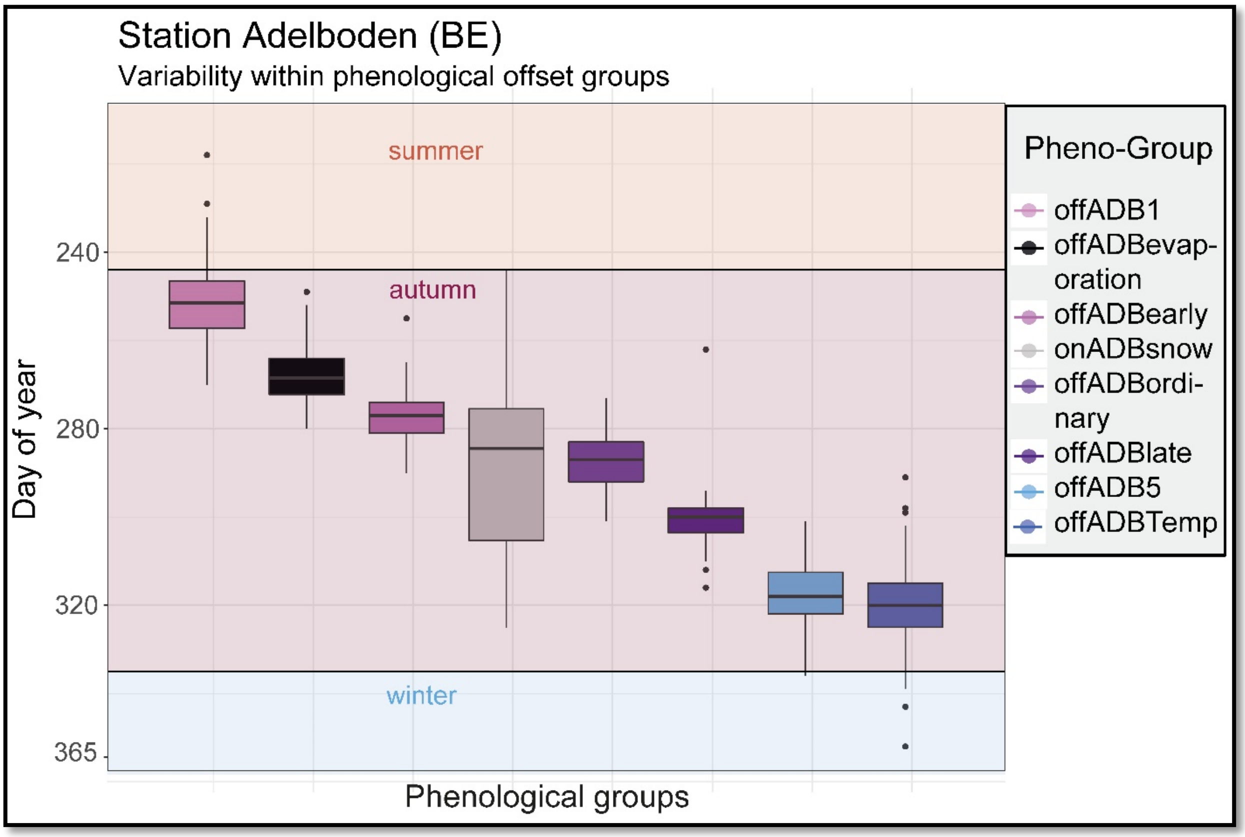

Figure 8. *Variability within phenological offset groups (ADB)*
Note, the stated background seasons are meteorological seasons.

4.3.2 Phenological circle for the Murg catchment (WIL)

At Wil, the onset can be divided into 11 (S_1-S_{11}) and the offset into eight different periods (W_1-W_8). The entire year is divided into seven phenological seasons. The mean on- and offsets from all the phenological groups are shown in the phenological circle (Fig. 9). The phenological features of the groups are listed in Table 3. The entire year is divided into seven phenological seasons. The figures of on- (Fig. 10) and offset days (Fig. 11) reveal the exact reference dates in each year through the research period. Finally, the figures of on- (Fig. 12) and offset groups (Fig. 13) show the variability within the WIL phenological groups.

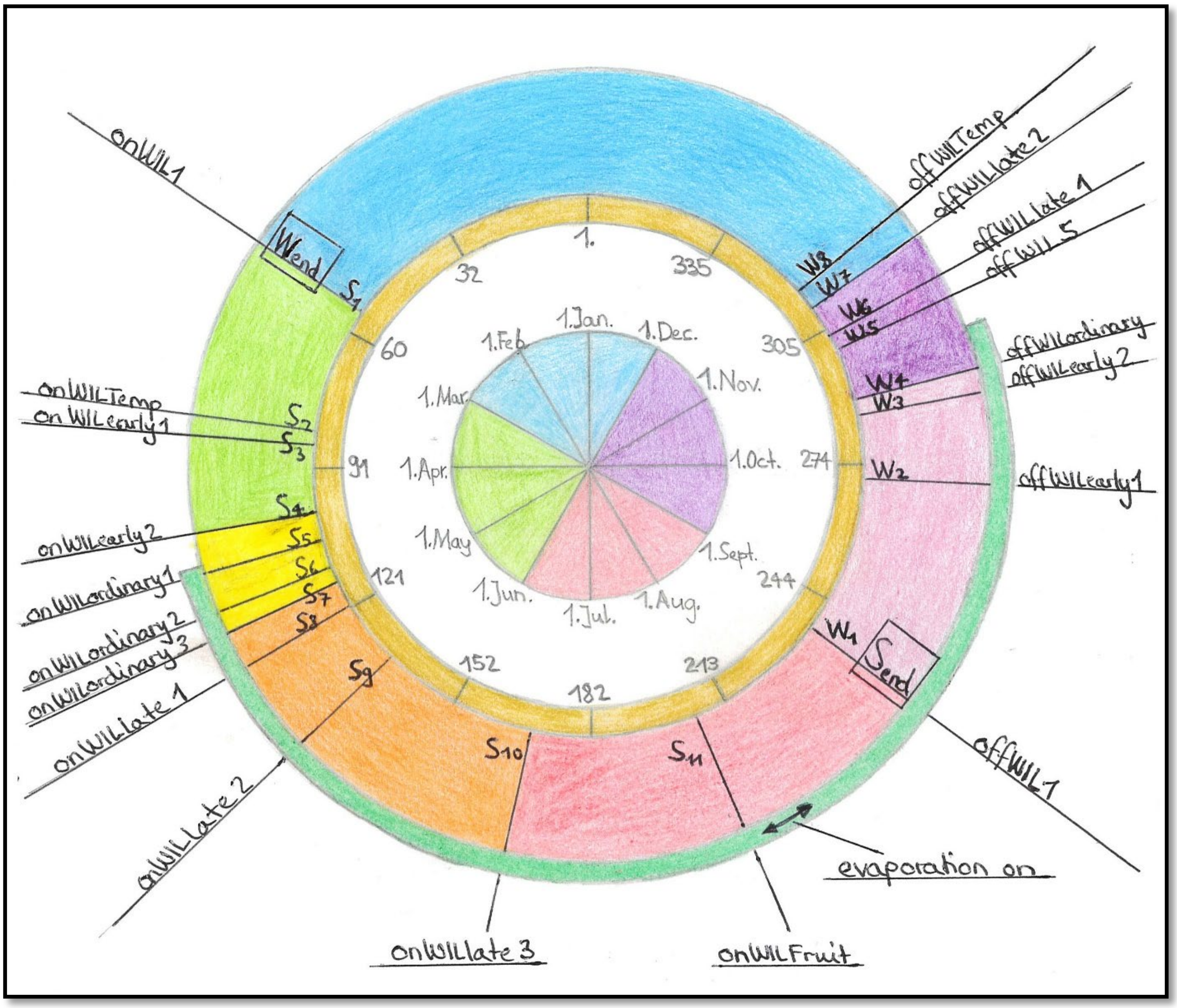

Figure 9. *Phenological circle WIL*

Figure 10. *Legend of the phenological seasons*

Table 3. *Summary of the phenological groups (WIL)*

Phenological group	n	normally distributed	variance homogeneity	*p - value*	Phenological feature
onWIL1	1	yes	-	-	Hazel - flowering (50%)
onWILearly1	2	no	yes	0.09	Wood anemone - flowering (50%), Coltsfoot - flowering (50%)
onWILearly2	4	yes	yes	0.25	Horse chestnut - leaf unfolding (50%), European rowan - leaf unfolding (50%), European white birch - leaf unfolding (50%), Larch - needle shoot (50%)
onWILevaporation	17	no	-	-	Spruce - needle shoot (50%), Larch - needle shoot (50%), Sycamore maple - leaf unfolding (50%), Beech - leaf unfolding (50%), Horse chestnut - leaf unfolding (50%), European white birch - leaf unfolding (50%), Large leaved lime - leaf unfolding (50%), Small leaved lime - leaf unfolding (50%), Common acacia - leaf unfolding (50%), Wood anemone - flowering (50%), Dandelion - flowering (50%), Coltsfoot - flowering (50%), Cocksfoot grass - flowering (50%), Field daisy - flowering (50%), Cuckoo flower - flowering (50%), Hazel - leaf unfolding (50%), European rowan - leaf unfolding (50%)
onWILordinary1	3	yes	yes	0.12	Cuckoo flower - flowering (50%), Cherry tree - flowering (50%), Large leaved lime - leaf unfolding (50%)
onWILordinary2	2	yes	yes	0.78	Spruce - needle shoot (50%), Sycamore maple - leaf unfolding (50%)
onWILordinary3	4	yes	yes	0.1	Common acacia - leaf unfolding (50%), Pear tree - flowering (50%), Small leaved lime - leaf unfolding (50%), Apple tree - flowering (50%)
onWILlate1	2	yes	yes	0.6	Cocksfoot grass - flowering (50%), European red elder - flowering (50%)
onWILlate2	2	no	yes	0.83	Field daisy - flowering (50%), Common acacia - start of flowering
onWILlate3	2	yes	yes	0.68	Large leaved lime - flowering (50%), Small leaved lime - start of flowering
onWILFruit	1	yes	yes	-	European rowan - fruit maturity (50%)
offWIL1	1	no	-		Autumn crocus - flowering (50%)
offWILearly1	2	no	no	0.96	European rowan - leaf coloring (50%), Horse chestnut leaf coloring (50%)
offWILearly2	2	no	yes	0.51	Beech - leaf coloring (50%), Sycamore maple - leaf coloring (50%)
offWILordinary	5	yes	no	0.97	Grape vine – vintage, Large leaved lime - leaf coloring (50%), European rowan - leaf drop (50%), European white birch - leaf coloring (50%), Larch needle - coloring (50%)
offWILevaporation	13	-	-	-	Larch needle - coloring (50%), Larch - needle drop (50%), Beech - leaf coloring (50%), Beech - leaf drop (50%), Horse chestnut leaf coloring (50%), European white birch - leaf coloring (50%), Large leaved lime - leaf coloring (50%), Common acacia - leaf drop (50%), Autumn crocus - flowering (50%), Grape vine – vintage, European rowan - leaf coloring (50%), European rowan - leaf drop (50%), Horse chestnut leaf drop (50%)
offWIL5	1	yes	-	-	Horse chestnut leaf drop (50%)
offWILlate1	2	yes	yes	0.94	Beech - leaf drop (50%), Common acacia - leaf drop (50%)
offWILlate2	2	yes	yes	0.32	Larch - needle drop (50%), European white birch - leaf drop (50%)

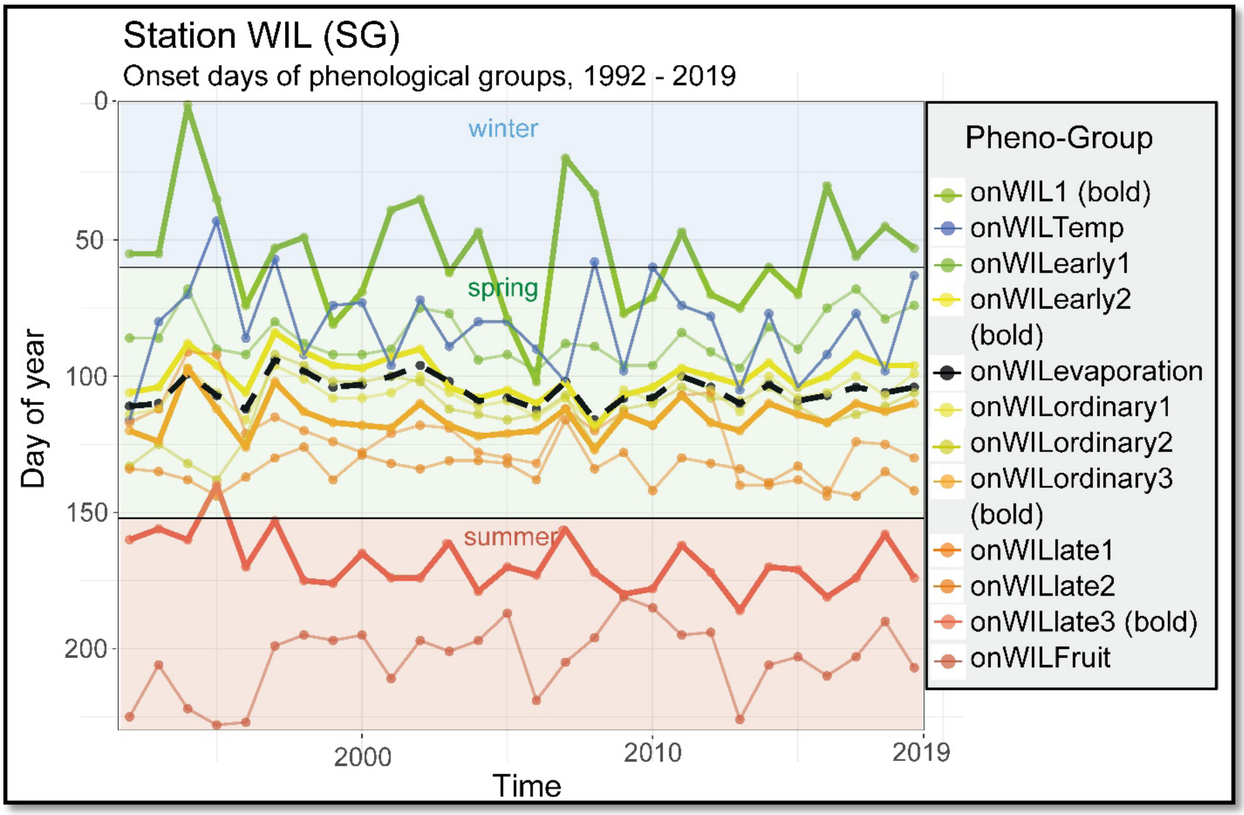

Figure 11. *Onset days through the years (WIL)*
Note, the stated background seasons are meteorological seasons.

