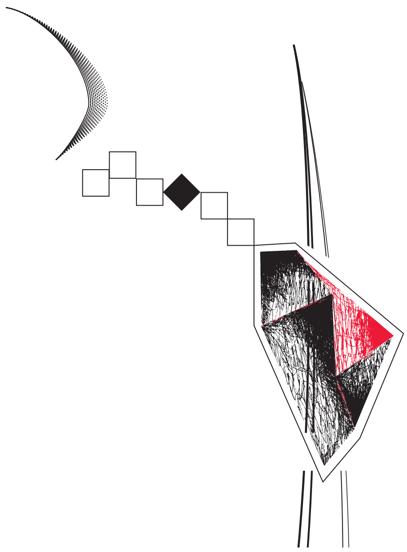
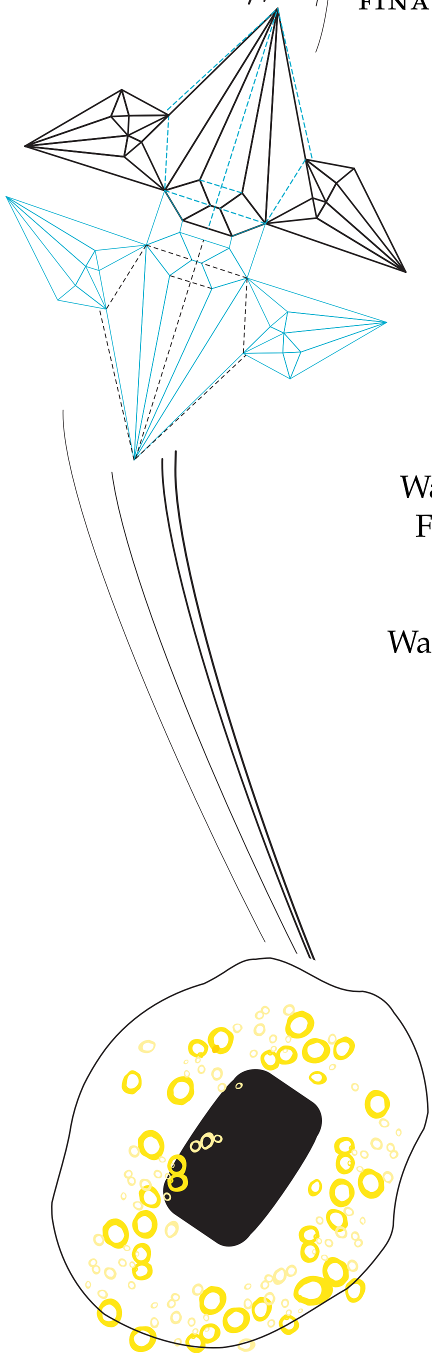


CHARACTERIZATION OF RECESSION BEHAVIOUR FOR UNGAUGED CATCHMENTS IN THE UNITED KINGDOM BASED ON CATCHMENT PROPERTIES

FINAL REPORT BACHELOR ASSIGNMENT



GEERT-JAN WILBRINK

Water Engineering and Management
Faculty of Engineering Technology
University of Twente

Water and Environmental Engineering
Faculty of Engineering
University of Bristol

December 1, 2014

CONTACT INFORMATION

PERSONAL INFORMATION

Geert-Jan Wilbrink
Student bachelor Advanced Technology
University of Twente
mail: g.j.wilbrink-1@student.utwente.nl

BACHELORS ASSIGNMENT COMMITTEE

Chairperson
Dr. Ir. Martijn Booij
Assistant Professor Water Engineering and Management
University of Twente
mail: m.j.booij@utwente.nl

Daily supervisor
Dr. Ross Woods
Senior Lecturer in Water and Environmental Engineering
University of Bristol
mail: ross.woods@bristol.ac.uk

External member
Prof. dr. ir. André de Boer
Full professor Faculty of Engineering Technology
University of Twente
mail: a.deboer@utwente.nl

SUMMARY

Recession analysis is about analyzing receding stream flow under dry conditions, i.e., when stream flow is due to groundwater drainage and other subsurface flows instead of directly related to precipitation. At the moment no general or global approach exist for recession analysis in ungauged catchments, i.e., catchments where stream flow is not measured, nor are there much data yet on recession behaviour in gauged catchments in the United Kingdom. The objective of this study is to characterize recession behaviour for ungauged catchments in the United Kingdom by relating recession behaviour to catchment properties.