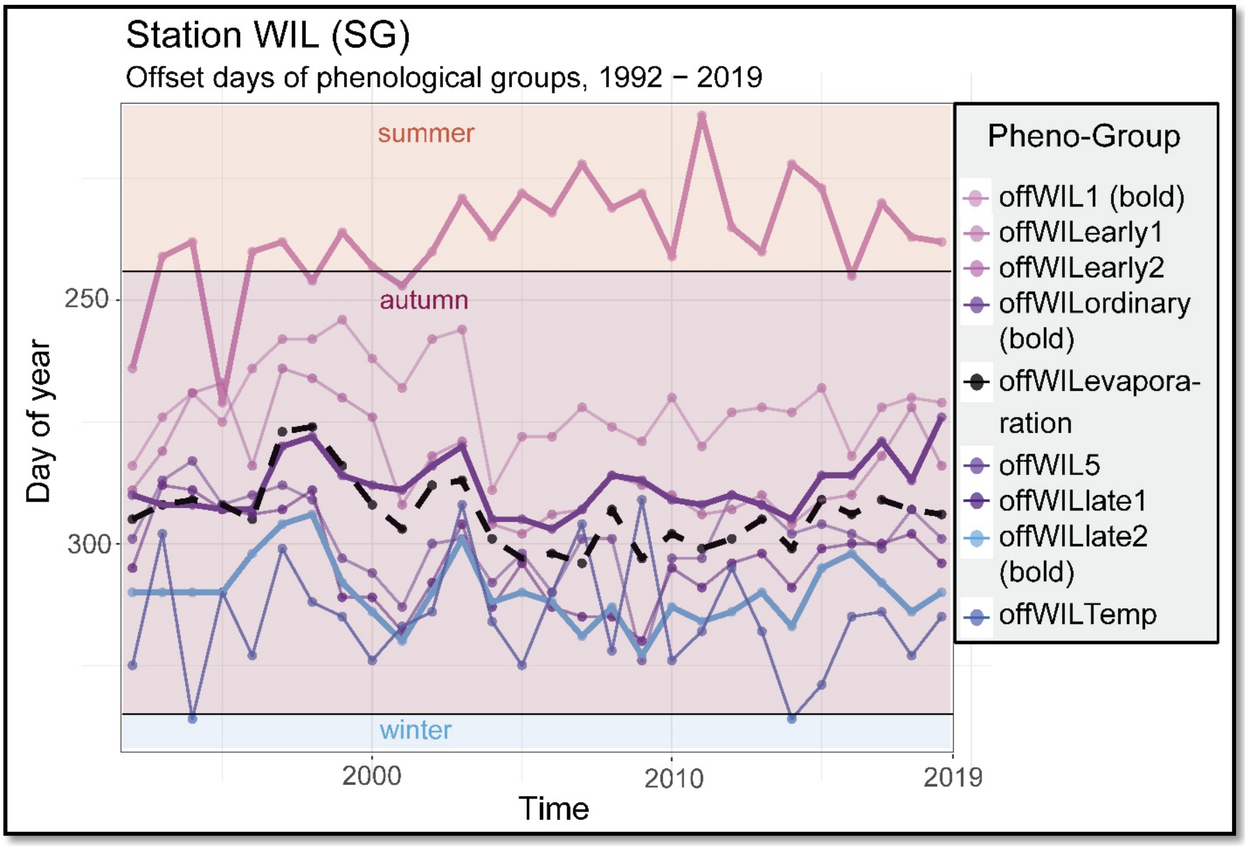

Figure 12. *Offset days through the years (WIL)*
Note, the stated background seasons are meteorological seasons.

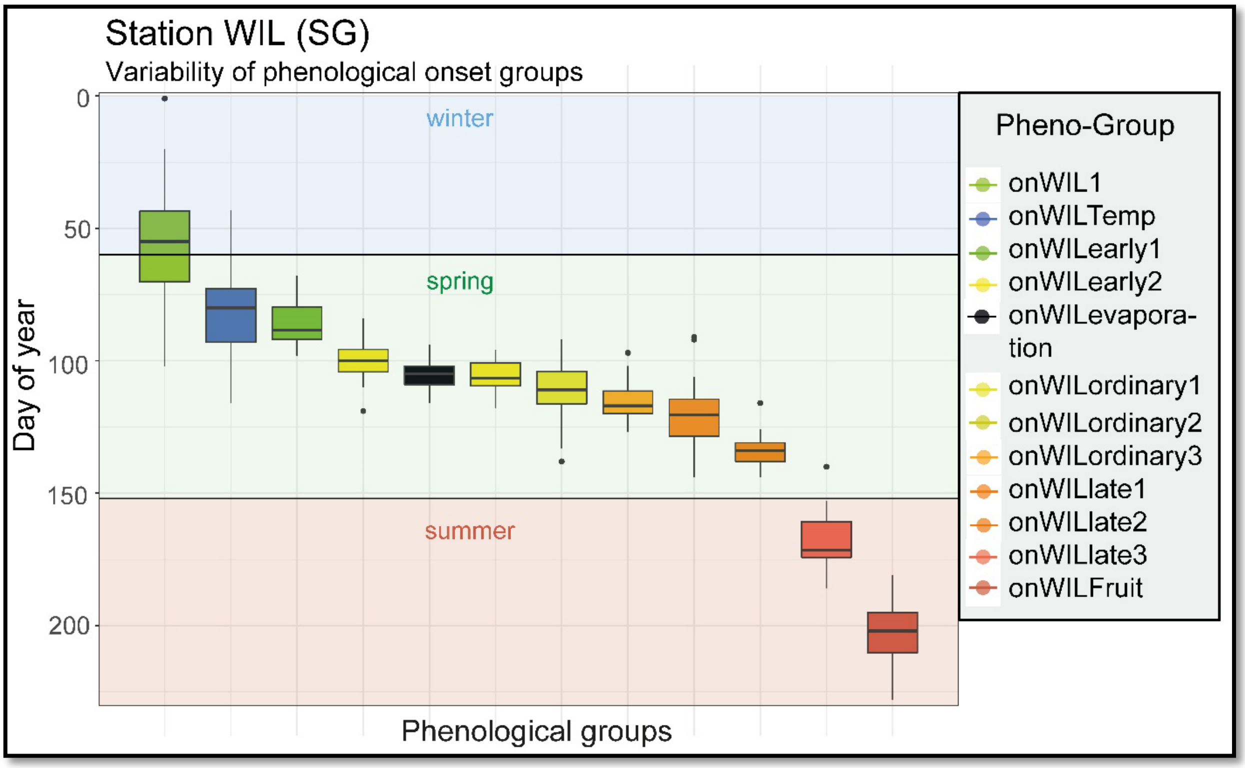

Figure 13. *Variability within phenological onset groups (WIL)*
Note, the stated background seasons are meteorological seasons.

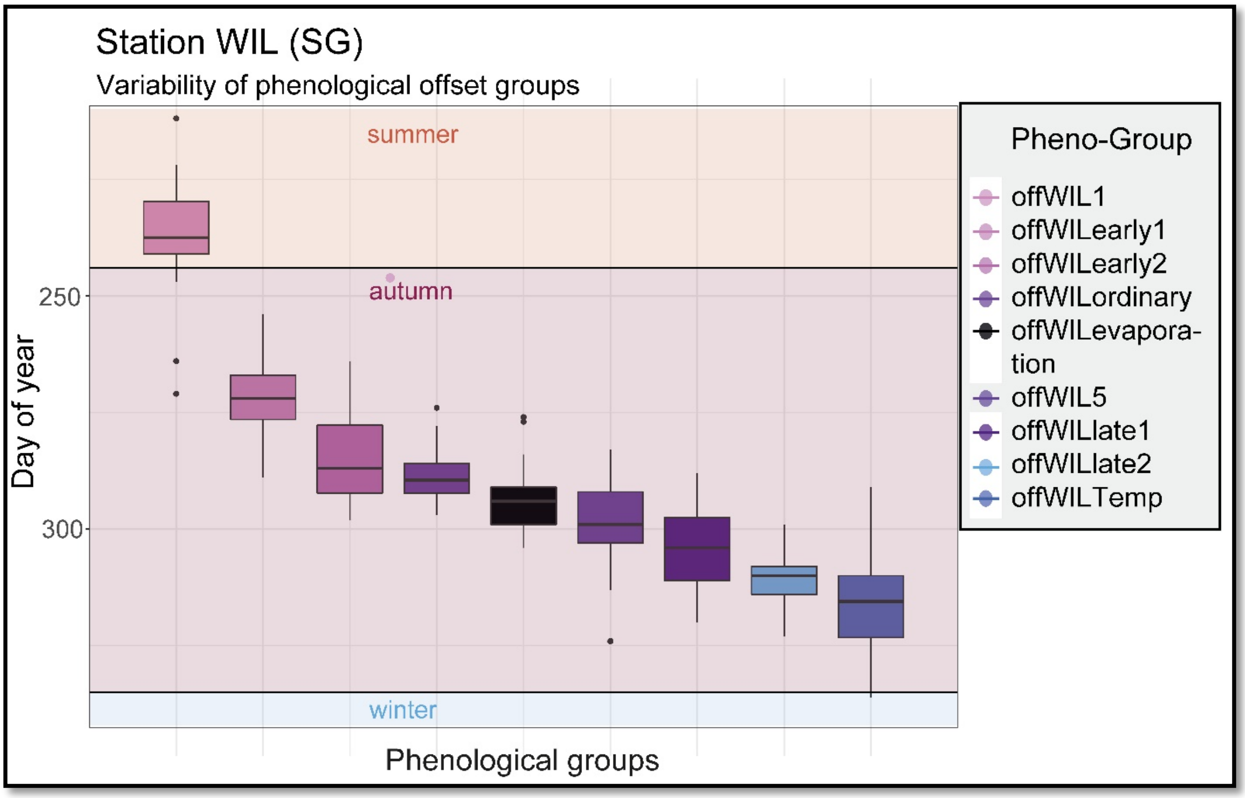

Figure 14. *Variability within phenological offset groups (ADB)*
Note, the stated background seasons are meteorological seasons.

4.4 Hydrological data processing

The foundation of the hydrological data analysis was the creation of a data frame for each catchment (Allenbach and Murg) with complete P, Q, and temperature data series and with the corresponding day of year and date. After that, the different on- and offset information of the phenological groups and the fixed calendar dates were used to extract the desired sections from the Q data series. This Q sections were than processed with different extraction methods.

4.4.1 Extraction method for visual assessment of recession behavior

To prevent the influence of quick overland runoff, three extraction steps were applied in sequence. First, all the days and the day after on which a P signal higher than 2 mm was recorded were filtered out. Second, all days with an increase or stagnation of Q rates were removed to obtain the recession events at all. The last extraction step was applied to filter out all single recession days with a two-day minimum-length recession filter. This extracted recession series was subsequently used for visual assessment and was not too strict in order to be able to observe differences in inter- and base flow recession behaviors.

4.4.2 Extraction methods for base flow R_C calculation

To select the base flow recession events, four extraction steps were applied in sequence. First, all days with a P signal higher than 2 mm were filtered out. Second, all days with an increase or stagnation of Q rates were removed to obtain the recession events at all. Third, all anomalous high recession rates were excluded to filter out quick flow and most of the quick interflow events. The estimation of the accurate day of transition from quick to base flow condition using a mean Q hydrograph was not effective. To make the recession dimensions more visible, relative decline values were used instead.
The results were fixed thresholds, estimated on the basis of the mean and quantile decline rates from all the available summer recession events (S_1 - S_{end}). In the Allenbach catchment (Fig. 15), the threshold was the decline rate of the 75th quantile (Q75 = 12.5%) from the fourth recession day. In the Murg catchment (Fig. 16), the threshold was the decline rate of the 75th quantile (Q75 = 16%) from the fifth recession day. At those two thresholds, the transition from quick to base flow condition takes place approximately. The last extraction step excluded all the single recession day events with a two-day minimum-length recession filter.

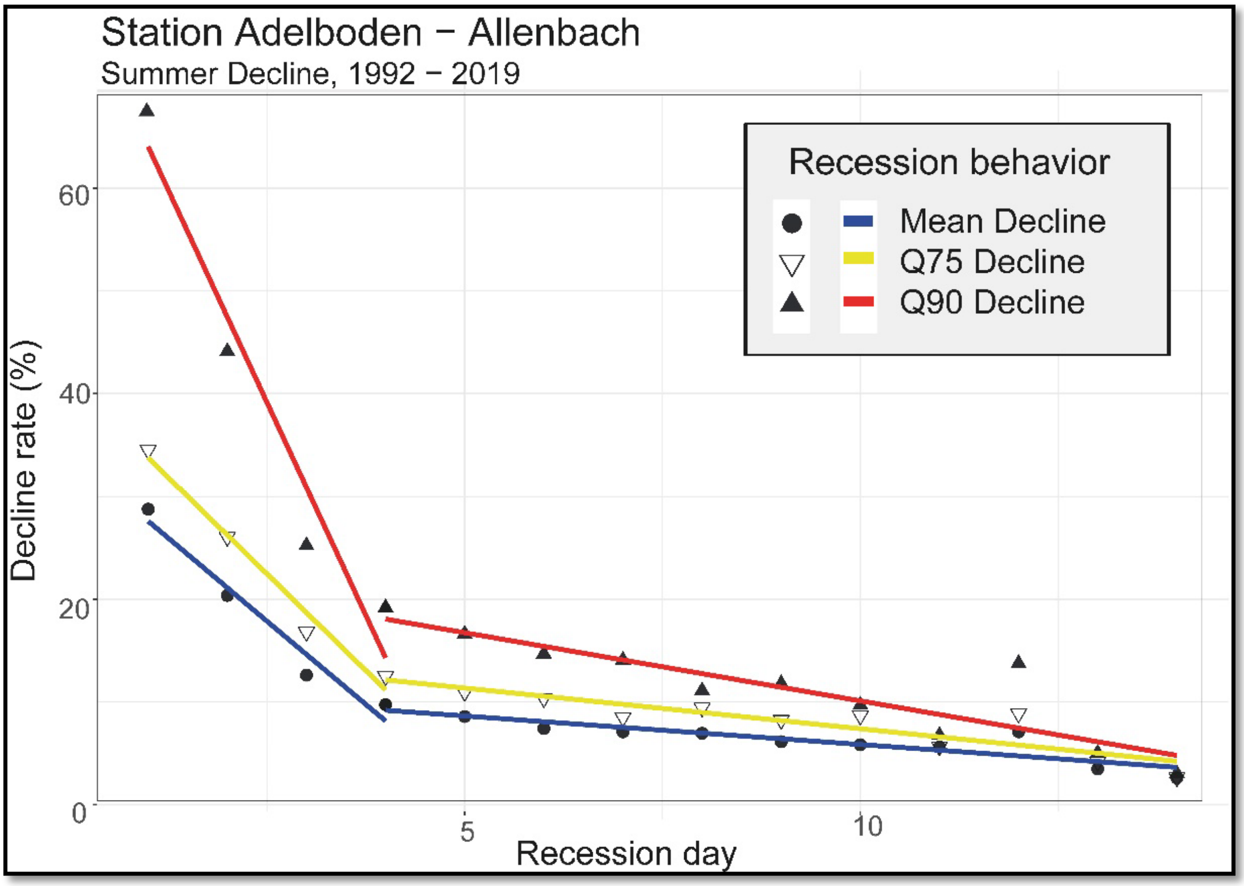

Figure 15. *Summer recession rates for Allenbach without extraction methods applied*

4.4.3 Recession analysis method

In this thesis, visible differences in the log-log recession scatterplots and the calculated R_C of base flow recession were used to assess recession behavior. The method and the analysis follow the example presented by Brutsaert and Nieber (1997). The visual results are shown on a log-log scatterplot with the mean Q value from two consecutive days ($Q = (Q_{t-1} + Q)/2$) on the x-axis and the negative difference of Q ($-\frac{dQ}{dt} = Q_{t-1} - Q$) on the y-axis (Brutsaert & Nieber, 1977; M. Stoelzle et al., 2013). To analyze the base flow R_C, the linear solution (b = 1) of the power-law relationship (Equation 3) was used. This was feasible because linear recession behavior was assumed under the applied decline thresholds for base flow R_C calculation (4.4.2). Rupp and Selker (2006) listed a considerable number of studies which used the linear solution (b = 1) for the late stage of recession both for horizontal and sloping aquifers. The exponential of the intercept (a in Equation 3the) on the y-axis from the resulting regression line on the log-log plot represents the R_C from the analyzed Q section.