Multiple recession analysis methods, which are based on a relation between stream flow Q and its time derivative dQ/dt, and extraction procedures, i.e., how recession period are extracted from a stream flow time series, are compared for a data set of 1194 gauged catchments. Large variations between different recession analysis methods and between individual recessions are found. This research suggest that most reliable results can be obtained when analyzing individual recessions instead of analyzing all recessions together in a cloud. A better understanding of the physical background of recession behaviour can be helpful in both validating the different recession analysis methods and explaining the variations between individual recessions of the same catchment.

The most reliable method, looking at the median of individual recessions, is selected. Recession behaviour is determined for 987 catchments in the United Kingdom using this method. Clear variations in recession behaviour are found between Wales, Scotland and the different regions of England.
Differences in results between the different catchments are tried to explain by relating recession behaviour to catchment characteristics as geology, land use, topography and climate. Relations between recession behaviour and catchment characteristics are found, most strongly with geology and BFIHOST, a catchment descriptor based on soil characteristics.

The correlations between recession behaviour and catchment characteristics are not strong enough to reliable characterize recession behaviour in ungauged catchments. It might be possible to find stronger correlations using more quantitative data for geology and land use. That could make reliable characterization of recession behaviour in ungauged catchments possible in future research.

CONTENTS

1 INTRODUCTION

This chapter will give an introduction on the topic, starting with the state of the art in section 1.1, followed by defining the research gap, section 1.2, and research objective and research questions, section 1.3. The outline of this report is presented in section 1.4.

1.1 STATE OF THE ART

Recession behaviour can be described as the behaviour of stream flow Q (in mm/day) in a dry period, i.e., when there is no significant precipitation P (in mm) over a particular period. Another way to describe recession behaviour is as the period in which there is a declining stream flow, thus $dQ/dt < 0$. Under the condition described as recession behaviour, stream flow will be mainly due to the base flow. The base flow is the part of the stream flow which is due to groundwater drainage and other subsurface flows (Brutsaert and Nieber, 1977). Storm flow, on the other hand, can be described as the part of the stream flow which is directly related to precipitation.
Recession analysis can be used among others in rainfall-runoff modeling, in hydrograph analysis, separating flow components as base flow and storm flow, for low flow statistics and for low flow forecasting (Tallaksen, 1995). Low flow forecasting is related to issues regarding contaminant dilution, stream ecology (Boulton, 2003) and adequate water supply for industry, agriculture and human consumption as summarized by Price (2011).

In the literature are many suggestions of methods for analyzing recession behaviour in gauged catchments. A first group of methods try to find a direct relation between stream flow Q and time, thus $Q = f(t)$. A number of these methods are discussed below.
The master recession curve method can be described as obtaining a general graph of stream flow as a function of time for a recession, based on multiple recessions of a catchment. A review by Tallaksen (1995) describes multiple master recession curve methods, as the matching strip method and the tabulating method. The matching strip method amplifies the stream flows of different recession curves, within the same catchment, in order to get the curves, which have different stream flows at the start of a recession, more or less overlapping. The master recession curve is then constructed as the best fitting curve trough these curves. The tabulating method uses a slightly different method, by using tables instead of a graphical approach.
A second group of recession analysis methods link stream flow to its time derivative in the following way: $dQ/dt = f(Q)$. These methods have the advantage of eliminating time as a relevant variable (Stoelzle et al., 2013).
The method by Brutsaert and Nieber (1977) is probably the most well-known of these methods. They define $f(Q)$ as a power function, thus: $dQ/dt = -a \cdot Q^b$, where parameter a can also be written as the recession constant k (Beck et al., 2013). A linear relation is obtained by setting parameter b to 1, thus getting $dQ/dt = -a \cdot Q$, as done by Brutsaert (2008) and Beck et al. (2013).
The method by Biswal and Marani (2014) is a variant of the method of Brutsaert. The main difference with the Brutsaert-method is that this method uses a different theoretical background for the method and defines the method using a dimensionless flow.
Most of the methods predefine the function of Q, for example being a linear function or a power function. Kirchner (2009) however uses a general function and adds precipitation and evapotranspiration E (in mm) to it. This lead to the following equation: $dQ/dt = f(Q) \cdot (P - E - Q)$. This method is however more suitable for stream flow prediction and can be used as a recession analysis method only if both E and P are small compared to Q.

Recession analysis have been performed for UK catchments, where a study by Lamb and Beven (1997) performs recession analysis for three UK catchments, leading to relations between stream flow and time, and between stream flow and subsurface storage.

The literature indicates that many diverse catchment properties exist that influences recession behaviour. Tague and Grant (2004) show for example a relation between geology and recession behaviour for catchments in Oregon. They use the equation by Brutsaert and Nieber (1977), $dQ/dt = -a \cdot Q^b$, and show for both parameters a and b a linear relation between geology and recession behaviour, with a coefficient of determination higher than 0.80. This is done by defining two main types of geology, based on the age of the underlying volcanic bedrock, and relating recession behaviour to the ratio of this two types of geology.
Rees et al. (2004) tried to find a relation between catchment properties and recession behaviour for catchments in the Himalayas. The authors show a relation between area and the recession constant k, with a coefficient of determination of 0.88. They also find relations between the start date of the recession T_0 and the initial flow Q_0 with catchment properties as elevation and geographical location, but both with a lower coefficient of determination. They use these relations to successfully predict recession behaviour for 13 catchments in the Himalayas.
A review by Price (2011) states that topography and geomorphology influence recession behaviour and the author indicates that especially the effect of slope, relief and drainage density on recession behaviour are noteworthy. A study by Beck et al. (2013) focuses, among others, on the prediction of the recession constant k based on 18 parameters, which are related to climate, topography, land cover, geology and soil. They use 3394 catchments which are mainly located in North America, Europe and Australia.
It can be concluded that different authors come to different conclusions about the most relevant catchment properties influencing recession behaviour. Tague and Grant (2004) show that only geology is enough to describe recession behaviour and according to Rees et al. (2004) catchment area is an important property. In contrast it can be concluded that climate, topography and land cover are more important properties than geology and soil, according to Price (2011) and Beck et al. (2013).

1.2 RESEARCH GAP

Altogether the literature shows that it is possible to characterize recession behaviour for gauged catchments and that there exists relations between catchment properties and recession behaviour. Recession analysis in the United Kingdom has only been performed for a small number of catchments. It has been shown that is it possible to characterize recession behaviour for ungauged catchments in specific regions based on catchment properties. No definite or highly reliable generic or global solution for predicting recession behaviour in ungauged catchments is available yet, nor is there research in the literature that describes recession behaviour for ungauged catchments specific in the United Kingdom.

This study will try to find the relevant catchment properties that relate to recession behaviour in catchments in the United Kingdom. When strong correlations are found, an attempt will be made to characterize recession behaviour for ungauged catchments in the UK, based on the found correlations. The focus of this study is thus only on a specific region and will not aim to find a more generic or global solution. However results of this study may be used for further research to test its applicability in other regions.

1.3 RESEARCH OBJECTIVE AND RESEARCH QUESTIONS

The objective of this study is to characterize recession behaviour for ungauged catchments in the United Kingdom by relating recession behaviour to catchment properties. In order to meet this objective the following research questions have to be answered:

1. Which methods for analyzing recession behaviour can be useful for predicting recession behaviour for gauged catchments in the United Kingdom?

2. How well can recession behaviour be characterized for gauged catchments in the United Kingdom?

3. Which catchment properties relate to variations in recession behaviour?

4. Are correlations between catchment properties and recession behaviour strong enough to characterize recession behaviour for ungauged catchments in the United Kingdom?

1.4 Outline report

This report will continue in chapter 2 by presenting the relevant available data and the study area. Chapter 3 will follow by describing the recession analysis methods in section 3.1 and their physical background in section 3.2. The extraction procedure and parameter fitting will follow in respectively sections 3.3 and 3.4. Section 3.5 will discuss methods for observing decadal, seasonal and regional variations. This is followed by methods for relating recession behaviour to catchment properties in section 3.6.

Chapter 4 will describe the most important results of this study, starting with the results of the extraction procedure in section 4.1. Section 4.2 describes the results for the combinations of various methods and parameter fitting procedures. Decadal, seasonal and regional variations will be discussed in respectively sections 4.3, 4.4 and 4.5. Section 4.6 relate recession behaviour to geology, land use and catchment descriptors and shows that some correlations exists between recession behaviour and these catchments properties.

Chapter 5 will discuss the most relevant results of this study, followed by conclusions and recommendations in chapter 6.

2 DATA AND STUDY AREA

This chapter will describe the available data set, consisting of 1194 catchments, with among others stream flow, precipitation and evapotranspiration time series and descriptions of geology and land use.