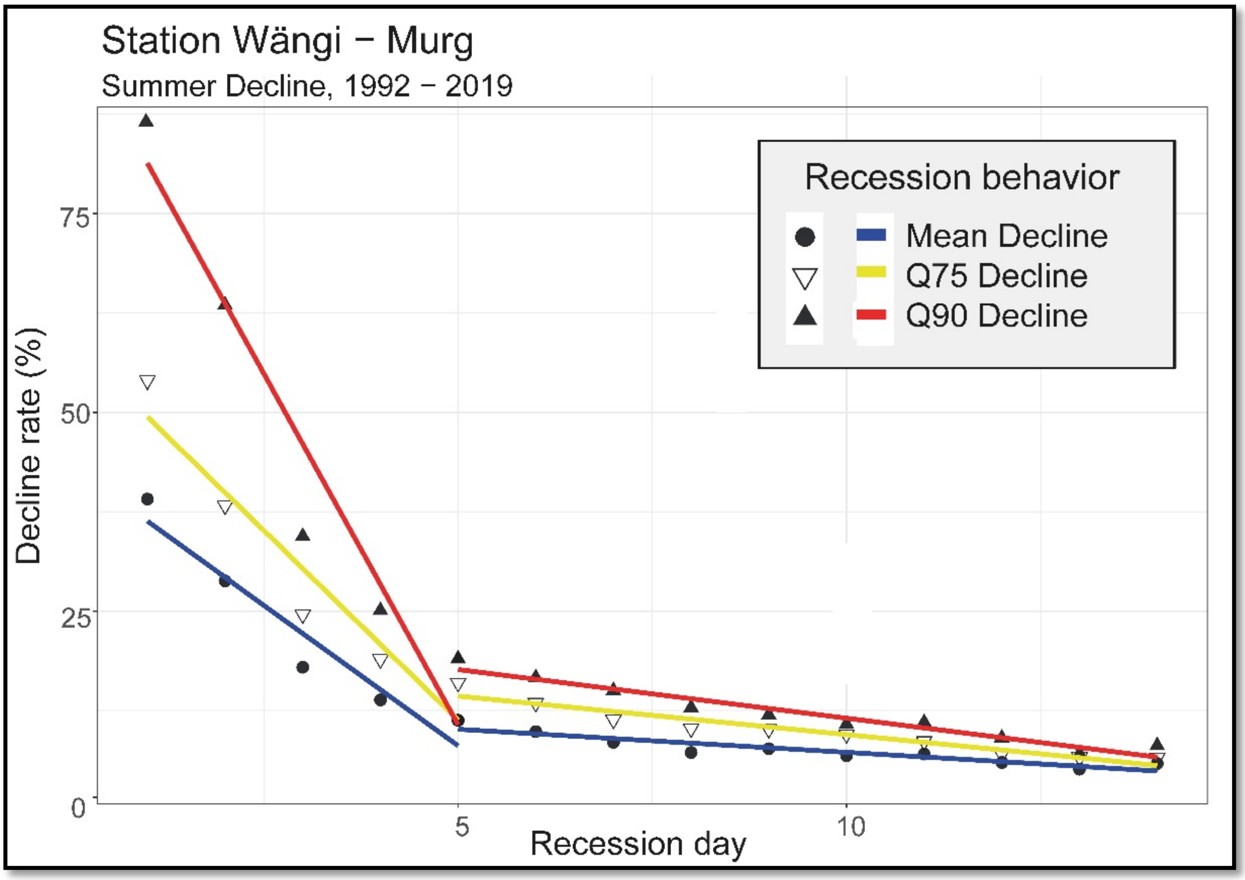

Figure 16. *Summer recession rates for Murg without extraction methods applied*

5. Results: Allenbach

The Allenbach catchment was characterized by recurrent variations in recession behavior during the relevant years, which can be observed in both the visual and R_C analyses.

5.1 Visual analysis of recession behavior

The extraction methods for the visual approach (4.4.1) lead to 3,405 recession days over the entire study period, that is, 33.3% of all days. The coloring of the recession days according to their feature "day of the year" immediately reveals a slight seasonality (Fig. 17). Each point represents a recession day with the corresponding Q value on the x-axis and the negative recession slope (- dQ/dt) on the y-axis. Days at the beginning and the end of the calendar year appear as blue points. Day 182 (1st July) is dyed in red. Recession days in between are dyed according to their feature "day of the year" with a gradient. By trend, the red days in the middle of the year are in the top-right corner, whereas the blue points are scattered in the bottom-left corner. This arrangement indicates the rough tendency that in summer the runoff and the recession rate are higher in the Allenbach. Conversely, days in winter (blue) are generally characterized by lower Q and decline values.

This finding is consistent through all the results. Figure 18 illustrates the difference in the recession behavior between the active and the dormant seasons of different approaches to divide the year into two seasons. The E division approach is illustrated in the top-left corner, the hydrological year division appears in the top-right corner, the temperature division appears in the bottom-left corner, and in the bottom-right corner are the two phenological groups (onADBlate2 – offADB5) that have the biggest difference between summer and winter base flow R_C (Table 4).

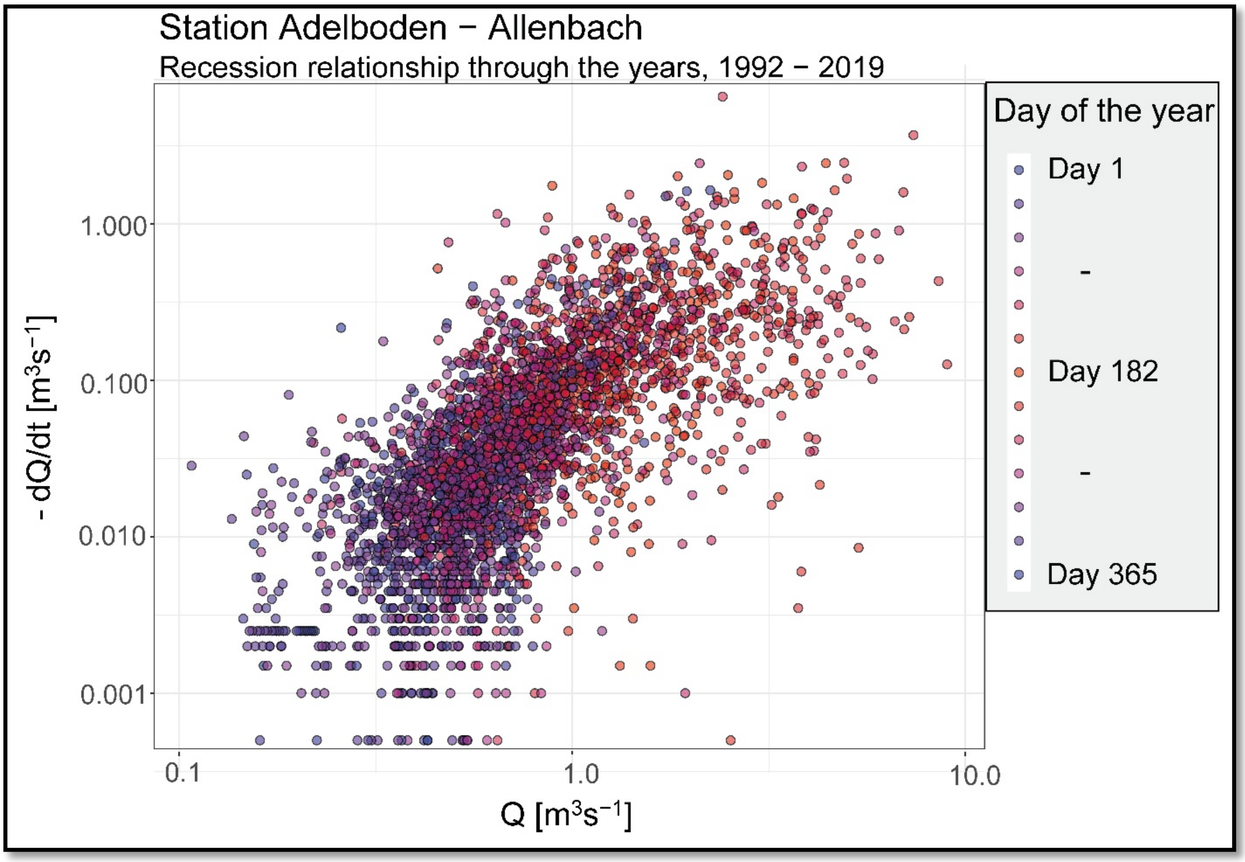

Figure 17. *Recession behavior for Allenbach with the feature "day of the year"*
Note, the x and y axes are logarithmic

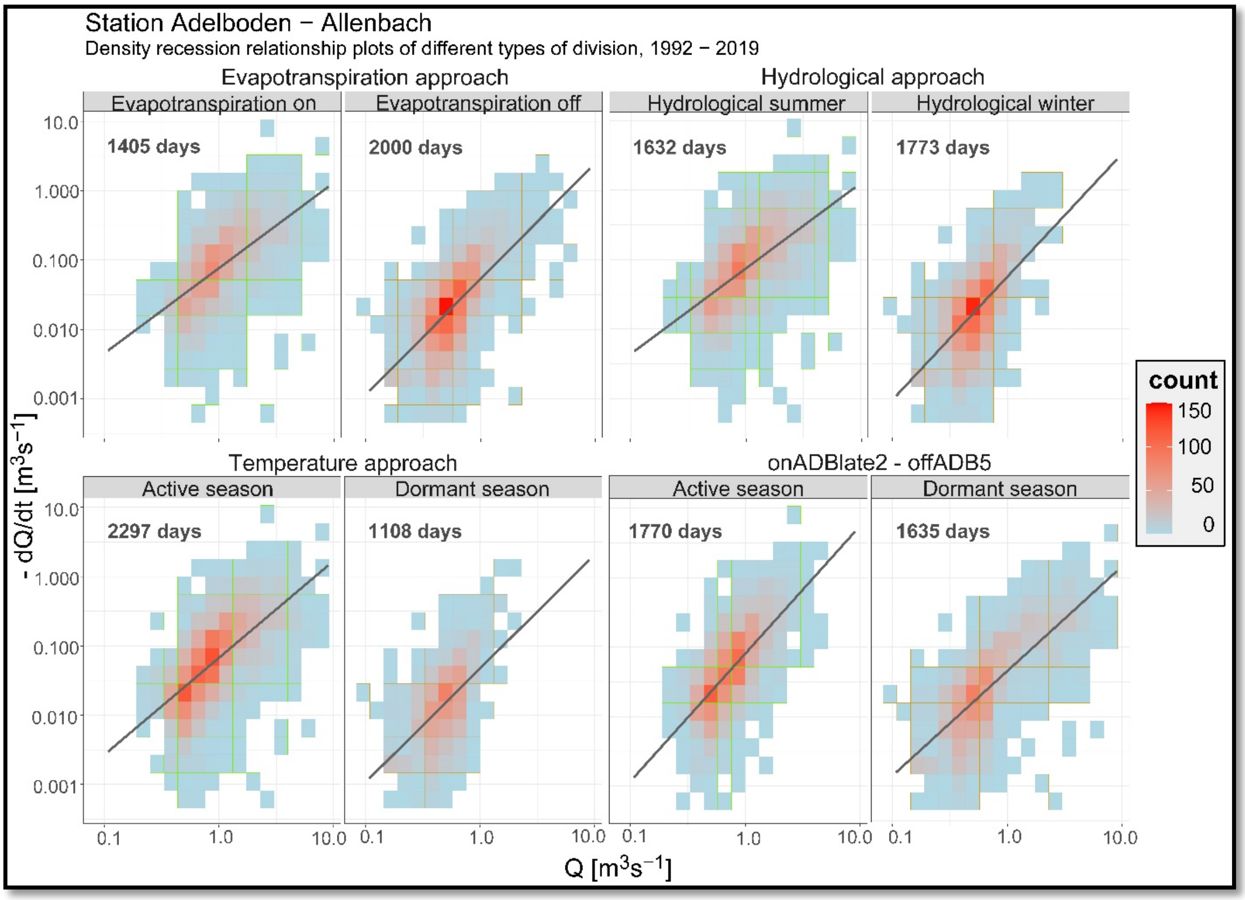

Figure 18. *Recession behavior for Allenbach with different division approaches by comparison*
Note, the x and y axes are logarithmic

The red squares in Figure 18 indicate a higher density of recession points in that area of the plot. The "hydrological summer" and "evapotranspiration on" seasons represent the active season. The core area of data points in the active season is noticeable with higher recession values and slightly higher Q values. That pattern is similar in all four division approaches. In addition, the number of recession days and the linear regression line are illustrated in the plot. The less step regression lines (e.g. hydrological summer) indicate higher recession rates even in lower Q conditions. Though, the regression lines should be treated with caution because the relationship of recession in nature is not linear with the rather soft extraction methods applied for these visual plots. In general, the percentage of recession days is higher through the winter season (Table 4). However, because of the long active season generated with the temperature division approach, the active season consists of more than twice as many recession days compared to the short dormant season. The visual differences between the varying on- and offset approaches are generally difficult to detect when dividing the year into only two seasons.

The difference in recession behavior between the seven elaborated phenological seasons are illustrated in Figure 19. In this case, the differences can be discerned more clearly. The seasons "late spring" and "early summer" are particularly conspicuous. By comparing the summer and winter recession plots, one can find the same pattern as in the "day of the year" plot (Fig. 17), but the differences are even more emphasized in this case. It is noticeable, that the early spring season illustrates values that are spread across the entire recession spectrum. Whereas during late spring and early summer, the recession rates and the Q values are considerable higher compared to the other seasons. The early autumn and late autumn recession behavior appears similar to the winter recession behavior. However, a slight trend from early autumn towards winter is recognizable with higher recession rates and fewer very low Q values in the early autumn season. Consequently, the lowest recession rates across the years can be found during the winter season. In addition, the Q values during the winter season are frequently lower compared to the other seasons, specifically in comparison with the late spring and early summer season. The degree to which the effect of snow melt causes the deviant recession behavior is illustrated in Chapter 5.3 and discussed later (Chapter 7.3.3). The same plot but with the base flow extraction methods can be found in Appendix C.

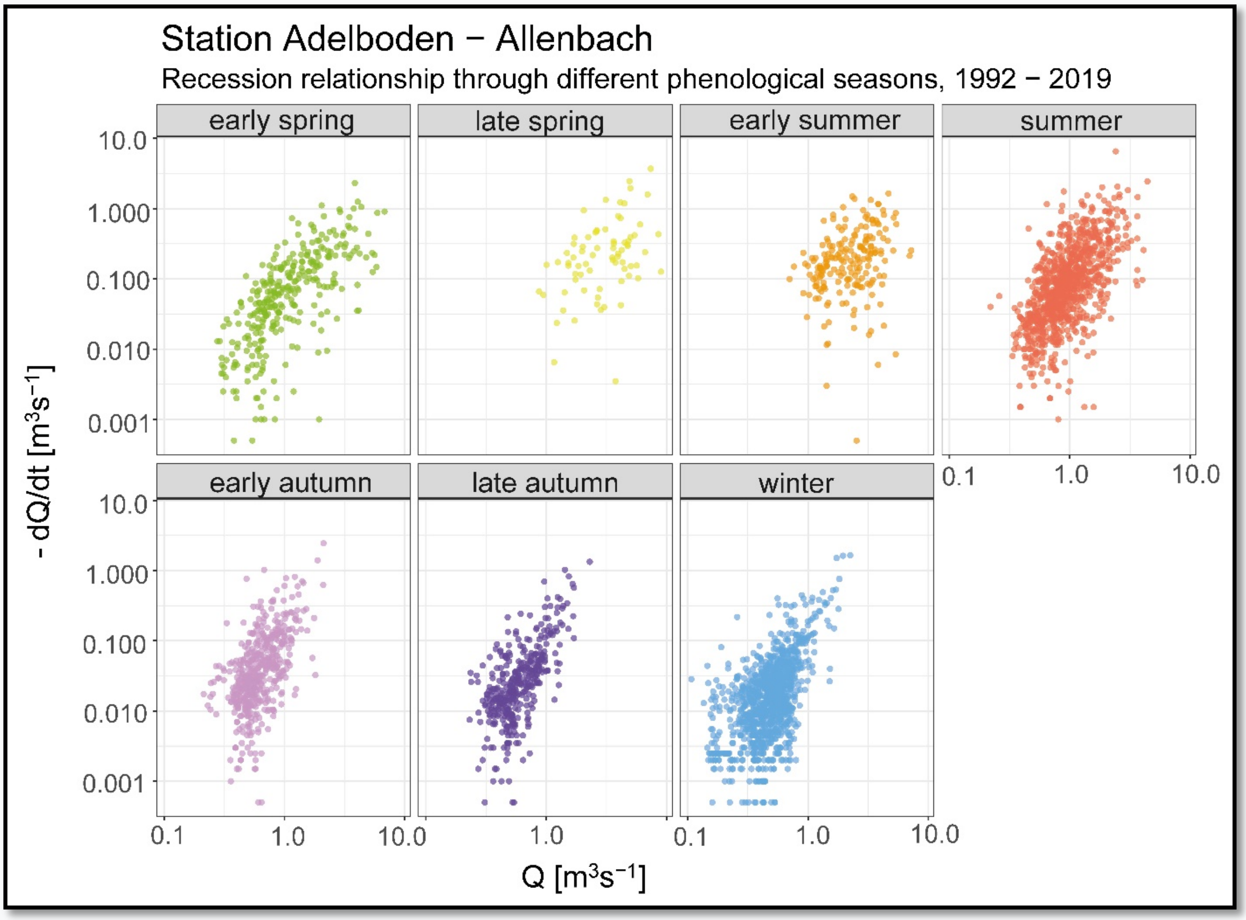

Figure 19. *Recession behavior for Allenbach within different phenological seasons*
Note, the x and y axes are logarithmic

5.2 Comparison of the base flow recession constants through the year

Figure 20 demonstrates the changing value of the base flow R_C through the year. The extraction methods for the base flow R_C calculation (4.4.2) lead to 2,925 recession days over the entire study period, that is, 28.6% of all days. In this plot, the phenological periods are roughly grouped into a "Spring & Summer" season ($S_1 – S_{12}$) and a "Autumn & Winter" season ($W_1 – W_6$). However, the interesting details are the changing R_C values of the individual phenological periods. On the x-axis below the labels of the phenological period, the corresponding accurate R_C value is indicated. W_5 represents the R_C value of the winter season on the phenological circle ADB (Fig. 3). Consequently, S_9 represents the R_C value of the summer season on the same phenological circle.