2.1 HYDROMETEOROLOGICAL DATA

The data set consists of 1194 catchments in the United Kingdom, where the hydrometeorological data are retrieved from the Centre for Ecology and Hydrology. Daily stream flow data are available for all catchments, with a data length ranging from 3 years up to 109 years. The average length of the stream flow time series is 37 years and 95 percent of the catchments have at least data for a 12 year period. Rainfall data are available for 1032 catchments with a length of 48 years and potential evapotranspiration data for 1027 catchments with a length varying from 48 years to 51 years. Figure 1 shows the distribution of the catchments and the availability of stream flow, rainfall and evapotransipration data per catchment.

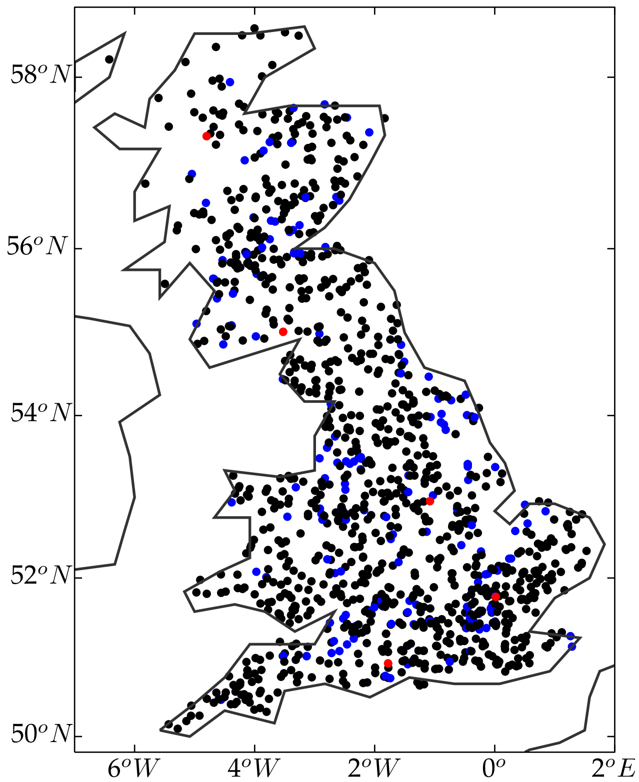


Figure 1: *Geographical distribution of 1194 gauged catchments in the United Kingdom, based on the location of the stream flow gauge. Black dots represents catchments with stream flow, rainfall and evapotranspiration data, red dots represents catchments with stream flow and rainfall data and blue dots represents catchments with only stream flow data*

2.2 GEOLOGY AND LAND USE

The data set contains qualitative information for 618 catchments about the type of stream gauge, artificial influences, for example groundwater extraction, catchment geology and land use. The data is obtained from the Environment Agency and only available for England and Wales. Figure 2 shows the geographical distribution of these catchments, as well as the distribution of a subset of uninfluenced catchments, as explained later in this chapter.

There are large variations in types of geology between the catchments, but a large part of them contain chalk, limestone, sandstone and clay. The descriptions of the geology are given as a enumeration of types of geology present in a catchment, mostly only qualitative, but sometimes given as percentages.

Land use is described, among others, as agricultural, arable, rural, forest, moorland, grazing and urban. Descriptions are again mostly qualitative, but sometimes given as percentages.