By trend, the later the examined summer period is located, the higher the corresponding R_C value. The only exception is the period S_6, that has a marginal lower R_C value compared to the period S_5. The considerable higher R_C values in summer are conspicuous, particularly the last period S_{12}. Conversely, the later the examined winter period, the lower the corresponding R_C. The trend from W_1 (early autumn until end of winter) to W_6 appears more continuous compared to the trend from S_1 (early spring until end of summer) to S_{12}.

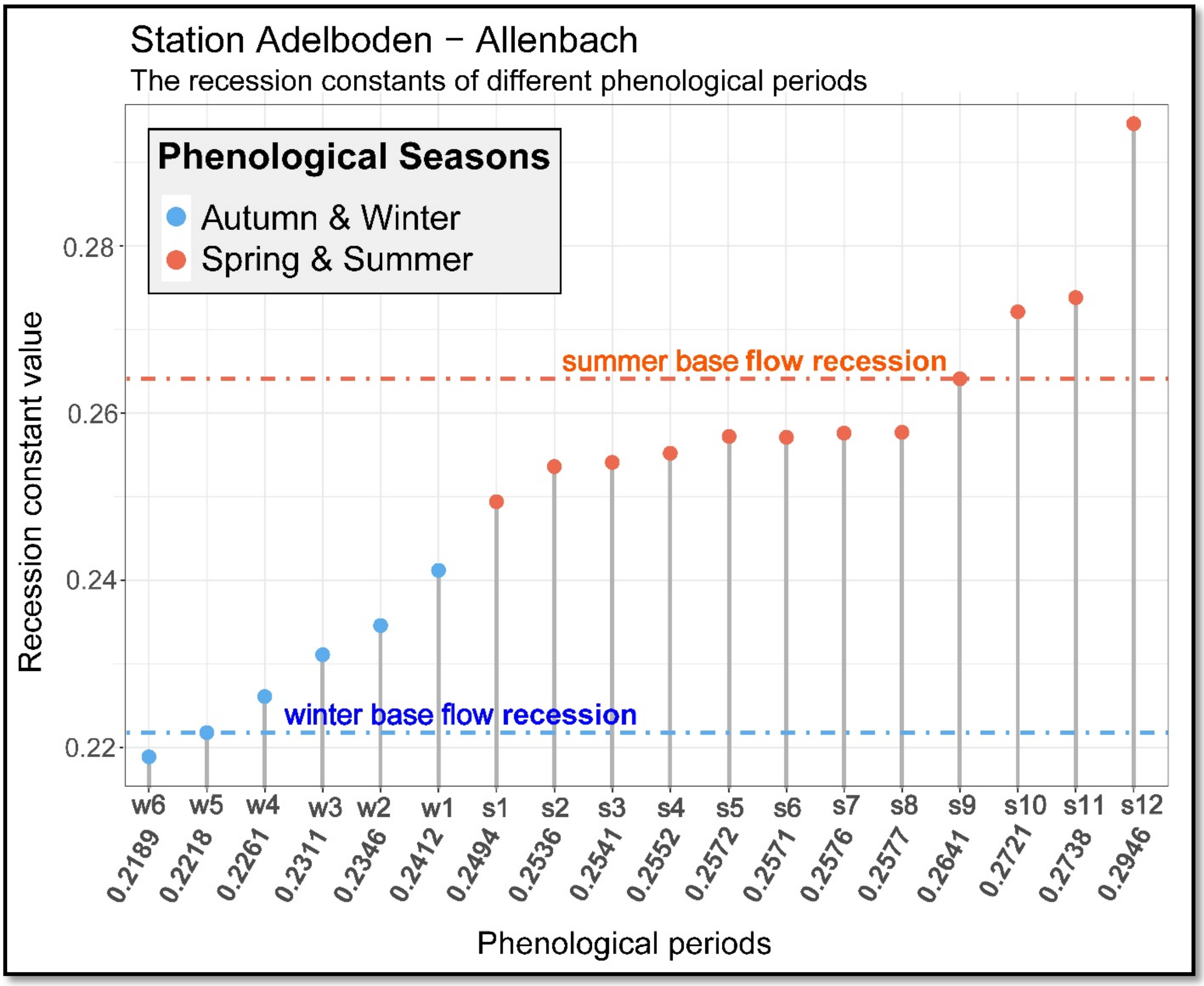

Figure 20. *Comparison of base flow R_C for Allenbach including all phenological periods*

5.2.1 Comparison of fixed versus flexible base flow R_C

Table 4 reveals a sizable number of base flow R_C from different division approaches for Allenbach. The first column specifies the type of division approach and therefore the investigated time period. The R_C in the second column is calculated from all base flow recession days, that are the days which passed the base flow extraction methods described in Chapter 4.4.2. The column "total days" indicates the amount of days that fell into the respective season through the entire examination period. The percentage in column five is calculated with "total days" and "recession days" and provides information about the portion of days that passed the base flow extraction methods. The last column reveals the corresponding difference between the summer and winter R_C.
The first three approaches are the calendar reference dates described in Chapter 4.2.3. The three dyed approaches (E, snow, and temperature) all include a R_C calculation with the annually flexible on- and offset days and the fixed (means) on- and offset days illustrated on the phenological circle ADB (Fig. 3). Finally, in the last row the phenological groups which produce the biggest difference between summer and winter base flow R_C are revealed.
The fixed calendar division approaches of the web search (Weather Spark) and the hydrological year produce similar R_C differences. However, the R_C difference between meteorological.s and meteorological.w is considerably less than the difference from all other division approaches. Interestingly, the R_C difference between the meteorological winter and spring compared to the meteorological summer and autumn is 0.0265 (not in the Table) and therefore higher than the other two fixed calendar reference date approaches. All three approaches which offer flexible and fixed divisions reveal similar characteris-

tics. The calculations with the flexible on- and offset days produce slightly higher R_C differences with one exception (onADBlate2-offADB5). The flexible temperature division approach produces the maximum season R_C difference of all indicators in the Allenbach catchment. In comparison, although the R_C of the active season of the flexible E division approach is higher, the difference between summer and winter recession is only slightly more than half as high. Finally, the summer division of onADBlate2 to offADB5 provides from all approaches the highest base flow R_C for the active season and the fixed temperature division approach provides the lowest R_C value for the dormant season.

Table 4. *Comparison of base flow R_C for Allenbach with different division approaches*
The letter "s" depicts summer season and the letter "w" indicates the winter season

Type of season division	Rc value	total days	recession days	Percentage	Difference
Weather Spark.s	0.2557	3752	935	24.92004	
Weather Spark.w	0.2341	6447	1721	26.69459	0.0216
Hydrological year.s	0.2554	5096	1124	22.05651	
Hydrological year.w	0.2333	5103	1573	30.825	0.0221
Meteorological.s	0.2489	5124	1059	20.66745	
Meteorological.w	0.2433	5075	1715	33.7931	0.0056
flexible evapotranspiration on	0.2566	3996	942	23.57357	
flexible evapotranspiration off	0.2398	6203	1738	28.0187	0.0168
fixed evapotranspiration on	0.2555	4004	940	23.47652	
fixed evapotranspiration off	0.239	6195	1750	28.24859	0.0165
flexible snow date.s	0.261	3013	847	28.11152	
flexible snow date.w	0.2363	7192	1810	25.16685	0.0247
fixed snow date.s	0.2573	2992	816	27.27273	
fixed snow date.w	0.2363	7213	1817	25.19063	0.021
flexible temperature date.s	0.2492	6801	1710	25.14336	
flexible temperature date.w	0.2173	3398	1018	29.9588	0.0319
fixed temperature date.s	0.2491	6804	1712	25.16167	
fixed temperature date.w	0.2211	3395	1026	30.22091	0.028
flexible onADBlate2-offADB5.s	0.2609	4255	1280	30.08226	
flexible onADBlate2-offADB5.w	0.2305	5944	1351	22.7288	0.0304
fixed onADBlate2-offADB5.s	0.2609	4256	1270	29.84023	
fixed onADBlate2-offADB5.w	0.2302	5943	1360	22.88407	0.0307

5.3 The influence of snow cover

Table 1 illustrates the six years that are investigated in more detail to evaluate the influence of snow on recession behavior during the spring and summer season. Figure 21 reveals the recession behavior after winter seasons with large amounts of snow (the years 1999, 2000, and 2018) and little snow occurrence (the years 1998, 2010, and 2011). The investigated season are early spring, late spring, early summer and summer and are dyed in their allocated color. Investigating three years provides only a few data points on the scatterplot. The Q values of late spring and early summer are considerable higher than the Q values of early spring and summer in all years. That overall pattern remains the same, despite the differences in snow height. In addition, the recession rates of the late spring and early summer season are higher too. Consequently, the data points of these two seasons are scattered in the top-right corner of their respective plots. After winters that produced a large snow cover, the differences from late spring and early summer to the early spring and summer season are even more pronounced. The generally higher recession rates after snowy winters are also demonstrated in the fact that the scale on the y-axis in Figure 21 is different for the much and little snow accumulation during winters. After winters with little snow cover, no recession day reached the value one, whereas after snowy winters several recession days top that threshold, especially during late spring. It is also noticeable that the summer recession behavior differs. After snowy winters the data cloud seems more round compared to the data cloud after little snow occurrence. Generally, the early spring and summer season reveal a wider spectrum in recession behavior compared to late spring and early summer.

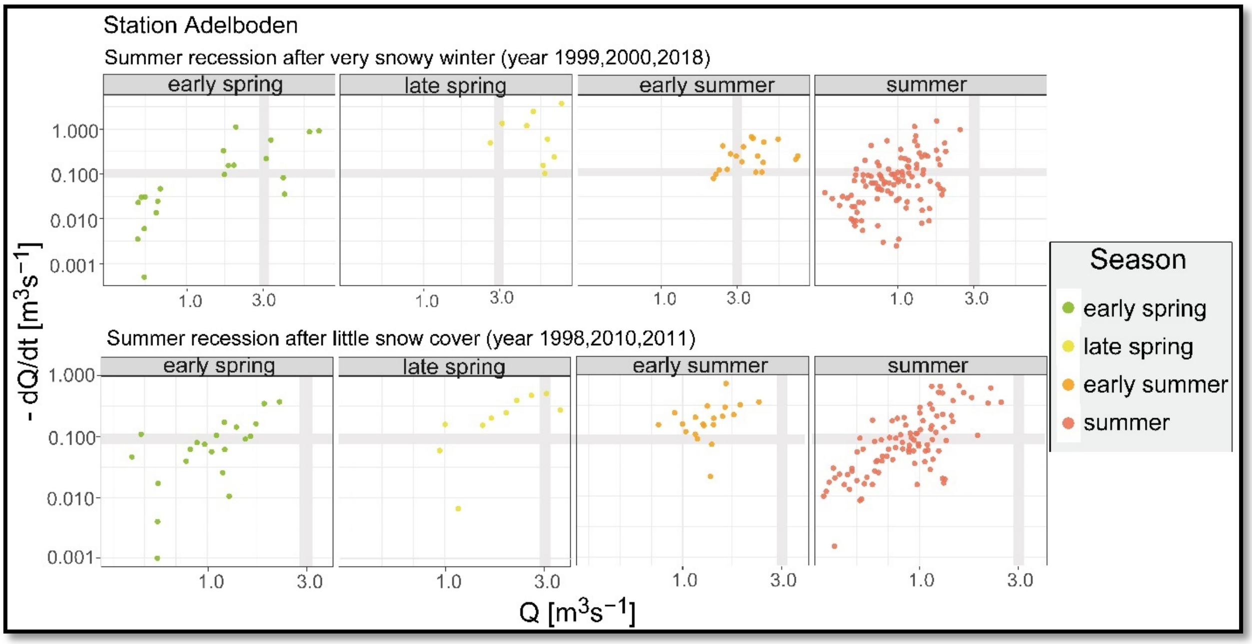

Figure 21. *Recession behavior for Allenbach after winters with much (top) and little (bottom) snow*
Note, the x and y axes are logarithmic

6. Results: Murg

Compared to the Allenbach catchment, the Murg catchment was slightly less characterized by recurrent variations in recession behavior during the relevant years. Particularly the visual differences are less evident compared to the Allenbach. However, the base flow R_C analysis illustrated conspicuous differences in base flow recession behavior between the active and the dormant season.

6.1 Visual analysis of recession behavior

The extraction methods (4.4.1) lead to 4,262 recession days over the entire study period, that is, 42.7% of all days. The coloring of the recession days according to their feature "day of the year" reveals a slight trend towards higher recession rates during the active season (Fig. 22). Although both colors can be found across the entire spectrum of Q values, outliers towards high recession rates (y-axis) are mostly red (in the middle of the year), especially in the lower Q range.

Figure 23 illustrates the difference in the recession behavior between the active and the dormant seasons of different approaches to divide the year into season. The E division approach is illustrated in the top-left corner, the hydrological year division appears in the top-right corner, the temperature division is illustrated in the bottom-left corner, and in the bottom-right corner are the two phenological groups (onWILearly2 – offWIL5) revealed that have the biggest difference between summer and winter base flow R_C (Table 5).

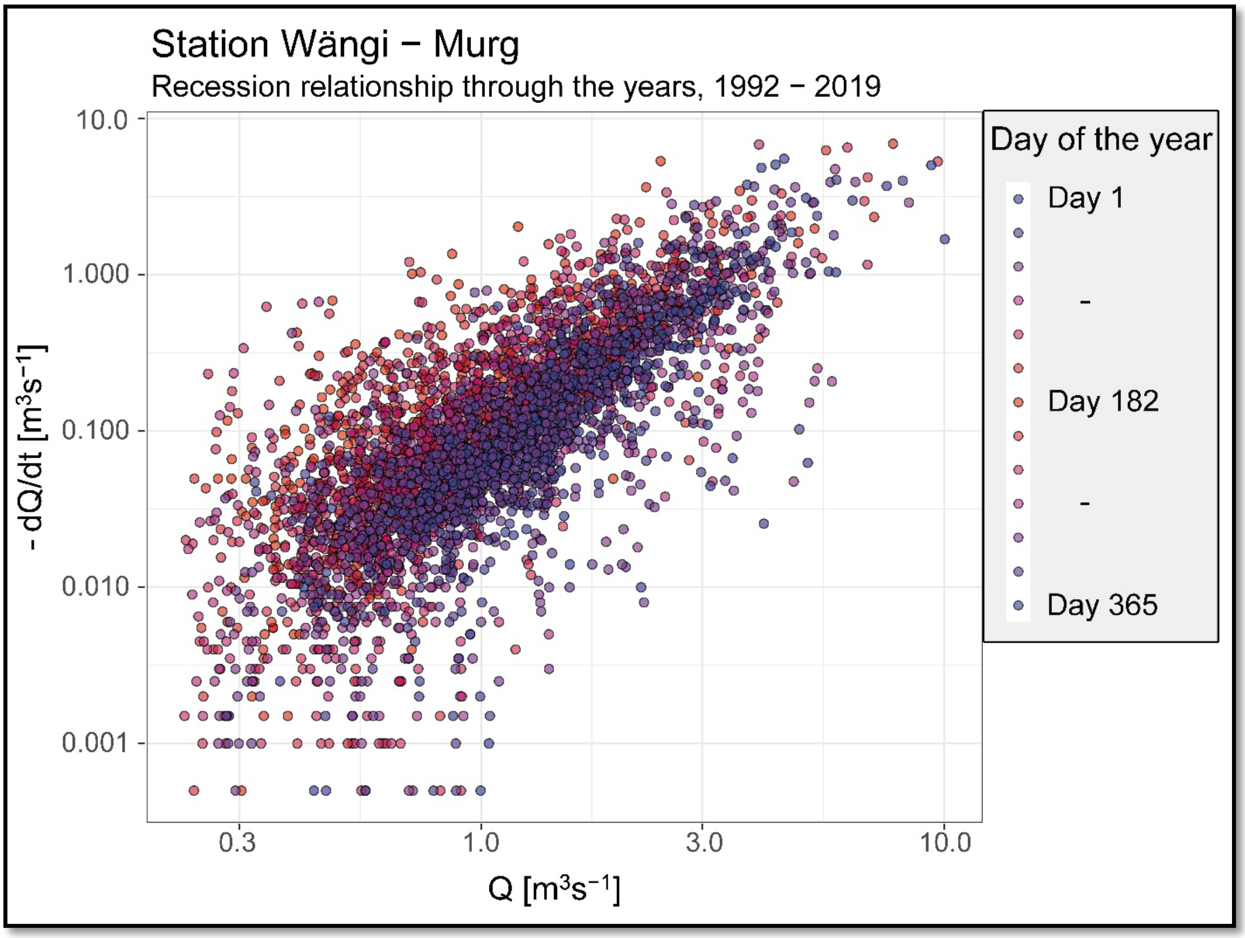

Figure 22. *Recession behavior for Murg with the feature "day of the year"*
Note, the x and y axes are logarithmic

The core area of data points in the active season is noticeable with lower Q values in all arrangements. However, the core area of the active and the dormant season appear approximately on the same recession level. That pattern is similar in all four division approaches. Consequently, recession rates are, in proportion to their corresponding Q values, generally higher during the active season. Though, the visual differences between the varying on- and offset approaches are somewhat difficult to detect when dividing the year into only two seasons.