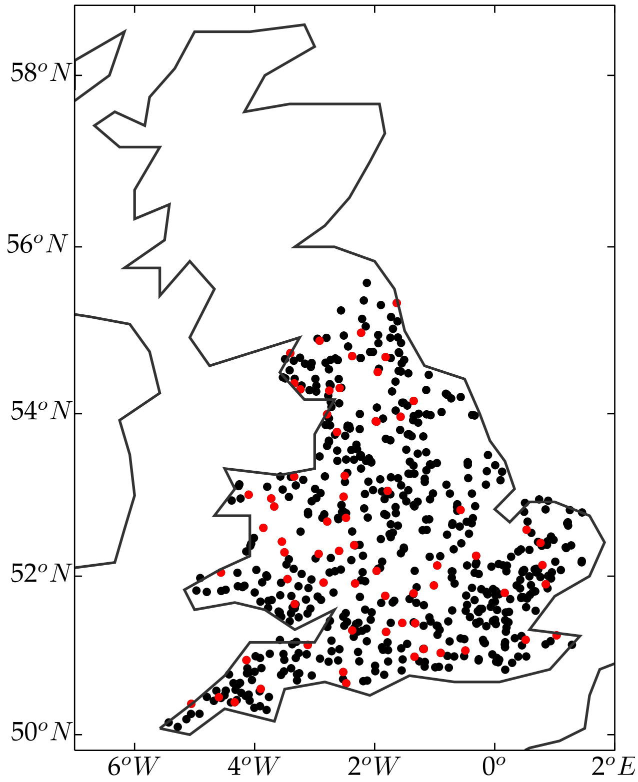


Figure 2: *Geographical distribution of 618 catchments, with geology and land use data and 22 catchment descriptors, the black and red dots, as well as the subset of 66 uninfluenced catchments, the red dots*

2.3 CATCHMENT DESCRIPTORS

Quantitative information is available for 618 catchments, again obtained from the Environment Agency and with the same geographical distribution as for geology and land use, see figure 2. This quantitative data is given as 22 so called catchment descriptors, which are listed below:

- DTM AREA: catchment area, varying from 2.3 to 9931 km^2 and on average 343 km^2
- ALTBAR: mean altitude of a catchment, ranging from 21 to 656 m and on average 171 m
- ASPBAR: the dominant direction of catchment slopes, measured on a 360 degree scale; all possible directions are reflected in the data
- ASPVAR: index describing the variability in the direction of catchment slopes, on a scale of 0 (inconsistent directions) to 1 (consistent directions), on average 0.19
- BFIHOST: an estimation of the base flow index based on catchment soil type. The base flow is the part of the stream flow which is due to groundwater drainage and other subsurface flows (Brutsaert and Nieber, 1977), the base flow index describes the base flow fraction of total stream flow. Values range from 0.18 to 0.97, with an average of 0.53

- DPLBAR: mean length of drainage paths (length of a river channel from the source to the outlet), ranging from 0.6 to 140 *km*, on average 19.7 *km*
- DPSBAR: dimensionless index describing steepness, ranging from 12 to 385, with an average of 82, where a value higher than 300 can be described as mountainous terrain and lower than 25 as a flat catchment
- FARL: index describing the influence of lakes and reservoirs on flood response, ranging from 0.65 to 1.00, where values lower than 0.8 indicate a significant influence on flood response and values close to 1 describe the absence of influence of lakes and reservoirs on flood response
- LDP: longest drainage path, ranging from 3.3 to 287 *km*, on average 36 *km*
- PROPWET: fraction of the time that the catchment soil is wet, ranging from 0.21 to 0.71, on average 0.41
- RMED: multiannual median of the annual maximum rainfall in *mm* over a period of 1 hour (RMED-1H), 1 day (RMED-1D) and 2 days (RMED-2D), ranging from 32 to 122 *mm* and on average 50 *mm*, for RMED-2D
- SAAR: average annual rainfall for the period 1961-1990 (SAAR) and the period 1941-1970 (SAAR4170), ranging from 555 to 2809 *mm* and on average 1006 *mm*, for the period of 1961-1990
- SPRHOST: an estimation of the percentage of rainfall that contributes to surface runoff, based on catchment soil type, ranging from 4.9 to 60 percent, on average 34 percent. BFIHOST and SPRHOST are negatively correlated
- URBCONC: concentration of urban and suburban land cover, where high values indicate concentrated urban land cover, measured in 1990 (URBCONC1990) and 2000 (URBCONC2000), ranging from 0.23 to 0.91 and on average 0.62, for the year 2000
- URBEXT: fraction of urban and suburban land cover on total catchment area, measured in 1990 (URBEXT1990) and 2000 (URBEXT2000), ranging from 0.00 to 0.59 and on average 0.03, for the year 2000
- URBLOC: location of urban and suburban land cover, where low index values indicate that urban and suburban land cover is located near the catchment outlet and high index values indicate that urban and suburban land cover is located far from the catchment outlet, measured in 1990 (URBLOC1990) and 2000 (URBLOC2000), ranging from 0.12 to 1.64 and on average 0.84, for the year 2000

2.4 Uninfluenced catchments

A subset of catchments is available with relative uninfluenced catchments, i.e., catchments not affected by water management, as for example groundwater extraction. A smaller subset, namely 66 of these catchments, also contain both geology data, land use data and the catchment descriptors. These uninfluenced catchments are geographical distributed as shown in figure 2.