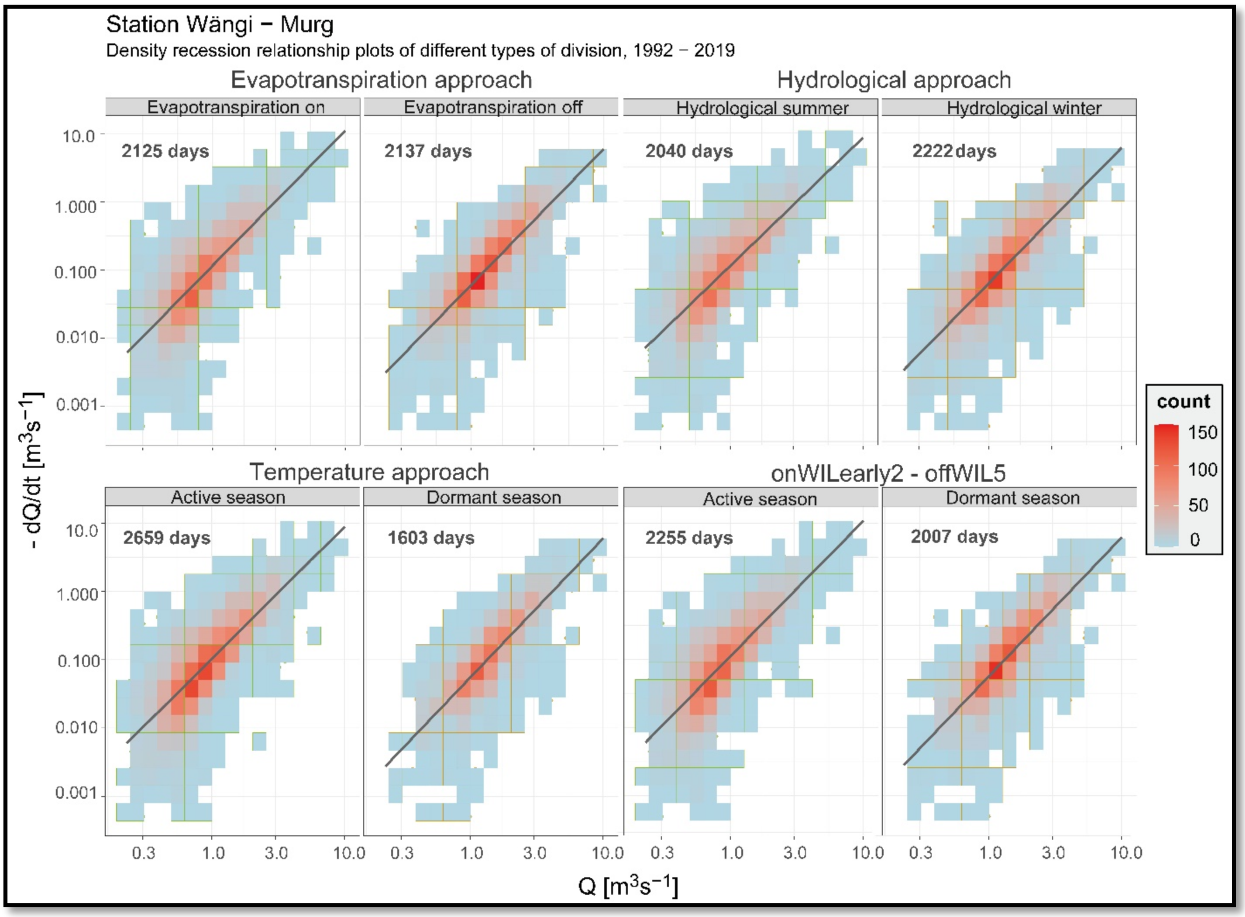

Figure 23. *Recession behavior for Murg with different division approaches by comparison*
Note, the x and y axes are logarithmic

The difference in recession behavior between the seven elaborated phenological seasons are illustrated in Figure 24. The differences between the two seasons are not as clearly visible as for the Allenbach catchment. On one hand, a clear tendency of decreasing Q values appears from early spring to summer. On the other hand, the tendency of decreasing recession values on the y-axis is only marginal. That tendency indicates again that during summer the recession rates do not decrease to the same extent as the corresponding Q values. By comparing the summer and winter recession behavior, a similar pattern as in the "day of the year" plot (Fig. 22) and in the hydrological division approach (Fig. 23) can be detected. The summer recession behavior is characterized by numerous values in the top-left area of the plot (high recession rates with low Q values).

It is noticeable, that the winter season illustrates values that are spread across the entire spectrum but contains only few points with very low Q values. I would argue that the early spring season demonstrates a great agreement with the winter recession behavior but more concentrated and without low Q values. The late autumn recession behavior reveals some similarity to the winter recession behavior. However, the recession behavior of the early autumn season has more similarity with the summer season than with the late autumn and winter season. The same plot for the Murg catchment but with the base flow extraction methods can be found in Appendix C

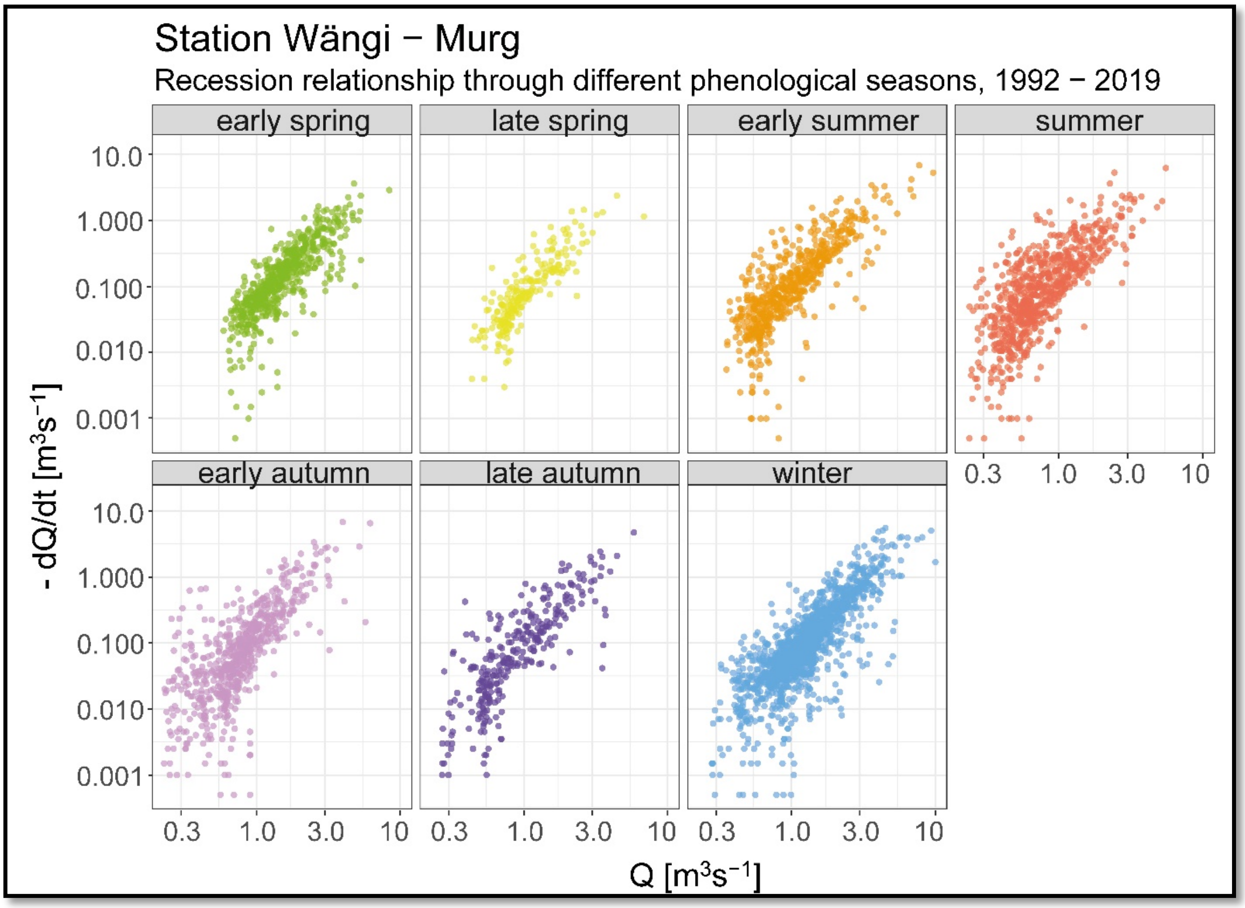

Figure 24. *Recession behavior for Murg within different phenological seasons*
Note, the x and y axes are logarithmic

Finally, the recession behavior is subdivided into even more section (periods). Figure 25 illustrates a division into 15 different periods but without the winter season. The division of this plot represents the most detailed temporal resolution for the visual analyzation that was possible with the phenological group approach. By comparing the recession behavior from top to the bottom, one can clearly detect the trend to lower Q values towards the end of summer and early autumn. Again, some outliers with high recession rates but low Q values are detectable during the transition from late summer to early autumn. Periods in the summer and the early autumn season reveal conspicuous similarities in recession behavior. Clear, strong changes between the consecutive periods cannot be detected. The same type of plot for the Allenbach catchment is demonstrated in Appendix C.

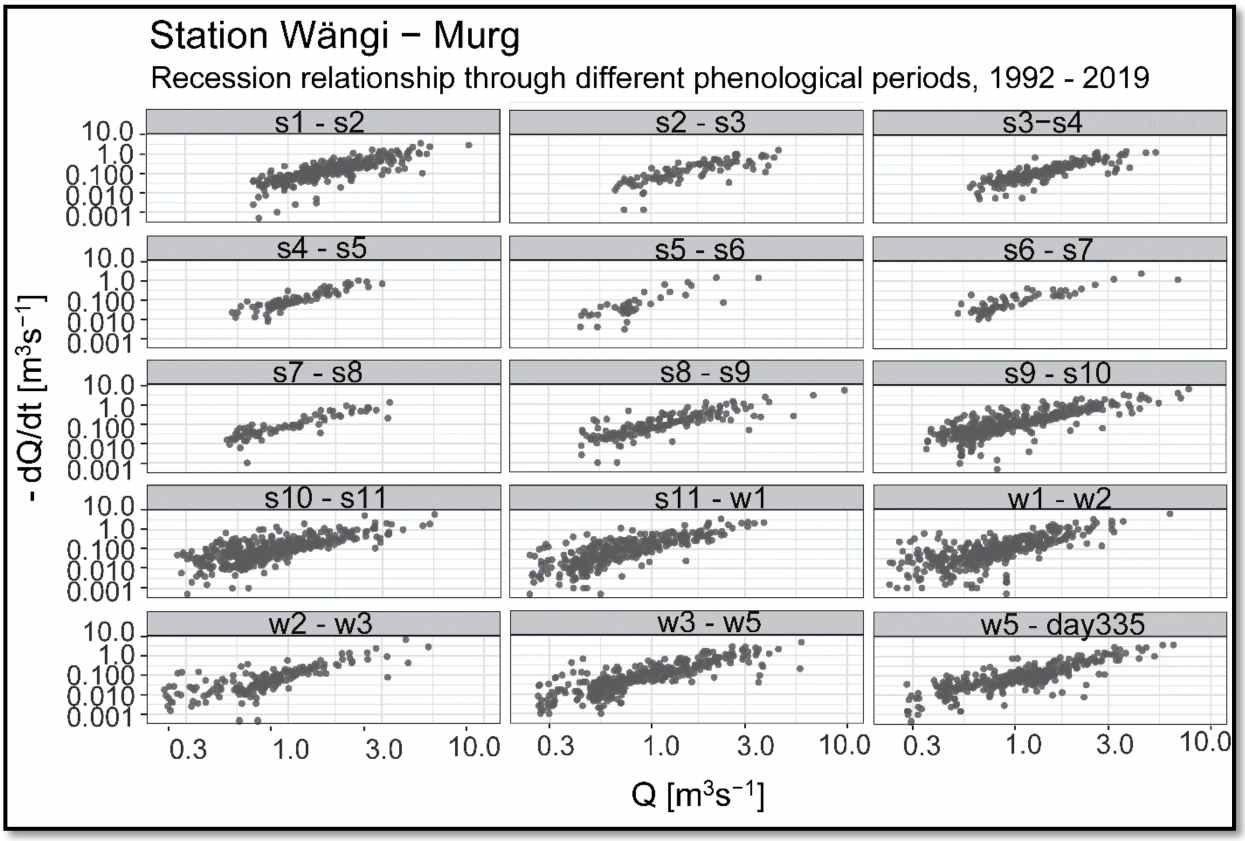

Figure 25. *Recession behavior for Murg within different phenological seasons*
Note, the x and y axes are logarithmic

6.2 Comparison of the base flow recession constants through the year

Figure 26 demonstrates the changing value of the base flow R_C through the year for the Murg. The extraction methods for the base flow R_C calculation (4.4.2) lead to 3,063 recession days over the entire study period, that is, 30% of all days. In this plot, the phenological periods are roughly grouped into a "Spring & Summer" season (S_1 – S_{12}) and a "Autumn & Winter" season (W_1 – W_6). On the x-axis, the corresponding accurate R_C value is indicated. W_7 represents the R_C value of the winter season on the phenological circle (Fig. 9) and S_{10} represents the R_C value of the summer season.
It is noticeable that the later the examined summer period is located, the higher the corresponding R_C value. However, there are two noticeable exceptions (S_7 and S_8). The considerable higher R_C values in summer are conspicuous. The last two periods (S_{10} and S_{11}) appear noticeable higher even when comparing them to the other "Spring & Summer" values. Conversely, the later the examined winter period, the lower the corresponding R_C value. The only exception is the period W_5, that has a slightly lower R_C value compared to the period W_6. The trend from the W_1 period to the W_8 period (autumn transition) appears much weaker compared to the trend from S_1 to S_{11} (spring and summer transition).

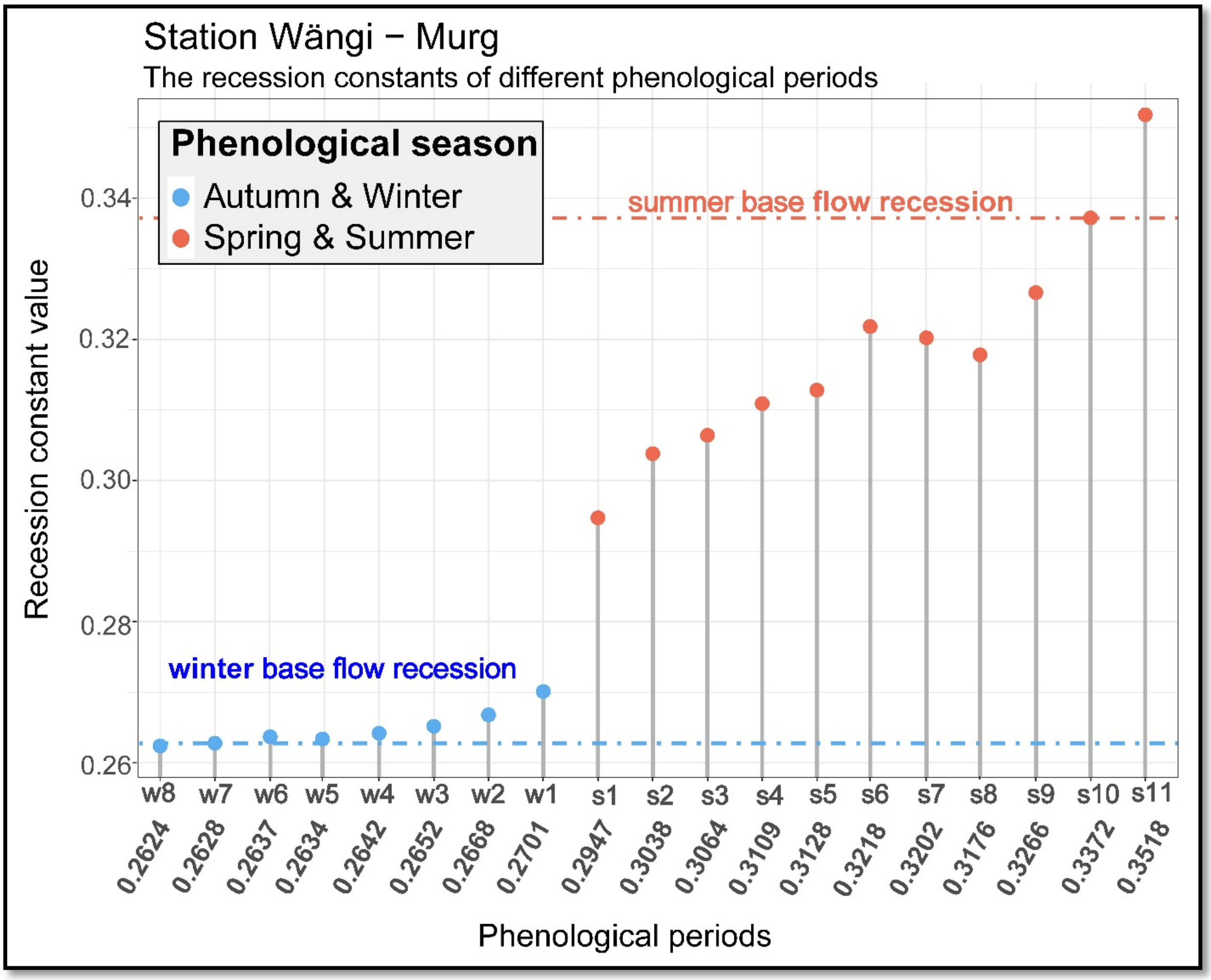

Figure 26. *Comparison of base flow R_C for Murg including all phenological periods*

6.2.1 Comparison of fixed versus flexible base flow RC

Table 5 reveals a sizable number of base flow R_C from different division approaches for the Murg. The first column specifies the type of division approach and therefore the investigated time period. The letter "s" depicts summer season and the letter "w" indicates the winter season. The R_C in the second column is calculated from all base flow recession days, that are the days which passed the base flow extraction methods described in Chapter 4.4.2. The column "total days" indicates the amount of days that fell into the respective season through the entire examination period. The percentage in column five is calculated with "total days" and "recession days" and provides information about the portion of days that passed the base flow extraction methods. The last column reveals the corresponding difference between the summer and winter R_C value.

The first three approaches are the calendar reference dates described in Chapter 4.2.3. The two dyed approaches (E, and temperature) both include R_C calculations with the annually flexible on- and offset days and the fixed on- and offset days illustrated on the phenological circle WIL (Fig. 9). Finally, the phenological groups which produce the greatest difference between summer and winter base flow R_C are revealed in the last row. The fixed calendar division approaches from Weather Spark and the hydrological year produce similar R_C differences. However, the R_C difference between meteorological.s and meteorological.w is considerably lower than the difference from all other division approaches. The E and the temperature division approach reveal similar characteristics. Both demonstrate slightly higher R_C differences when using the fixed on- and offset dates compared to the flexible on- and offset dates. The fixed E division approach produces the maximum season R_C difference of all indicators in the Murg catchment. However, the highest summer base flow R_C is obtained with the Weather Spark division approach. The difference between onWILearly2-offWIL5.s and onWILearly2-offWIL5.w is noticeably larger than the difference with the E division approach and therefore produces the biggest difference of all flexible approaches. Different from the E and temperature division approach, the phenological groups onWILearly2 and offWIL5 reveal a bigger difference between R_C with the flexible on- and offset dates compared to the fixed dates. Finally, the winter R_C of the temperature division approach reveals the lowest value of recession when dividing the hydrological year into only two seasons.

Table 5. *Comparison of base flow R_C for Murg with different division approaches*
The letter "s" depicts summer season and the letter "w" indicates the winter season

Type of season division	Rc	total days	recession days	Percentage	Difference
Weather Spark.s	0.3086	5600	1424	25.42857	
Weather Spark.w	0.267	4570	1594	34.87965	0.0416
Hydrological year.s	0.3059	5096	1280	25.11774	
Hydrological year.w	0.2663	5074	1730	34.09539	0.0396
Meteorological.s	0.2944	5124	1349	26.32709	
Meteorological.w	0.2711	5046	1689	33.47206	0.0233
flexible evapotranspiration on	0.3085	5281	1341	25.39292	
flexible evapotranspiration off	0.2665	4889	1671	34.17877	0.042
fixed evapotranspiration on	0.3093	5292	1325	25.03779	
fixed evapotranspiration off	0.2666	4878	1695	34.74785	0.0427
flexible temperature date.s	0.3015	6540	1722	26.33028	
flexible temperature date.w	0.2638	3630	1294	35.64738	0.0377
fixed temperature date.s	0.3007	6524	1755	26.90067	
fixed temperature date.w	0.2617	3646	1275	34.96983	0.039
flexible onWILearly2 - offWIL5.s	0.3081	5573	1432	25.69532	
flexible onWILearly2 - offWIL5.w	0.2655	4597	1581	34.39199	0.0426
fixed onWILearly2 - offWIL5.s	0.3078	5572	1422	25.52046	
fixed onWILearly2 - offWIL5.w	0.2664	5498	1582	34.40626	0.0414

7. Discussion

By combining the results from Allenbach and Murg, some of the detected patterns in recession behavior become clearer, others rather fade. The most important finding is the certainty that recession behavior reveals noticeable changes through the course of the year. The recurrent variations in recession behavior can be recognized in both catchments. The enhanced recession rates during the plant active season are demonstrated by both, the visual and the base flow R_C analyses. Conversely, the recession rates are lower during the dormant season. These general findings are consistent with the literature. Federer (1973), Trainer & Watkins (1974), and Czikowsky & Fitzjarrald (2004), for example, received the same results. The main objective of this thesis was the precise analysis of recession behavior through the year by incorporating plant phenological data. Consequently, many different phenological data are included to divide the year in numerous ways and into various sections. The phenological data preparation is summarized best in Figure 3 for the Allenbach catchment and in Figure 9 for the Murg catchment. Because the same methods are used for both catchments, the comparison of recession behavior is admissible. Otherwise, the comparison of hydrological characteristics is usually highly problematic (M. Stoelzle et al., 2013).

7.1 Evaluation of the main research question

The division of the hydrological year into seven different phenological seasons and even more periods certainly revealed an accurate insight into variations in recession behavior through the year. However, by combining the results from both catchments in the end, the interpretation becomes difficult. For example, in the Allenbach catchment, the flexible division approaches of E, snow and temperature offered a higher difference between the active and the dormant seasons R_C. Conversely, in the Murg catchment, the fixed division approaches usually offered higher differences in R_C.
Another important finding when comparing the two catchments was the opposing trend of winter Q characteristics. During the winter season, the Allenbach revealed the lowest Q values, whereas the Murg had the lowest Q values typically at the end of the summer season into early autumn. The Allenbach behavior is characteristic of cold regions as mentioned by Smakhtin (2001) and explained in Chapter 1.6.1. The difference in winter recession behavior is a strong example of the various types of catchments even in relatively close air-line distance to each other. However, the recession rates in both seasons were lowest during the winter season. Clearly, the comparison between the Murg and the Allenbach recession behavior is difficult during winter until early summer, because of the influence of snow, ice, and permafrost occurrence in the mountainous terrain around Adelboden. Consequently, snowmelt processes are an important hydrological factor for the Allenbach and any other catchment, which is characterized by a pronounced snow season.

7.1.1 The limits of temporal resolution

The division into different phenological seasons explains the recession behavior of a stream in more detail. However, I would argue that there are limitations regarding the number of divisions within one hydrological year. Figure 25 and the plot "Allenbach periods" in Appendix C illustrate the differences in recession behavior of the periods in between the individual phenological groups. That is the most detailed temporal resolution that was possible with the available phenological data. The general trends, also demonstrated in the "season plots" (Fig. 19 & 24), are also clearly visible, but the differences between the successive periods become less. One problem that emerges, is that some of the periods are very short. In this case, the visible extraction methods from Chapter 4.4.1 are used. Consequently, not many recession days are excluded from the "period plot" (Fig. 25). If stricter extraction methods would be used, at some point, there would no longer be any recession points left (especially during the spring season). In addition, even if some isolated recession points are retained, their informative value is minor because in the end, they are at risk of representing only a fraction of the original recession event. One strength of the logarithmic plot (-dQ/dt vs Q) is that one can detect patterns in a big data cloud. That strength diminishes, if the analyzed period becomes too short by subdividing the hydrological year into smaller and small parts. Consequently, I would argue that seven seasons are an appropriate number of divisions and that one has to be careful when applying a more detailed phenological division approach (e.g. with extraction methods, length of the investigation period). In addition, the most plant phenological features occurred in the same time period anyway.

7.1.2 Analyzing recession behavior in more detail

It is noticeable, that the percentage of recession days, that pass the extraction methods, is generally higher during the winter season (Table 4 & 5). Consequently, more base flow recession events can be observed during the dormant season compared to the active season. One reason may be the more frequent occurrence of convective precipitation throughout the active season compared to the dormant season. However, for the snow approach in the Allenbach catchment and the phenological period onADBlate2 - offADB5 that norm is not true. The explanation for this are snowmelt processes, which diminish the percentage of inter- and base flow recession days during late spring and early summer quite strongly in the Allenbach catchment. The high amounts of meltwater superimpose the base flow recession behavior and therefore make the analysis complicated.
Another important finding is that the recession characteristics change not immediately, but slowly, continuously, and with a certain time lag. That time lag is demonstrated for the Allenbach in Figure 19 and for the Murg in Figure 24, respectively. The base flow recession behavior plots (Fig. 20 & 26) also demonstrate little changes of R_C in the time of most phenological development, but later the changes become obvious. Assessing the time lag in an accurate number of days was not part of the scope of this thesis, but some characteristics are noticeable. Most of the phenological features are centered around a relatively short time period in the late spring season. However, changing recession rates are visible only in the early summer, summer and early autumn season. On one hand, the highest base flow recession rates appear not in spring, at the time the vegetation thrive and flourish, but instead the highest recession rates in both catchments appear in late summer. On the other hand, the lowest recession rates appear not in autumn but in late winter or even early spring (Murg). Therefore, with the hydrological time lag in mind, the best phenological features to divide the Q series in two seasons are features that appear rather late. In other words, the phenological early spring season possesses hydrologically more similarities with the winter season than with the late spring or the summer season. Conversely, after the first phenological signals of autumn (e.g. leaf coloring of European rowan), the hydrological characteristics remain similar to the characteristics of the hydrological summer for some time. Consequently, I would suggest choosing rather late phenological features to divide the year into the desired number of subdivisions. Assessing the accurate month or even week of the change of direction of hydrological recession behavior could be an interesting approach for investigating the time lag of recession behavior compared to phenological signals.

7.1.3 Evaluation of the research hypothesis

The null hypothesis in Chapter 2.3 is twofold, but both parts of the hypothesis are evaluated to be true. Therefore, the null hypothesis will not be rejected. Although the visual analysis is highly subjective, the changes in recession behavior through the year are at least implied and according to expectations. I also managed to increase the difference between winter and summer base flow R_C to the fixed calendar dates in both catchments by choosing the phenological groups (onADBlate2 - offADB5 and onWILearly2 - offWIL5) that provided the biggest difference between active and dormant R_C values (Table 4 & 5). In addition, several other combinations of phenological groups provided higher differences in base flow R_C compared to the fixed hydrological or meteorological on- and offset dates.

7.2 Evaluating the sub questions

The consecutive evaluation of the five sub questions reveals further important and interesting discussion points triggered by the hydrological results.

How do other annually changing indicators (temperature, snow cover) compare with the plant phenological information?

In the alpine Allenbach catchment, the temperature and snow division approach both provided high base flow R_C differences. Both indicators revealed better results with the flexible on- offsets compared to the fixed on- and offset dates. The variability within the temperature and snow group is high (Fig. 7 & 8), therefore it reflects the high variability of alpine weather. For the Murg, the tendency just mentioned is contrary. In the Murg catchment, located in the eastern Swiss midlands, the fixed on- and offsets provided higher base flow R_C difference and the temperature division approach was not as good as the phenological groups at providing large R_C difference between the active and the dormant season. The variability of reference dates from temperature in the Murg catchment (Fig. 13 &14) was about the same magnitude or only slightly higher compared to the phenological groups. The reason why the flexible on- and offsets of the temperature and E groups provided lower R_C differences in the Murg catchment could not be answered. Although, the difference between the fixed and flexible on- and offset dates of the same indicator was generally rather small. Concluding, I argue that these two indicators (temperature, snow cover) are promising, especially in mountainous terrain whit recurrent occurrence of snow, ice and frost. Therefore, further research is recommended.

How do fixed meteorological and hydrological calendar dates compare to the flexible plant phenological groups?

The fixed hydrological calendar dates revealed a similar recession behavior by dividing the year into only two seasons (Fig. 18 and Fig. 23) as flexible division approaches did and the base flow R_C calculation with the fixed hydrological dates also provided acceptable results. However, dividing the year into only two meteorological seasons, by simply allocating the meteorological spring and summer season together, will lead to an unsatisfactory outcome. If working with meteorological dates, I highly suggest allocating the summer and autumn season together instead. It is noticeable that hydrological calendar dates compare better against the flexible phenological groups in the alpine catchment compared to the catchment on lower altitude. However, when the right phenological groups are chosen, the flexible phenological groups provided better results in both catchments.

How large is the variability in the reference dates between and within the different indicator groups? Are yearly shifts consistent?

The large variability between the on- and offset days of the different phenological groups was intended. The onset variability in both catchment from the first to the last group was approximately 200 days and the offset variability was approximately 80 days. In the plots that illustrate the variability within the phenological groups (Fig. 7, 8, 13, 14) a congruent pattern can be recognized. The plant phenological groups located near to the winter or summer season revealed larger variability. That the phenological groups near the winter or summer season often only consist of one plant feature is not the explanation. The phenological features that are imbedded in the phase in which many phenological properties usually emerge one after the other (late spring and early summer), all demonstrated less variability. I think that is related to the findings of Körner & Basler (2010) who stated that short-lived plant species adopt a riskier life strategy and sprout as soon as temperatures are in their favor. Conversely, long-lived species (e.g. trees) do not react to brief warm weather periods during early spring. Trees usually secure themselves from early germination by internal controls (e.g. photoperiod threshold) set by genes

(Körner & Basler, 2010). Therefore, the early spring features (riskier lifestyle) are characterized by onset variability which is comparable to the variability of the onset dates determined by temperature.
The yearly shifts of on- and offset days were below my initial expectations. Although some years revealed a consistent shift, most of the on- and offset days seemed randomly distributed. The only consistent shift in the onset timing in both catchments was revealed in the year 2007. In addition, a consistent shift of several phenological groups to an earlier onset day can be identified in the season of 2003, 2007, and 2011 at Adelboden (ADB) and in the season 1997, and 2007 at Wil (WIL). Conversely, a consistent shift to a later onset day can be identified in 2016, and 2019 at Adelboden (ADB) and in 1996, and 2013 at Wil (WIL). The offset days seemed to be distributed even more randomly. I could not find a single year with a consistent shift of the offset date at Adelboden and only two at Wil. Interestingly, the year 2003 saw a consistent shift to an earlier offset day at WIL. Because of the hot summer and pronounced drought event, that year clearly remains in people's minds.

By incorporating the phenological data, how accurate is the zoom into the transition periods during spring and autumn and is the information gained useful for further hydrological analysis?

One part of that question is already answered in Chapter 7.1.1. Therefore, I would like to explain more of the differences between the two transition periods here. As mentioned by Jeanneret, Rutishauser and Brügger (2011), defining the phenological autumn is more challenging than finding onset dates. While processing the phenological data, I made the same experience. I summarize, in the spring season the phenological analysis provides simply more but also clearer knowledge about the possible division of the Q data series, but the hydrological analysis during the spring season is generally more problematic. There often are influences of snowmelt processes and Q usually is higher in general during the spring season, which means that interflow and base flow recession is less common. Consequently, although it is easier to divide the spring season precisely with phenological features, the hydrological analysis of these small Q series is difficult. In the autumn season, the phenological subdivision is usually associated with more uncertainties and the phenological signal often is not as clear, but typically there tend to be more interflow and base flow events in that time of the year. Therefore, the hydrological analysis is easier in the autumn season, with the risk of not knowing which phenological period is investigated exactly. In this case, the just described contradictory behavior is specifically related to the two examined catchments of this thesis.

What are the differences between alpine and catchments on lower altitudes?

The major hydrological differences during the winter season are explained in Chapter 7.1. However, there are differences in the summer and autumn season as well. The annually low Q values of the Murg overlap with the time period that is characterized by high recession rates, the only aquifer is used by pumping stations and the catchment contains no lakes or marshes. For these reasons I see the Murg in much higher danger of desiccation during an extraordinary drought event. One possible argument against this assumption is the fact that the soils in the Murg catchment are much deeper compared to the typically shallow soils of alpine catchments (Menzel, 1999).
Interestingly, the visual differences in recession behavior are better detectable for the Allenbach catchment, but the calculated base flow R_C difference between the two seasons is smaller than in the Murg catchment. The higher difference in R_C in the Murg catchment could be an indication of the fact that the Murg is exposed to riparian vegetation much longer than the Allenbach. Consequently, the active vegetation affects inter and base flow recession behavior more in the Murg catchment.
There are some indicators that the flexible on- and offset dates yield a slightly higher improvement in R_C differences in the alpine catchment compared to the low altitude catchment.

7.3 Limitations and uncertainties

There are uncertainties and limitations for all indicators, regardless of whether they are phenological or meteorological. Hereinafter, I want to address in detail the most important limitations of this thesis.

7.3.1 Phenological data availability and altitude gradient

At the beginning of data acquisition, the decision was to order only plant phenological data to determine the vegetation period. Animal (mainly birds) and abiotic observations would have been another option, but I focused on plants. For further research I suggest considering animal related or abiotic observations for offset dates, as this could lead to a better assessment of the autumn season.
The resulting difference in hydrological recession behavior between the active and dormant season generated with the E division approach for the Allenbach catchment was remarkably poor. However, it can be used as a good explanation and example of the difficulties dealing with phenological data. The comparison with the two phenological groups that provided the biggest difference in R_C (onADBlate2 – offADB5) reveals the problem of the E on- and offset dates. The E onset days start the active season too early and the offset days also end the active season too early in the year. After analyzing the recession behavior with other combinations of phenological groups, I concluded that the early offset days of the E group are the bigger source of error. There are at least two reasons behind the poor estimation of the offset date. First, the data availability of the grassland category and second the missing altitude gradient. The indicators of the grassland category are all flowers and are characterized by many early and ordinary onset dates and a few late onset dates. However, in both catchments there was only one real phenological feature that determined the offset date of the grassland category, 60% of the surface area in the Allenbach catchment after all. That phenological feature was "Autumn crocus - flowering (50%)". In addition, I did not include an altitude gradient in the E group calculation. Because a large portion of the grassland is located at higher altitudes compared to the forest and shrubbery categories, that gradient would have shifted the offset date backward. In my case, the grassland was too assertive compared to the other vegetation classes. However, even if incorporating an altitude gradient is certainly a strong demand from a scientific point of view, a discussion about the possible improvement of the E division approach with a gradient only coats the problem of lacking phenological grassland data in the autumn season. The poor data availability of grassland offset features was identified early on. At the beginning of the phenological data processing process, the E offset dates were calculated without the grassland class. Later I discovered the autumn crocus data set and was satisfied to now possess features from all three categories. After I realized the possible magnitude of the problem while analyzing first Q series, the approach was to find more grassland, harvest or other type of grain data sets, however, there were no additional data findable. Now, I would argue that the exclusion of the entire grassland category would have been probably the easiest and best solution.
The same problem occurred in the Murg catchment, but several reasons diminished the assertiveness of the feature "Autumn crocus - flowering (50%)". First, the grassland category in this catchment is with 53% slightly less important. Second, the altitude gradient of the catchment is smaller, and the distribution of the categories is reversed. Grassland often is located at the valley's bottom and forests are covering the hills. Third, another phenological feature ("Grape vine – vintage") is included in the calculation to receive later offset dates. As a representative of agricultural land, grape vine can also be remotely assigned to the grassland category. This artifice induced later offset dates and the difference in base flow R_C appeared much higher in the end. The analysis reveals that the time around offADB1 and offWIL1 is crucial for recession behavior investigations. Consequently, later offset days of even some weeks induced noticeably higher R_C differences between the seasons.

7.3.2 Temperature division approach

As mentioned in Chapter 4.2.1, the spring season onset dates could be adopted exactly on the basis of the definition by B. Primault from MeteoSwiss (MeteoSwiss, 2020). However, because of the temporal resolution of the temperature data, only the first premise of the definition for the offset dates was adopted. That is the reason why the "offTemp" groups are both located in the phenological winter season. Otherwise the premise two and three would have shifted the offsets to earlier dates. Because recession behavior revealed a considerable time lag, the periods W_6 for the Allenbach and W_8 for the Murg catchment demonstrated the lowest R_C values of all investigated periods (Fig. 20 & 26). The approach is sensitive to unusually warm periods during the winter season (they are corrected, see Chapter 4.2.1) and does not account for cold weather conditions once the threshold of seven consecutive days with mean temperatures of at least 5°C is exceeded.

7.3.3 Snow as a compounding factor

The characteristics in recession behavior because of differential snow covers (Fig. 21) is explained in Chapter 5.3. The dates of complete snowmelt were relatively easy to define but assessing the beginning of the snow season in autumn was challenging because of short periods of snow occurrence in the early autumn season that melted away short after. High snow depths clearly influenced the recession behavior of the Allenbach, especially through the late spring and early summer season. The effect of snow is demonstrated by higher Q and higher recession rates even in years with little snow. That the stored water in the form of snow is responsible for the deviant recession behavior in these two seasons is demonstrated by the differences between the years with high snow cover and the years with low snow cover. It seems that snow primary has an influence on the amount of Q and the recession rates in the late spring and early summer season. The influence on the summer season is less obvious. Even if after years with high snow cover the recession behavior through the summer season seems more homogenous, I would not drive any assumption on summer recessions yet. However, snow melting processes definitely represent an additional challenge for recession behavior investigation during a phenologically very interesting period.

7.3.4 Anthropogenic influences

The various influences of people lifestyle on recession behavior is listed in detail in Chapter 1.6.2. It can be assumed that the local people also influence the recession behavior of the two examined catchments in this thesis. Be it the fast-growing communities over the recent decades in the Murg or the ski slopes and snow cannons influence in the Allenbach catchment. The impact of these influences is difficult to assess, and the chosen analysis approach of this thesis makes that assessment impossible. To investigate the growing (or decreasing) influence of people in a catchment, the years (or decades) must be examined separately in order to detect long time tendencies imposed by people.

7.3.5 Extraction methods

The effects of different extraction methods to estimate physical characteristics of a catchment are substantial. Stoelzle et al. (2013) found the most consistent rankings of hydrological characteristics within the same extraction procedures. Stoelzle et al. (2013) thus suggested a multi extraction method for good assessments. Consequently, the comparison between studies is only justified, if related extraction and recession analysis methods were used (M. Stoelzle et al., 2013). In this study several extraction methods are applied in sequence (Chapter 4.4). Thereby, the most important extraction step was setting the threshold for maximum decline rates. First, the approach was to find a threshold from the mean Q recession hydrograph. However, after several tests the decision was made on the relative decline rates. Because the Murg revealed a slower recession behavior compared to the Allenbach, the selected recession days were not the same. It is likely that the slower recession behavior of the Murg is in association with deeper soils and the larger area what makes fast interflow possible for a longer period of time (Menzel, 1999).

The minimum recession length in this thesis is only two days. On one hand, that is much less compared to, for example, Vogel and Kroll, 1992 and Brutsaert (2008) who used minimum recession lengths between six and ten days. On the other hand, it is more compared to Kirchner (2009) who used a one-day minimum length. Again, that reveals the subjective manner of extraction methods. Hydrologists often adapt their extraction methods to the available Q series and local climatological properties (Tallaksen, 1995).

Finally, the high percentage of incorporated recession days in the R_C calculation reveals that my base flow extraction methods could have been even stricter. That could have been done with a longer minimum recession day filter (e.g. 4 days). The received results would have made an even better understanding of base flow recession behavior possible. However, the determination of purely base flow and slow interflow is arbitrary anyway. Other uncertainties regarding the analyzation of hydrological data are familiar. Especially during base flow conditions, the lowest values of dQ/dt can be influenced by Q measurements precision at the gauging station.

8. Conclusion

The main objective of this study was to analyze changing recession behavior between different phenological seasons and periods. Thereby, the thesis demonstrates different approaches of using phenological data which can be used to divide the year in different ways into the active and the dormant season or subdivide the year into any number of seasons. The annual subdivision into seven phenological season with annually changing (flexible) on- and offset dates provided an accurate insight of changing recession behavior. The tendency of higher R_C values combined with the visual assurance from the logarithmic recession behavior plots illustrated the impact of E on recession behavior during the active season of vegetation. These findings are consistent with literature by Federer (1973), Trainer & Watkins (1974), and Czikowsky & Fitzjarrald (2004).

The alpine catchment revealed the lowest Q values during the winter season and the highest both Q values and recession rates in the late spring and early summer season. That is the time in which the recession behavior is dominated by snow melt processes. At Allenbach, the E approach failed because of missing phenological grassland data and a missing altitude gradient. However, the snow and temperature division approach revealed promising results in the mountainous catchment.

The subdivision with different phenological groups and the E division approach provided good results in the lower altitude catchment (Murg). However, from the results it is not clear if flexible on- and offset dates represent an improvement compared to the fixed on- and offset dates of the same phenological groups. The reference dates from the webpage "Weather Spark" also revealed high differences between R_C values between the active and the dormant season. This is another indication that good phenological mean values work very well to divide the year into two seasons.

Through the examined 28 years, the recession characteristics usually changed not immediately, but slowly, continuously, and with a certain time lag after the phenological signals. Consequently, the early spring season was from a hydrological point of view more similar with the winter season than with the late spring or the summer season. Conversely, the early autumn season revealed hydrological characteristics that were similar to the summer season but very different from the winter season. Therefore, I suggest rather late phenological features to divide the year into seasons.

Yearly shifts of on- and offset dates between different phenological groups within one year seemed to have a random distribution, only groups that had close on- and offset dates revealed some kind of conformity. Therefore, the observation of phenological features in the early spring season does not promise an additional value to the phenological behavior, for example, in late spring.

Recession behavior assessments promise manifold opportunities in various domains either scientifically or with direct socio-cultural, economic, and environmental benefits (Smakhtin 2001). Consequently, the need for further studies on recession behavior will not disappear anytime soon, rather the opposite.

I would like to see further research on the difference between the fixed vs flexible on- and offset dates, especially regarding possibly beneficial differences between alpine and Swiss midland catchments. As mentioned in Chapter 7.3.1, research with abiotic or animal related phenological data could improve the assessment of the autumn transition season and therefore enable improved recession behavior investigations. In addition, because of the resistance to abnormal early phenological signals, it seems that tree data series are favorable compared to flowers, especially regarding the time lagging hydrological behavior. Finally, the accurate time lag assessment of recession behavior compared to previous phenological changes is an ongoing study area that seems to have not received much attention in recent years but is certainly an important aspect of hydrological characteristics in a catchment.

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Appendix

Appendix A: Legend of the reviewed phenological data

Species and feature	Translation	Shapiro-Wilk normality test: ($p \geq 0.05$, normal distribution)
Allenbach: 33 (14 trees, 9 grassland, 10 shrubbery)		
Trees: 14		
Apple tree - flowering (50%)	Apfelbaum – Blüte	p = 0.07669
Cherry tree - flowering (50%)	Kirschbaum – Blüte	p = 0.07551
Sycamore maple - leaf unfolding (50%)	Bergahorn – Blattentfaltung	p = 0.8188
Sycamore maple - leaf colouring (50%)	Bergahorn – Blattverfärbung	p = 0.03594
Beech - leaf unfolding (50%)	Buche – Blattentfaltung	p = 0.9691
Beech - leaf drop (50%)	Buche – Blattfall	p = 0.01089
Beech - leaf colouring (50%)	Buche – Blattverfärbung	p = 0.3823
Spruce - needle shoot (50%)	Fichte – Nadelaustrieb	p = 0.2724
Larch - needle shoot (50%)	Lärche – Nadelaustrieb	p = 0.9617
Larch - needle drop (50%)	Lärche – Nadelfall	p = 0.8401
Larch needle - colouring (50%)	Lärche – Nadelverfärbung	p = 0.000018
Horse chestnut - leaf unfolding (50%)	Rosskastanie – Blattentfaltung	p = 0.5884
Horse chestnut leaf drop (50%)	Rosskastanie – Blattfall	p = 0.8646
Horse chestnut leaf colouring (50%)	Rosskastanie -Blattverfärbung	p = 0.9277
Grassland: 9		
Wood anemone - flowering (50%)	Buschwindröschen – Blüte	p = 0.4359
Dandelion - flowering (50%)	Löwenzahn – Blüte	p = 0.2171
Hay harvest – start	Heuernte – Start	p = 0.1712
Coltsfoot - flowering (50%)	Huflattich – Blüte	p = 0.6744
Willow herb - flowering (50%)	Weidenröschen – Blüte	p = 0.1703
Cocksfoot grass - flowering (50%)	Knäuelgräser – Blüte	p = 0.5609
Field daisy - flowering (50%)	Gänseblümchen – Blüte	p = 0.796
Cuckoo flower - flowering (50%)	Wiesenschaumkraut – Blüte	p = 0.1478
Autumn crocus - flowering (50%)	Herbstzeitlose – Blüte	p = 0.1707
Shrubbery: 10		
Hazel - leaf unfolding (50%)	Haselstrauch – Blattentfaltung	p = 0.06795
Hazel - flowering (50%)	Haselstrauch – Blüte	p = 0.6801
European rowan - leaf unfolding (50%)	Vogelbeere – Blattentfaltung	p = 0.2858
European rowan - leaf drop (50%)	Vogelbeere – Blattfall	p = 0.14
European rowan - leaf colouring (50%)	Vogelbeere – Blattverfärbung	p = 0.7817
European rowan - fruit maturity (50%)	Vogelbeere – Fruchtreife	p = 0.5849
European red elder - flowering (50%)	Roter Holunder – Blüte	p = 0.866
European red elder - fruit maturity (50%)	Roter Holunder – Fruchtreife	p = 0.4138
European elder - flowering (50%)	Schwarzer Holunder – Blüte	p = 0.1828
European elder - fruit maturity (50%)	Schwarzer Holunder	p = 0.7075

Murg: 47 (27 trees, 10 grassland, 10 shrubbery)

Trees: 27		
Apple tree - flowering (50%)	Apfelbaum – Blüte	p = 0.6884
Pear tree - flowering (50%)	Birnenbaum – Blüte	p = 0.4029
Cherry tree - flowering (50%)	Kirschbaum – Blüte	p = 0.4173
Sycamore maple - leaf unfolding (50%)	Bergahorn – Blattentfaltung	p = 0.098
Sycamore maple - leaf colouring (50%)	Bergahorn – Blattverfärbung	p = 0.00074
Beech - leaf unfolding (50%)	Buche – Blattentfaltung	p = 0.0477
Beech - leaf drop (50%)	Buche – Blattfall	p = 0.2187
Beech - leaf colouring (50%)	Buche -Blattverfärbung	p = 0.3197
Spruce - needle shoot (50%)	Fichte – Nadelaustrieb	p = 0.3107
Larch - needle shoot (50%)	Lärche – Nadelaustrieb	p = 0.1659
Larch - needle drop (50%)	Lärche – Nadelfall	p = 0.2369
Larch needle - colouring (50%)	Lärche – Nadelverfärbung	p = 0.591
Horse chestnut - leaf unfolding (50%)	Rosskastanie – Blattentfaltung	p = 0.987
Horse chestnut leaf drop (50%)	Rosskastanie – Blattfall	p = 0.4747
Horse chestnut leaf colouring (50%)	Rosskastanie -Blattverfärbung	p = 0.1889
European white birch - leaf unfolding (50%)	Hängebirke – Blattentfaltung	p = 0.2453
European white birch - leaf drop (50%)	Hängebirke – Blattfall	p = 0.08299
European white birch - leaf colouring (50%)	Hängebirke – Blattverfärbung	p = 0.2159
Large leaved lime - start of flowering	Sommerlinde - Start der Blüte	p = 0.7603
Large leaved lime - leaf unfolding (50%)	Sommerlinde Blattentfaltung	p = 0.5938
Large leaved lime - leaf colouring (50%)	Sommerlinde Blattverfärbung	p = 0.1843
Large leaved lime - flowering (50%)	Sommerlinde – Blüte	p = 0.1305
Small leaved lime - leaf unfolding (50%)	Winterlinde – Blattentfaltung	p = 0.3114
Common acacia - start of flowering	Akazie - Start der Blüte	p = 0.6429
Common acacia - leaf unfolding (50%)	Akazie – Blattentfaltung	p = 0.375
Common acacia - leaf drop (50%)	Akazie- Akazie – Blattfall	p = 0.06565
Common acacia - flowering (50%)	Akazie- Blüte	p = 0.4162
Grassland: 10		
Wood anemone - flowering (50%)	Buschwindröschen – Blüte	p = 0.3201
Dandelion - flowering (50%)	Löwenzahn – Blüte	p = 0.01338
Hay harvest – start	Heuernte – Start	p = 0.3285
Coltsfoot - flowering (50%)	Huflattich – Blüte	p = 0.03422
Willow herb - flowering (50%)	Weidenröschen – Blüte	p = 0.00102
Cocksfoot grass - flowering (50%)	Knäuelgräser – Blüte	p = 0.05548
Field daisy - flowering (50%)	Gänseblümchen – Blüte	p = 0.01356
Cuckoo flower - flowering (50%)	Wiesenschaumkraut – Blüte	p = 0.3263
Autumn crocus - flowering (50%)	Herbstzeitlose – Blüte	p = 0.04231
Grape vine – vintage	Weinlese	p = 0.3105
Shrubbery: 10		
Hazel - leaf unfolding (50%)	Haselstrauch – Blattentfaltung	p = 0.03026
Hazel - flowering (50%)	Haselstrauch – Blüte	p = 0.8779
European rowan - leaf unfolding (50%)	Vogelbeere – Blattentfaltung	p = 0.864
European rowan - leaf drop (50%)	Vogelbeere – Blattfall	p = 0.9556
European rowan - leaf colouring (50%)	Vogelbeere – Blattverfärbung	p = 0.00212
European rowan - fruit maturity (50%)	Vogelbeere – Fruchtreife	p = 0.1056
European red elder - flowering (50%)	Roter Holunder – Blüte	p = 0.4867

European red elder - fruit maturity (50%)	Roter Holunder – Fruchtreife	p = 0.4517
European elder - flowering (50%)	Schwarzer Holunder – Blüte	p = 0.3385
European elder - fruit maturity (50%)	Schwarzer Holunder	p = 0.4153

Appendix B:

Additional information on E groups calculation

The relative percentage of the tree type of mixed forest is stated on the FOEN and on the hydrological atlas of Switzerland website. The percentage is separated and newly assigned to the respective tree class. There are pure coniferous or deciduous forests and forests that are dominated by either one class (75% of all trees).

Tree type:
ADB:
coniferous trees make up 11/12 of all forests.
deciduous trees make up 1/12 of all forests.

WIL:
coniferous trees make up 3/4 of all forests.
deciduous trees make up 1/4 of all forests.

Coniferous trees: Both catchments are represented with the same tree species. The two indicators are the only available phenological data, Spruce - needle shoot (50%) and Larch - needle shoot (50%). In both catchments the two indicators are normal distributed. Data are available from 1992 to 2019.
Deciduous trees: Less indicators were available for ADB compared to WIL. All the onsets are taken from different species and are normal distributed, except the beech leaf unfolding at Wil because of one big outlier. Data are available from 1992 to 2018.

Missing values: If a surface category contained missing values, these years are filled with mean on- and offset values **before** the categories are calculated together according to their weight. That step is important because otherwise some years would be derived only from one category. With the correction before the further calculation the resulting on- and offset dates are more homogeneous.

Absolute and relative E values Menzel (1999):

All altitudinal belts:
Forest: 616 mm are than **0.59**
Grassland: 436 mm are than **0.41**

ADB, 1800 m altitudinal belt:
Forest: 523 mm are than **0.61**
Grassland: 334 mm are than **0.39**

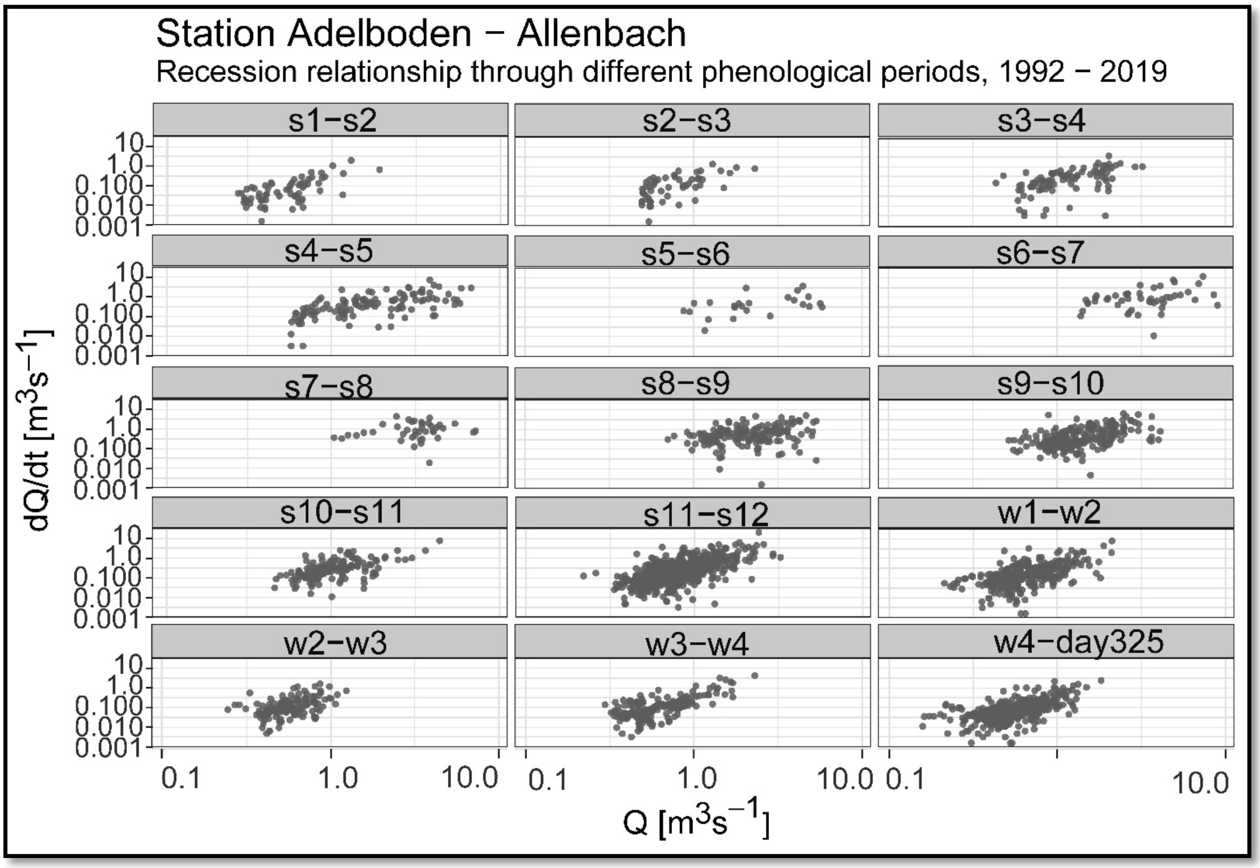
WIL, 600 m altitudinal belt:
Forest: 712 mm are than **0.57**
Grassland: 537 mm are than **0.43**

Gradient: 1% / 300m more E of forests compared to grass- agricultural land, however the relationship is not linear.

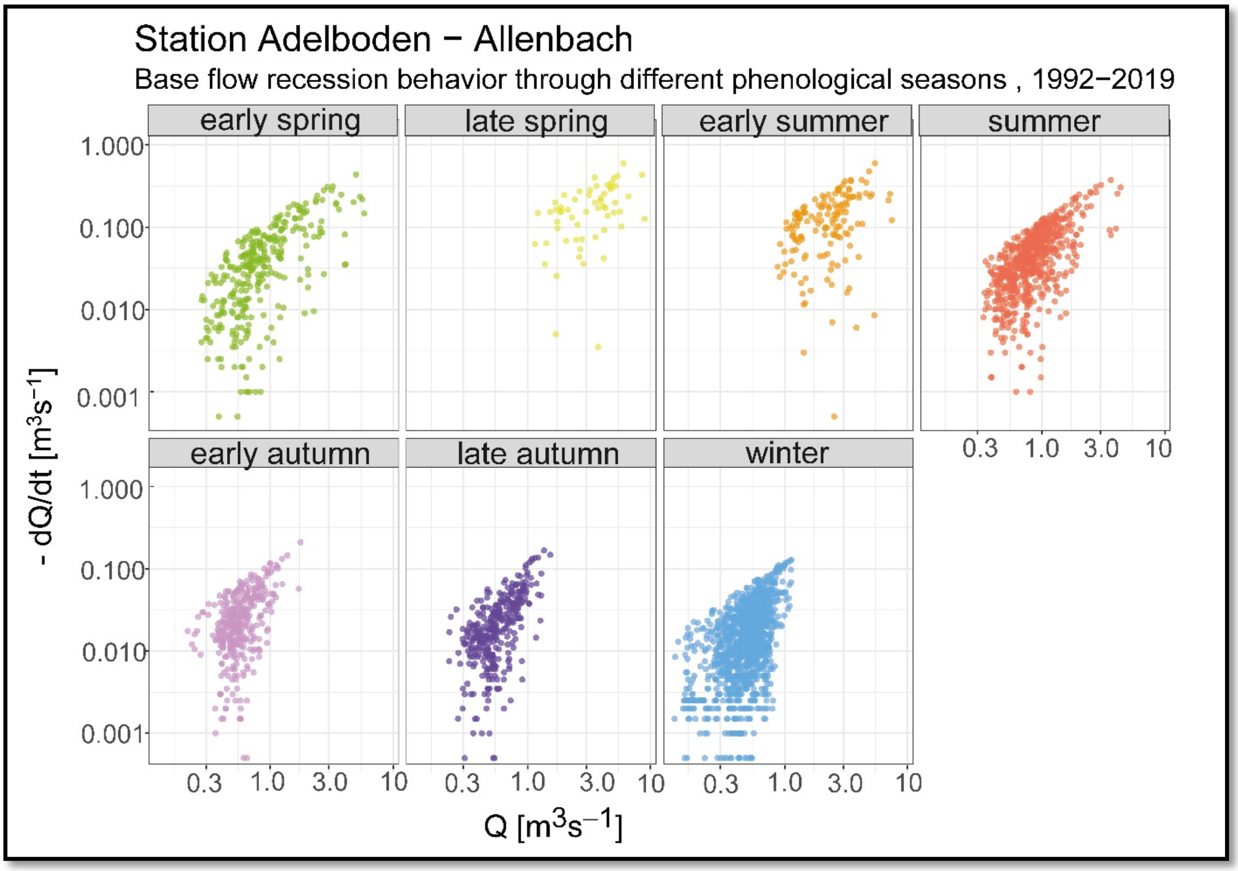
Appendix C:

Additional plots

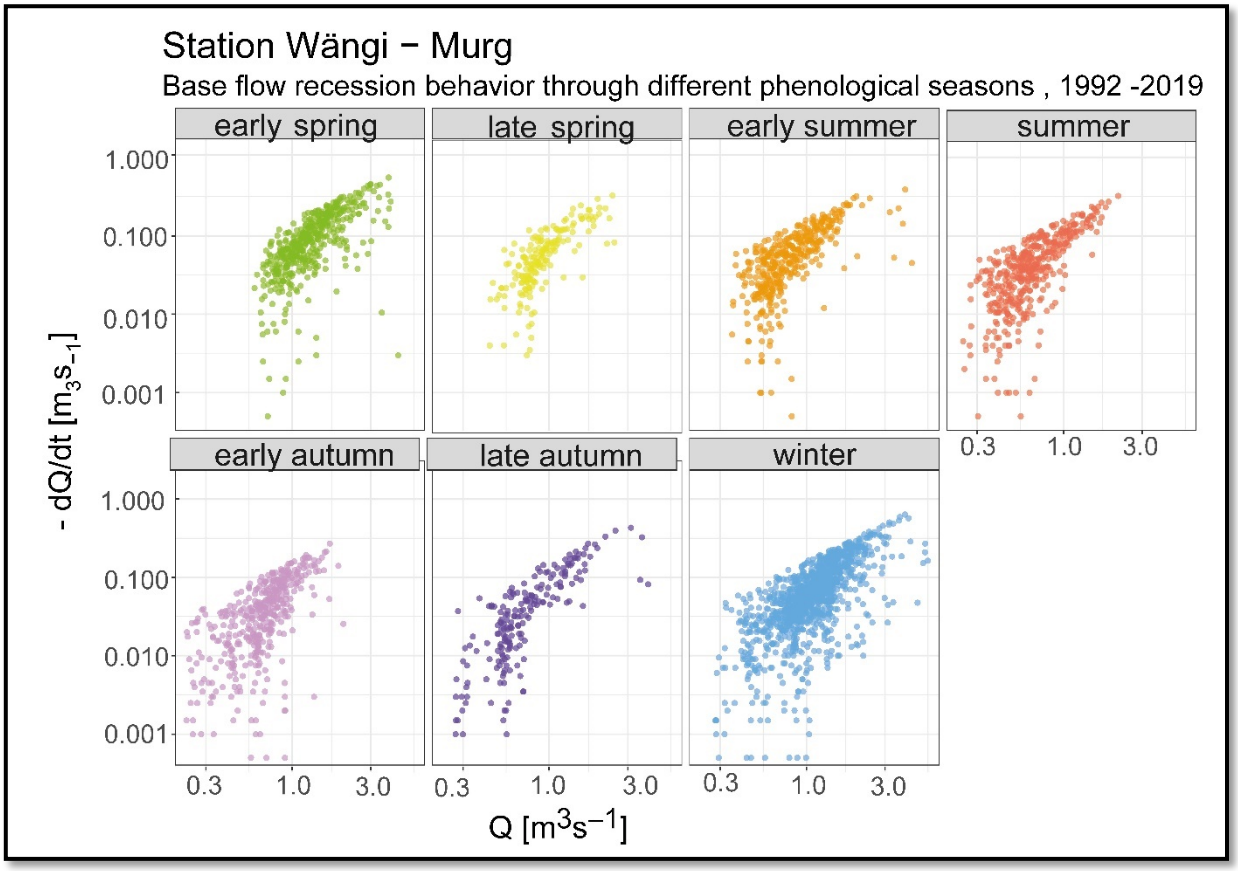
1. Plot: *Allenbach Periods*



2. **Plot:** ***Recession behavior for Allenbach with base flow extraction methods***



3. Plot: ***Recession behavior for Murg with base flow extraction methods***



Personal declaration

I hereby declare that the submitted Thesis is the result of my own, independent work. All external sources are explicitly acknowledged in the thesis.

Unterlunkhofen, 31.01.2021 Hannes Tobler