3 METHODOLOGY

This chapter will explain the methodology used for this study. First the different recession analysis methods and their theoretical backgrounds will be explained in respectively sections 3.1 and 3.2. After that section 3.3 about the extraction procedure of recession periods and section 3.4 about parameter fitting methods will follow. Section 3.5 will describe methods for analyzing decadal, seasonal and regional variations. This chapter will end in section 3.6 with the methods for relating variations in results to geology, land use and catchment descriptors.

3.1 RECESSION ANALYSIS METHODS

In this section selection criteria will be explained and based on that a selection of the recession analysis methods will be made. After that an overview will be given about the two selected methods and their physical backgrounds.

3.1.1 *Selection criteria*

A selection will be made for the recession analysis methods that will be used for this study. The available methods are explained in paragraph 1.1. The selection will be made according to the following criteria:

- The number of parameters of the method. This is relevant because in this study relations have to be found between these parameters and catchments properties. A method with more parameters is less unique than one with fewer parameters and is therefore less useful.
- Usability with computer programming. There are daily stream flow data for 1194 catchments, so only methods which can be used with computer programming can be useful, as processing them all by hand will not be feasible in the time given for this study.
- Usability of the methods with the available data: some of the methods require data that are only available for a part of the catchments, for example evapotranspiration data, and these methods are thus less useful than methods which can be used for a larger part of the catchments.

Based on the above mentioned criteria only the Brutsaert-method and the Biswal-method will be used. These methods have only 2 parameters, they are feasible to implement in MatLab and the needed data are available for a large part of the catchments.
The matching strip method and the tabulating method will not be used because it is difficult to implement in a computer program and they do not give more information about recession characteristics than the Brutsaert-method and Biswal-method.
The method by Kirchner will not be used because it is a variant on the Brutsaert-method, with the advantage of predicting all stream flow values instead of only stream flow values in a recession period. This study aims however on describing recession behaviour, thus describing all stream flow values is it that sense not an advantage. This method also differs from the Brutsaert method by using a quadratic relations and a binning procedure instead of a simple linear relation. Quadratic relations and binning can however also be used with the Brutsaert-method and Biswal-method.

3.1.2 *Brutsaert-method*

In order to eliminate time as an important variable, Brutsaert and Nieber (1977) come with a relation between stream flow Q (in mm/day) and stream flow recession dQ/dt (in mm/day^2) as described in equation 1. Parameter a is in $mm^{1-b}\ day^{b-2}$ and parameter b is dimensionless.

$$\frac{dQ}{dt} = -a \cdot Q^b \tag{1}$$

As shown in equation 2, stream flow recession will be estimated by taking the difference in Q between two successive days. Stream flow will be calculated as the mean value over two successive days, see equation 3. Taking the mean value over two days will result in making a shift of half a day, which will link Q and dQ/dt correctly, as described by Brutsaert and Nieber (1977).

$$\frac{dQ}{dt} = Q(t+1) - Q(t) \tag{2}$$

$$Q = \frac{Q(t) + Q(t+1)}{2} \tag{3}$$

Dimensionless flow

Because the dimensions of parameter a depend on the value of parameter b, it is hard to compare values of a which have different b values. This problem can be overcome by defining a dimensionless flow. First a long time mean of the stream flow is defined as $\overline{Q}$. Now is it possible to define a dimensionless flow q as the ratio of Q to $\overline{Q}$, thus making $q = Q/\overline{Q}$. Dividing both sides of equation 1 by $\overline{Q}$ and substituting $q = Q/\overline{Q}$ results in equation 4. This equation can be simplified to equation 5 by substituting $1/c = a \cdot \overline{Q}^{b-1}$, with parameter c in *days*. The parameter c is then a measure of the time it takes to reduce Q by a factor e, under the assumption that Q is at $\overline{Q}$.

$$\frac{dq}{dt} = -a \cdot \overline{Q}^{b-1} \cdot q^b \tag{4}$$

$$\frac{dq}{dt} = -\frac{1}{c} \cdot q^b \tag{5}$$

A solution to the differential equation described in equation 5 is shown in equations 6 (for $b = 1$) and 7 (for $b \neq 1$), with q_0 as the initial stream flow (thus q at $t = 0$).

$$q(t) = q_0 \cdot e^{-t/c} \qquad \text{if } b = 1 \tag{6}$$

$$q(t) = \left[(b-1) \cdot \frac{t}{c} + q_o^{1-b}\right]^{\frac{1}{1-b}} \qquad \text{if } b \neq 1 \tag{7}$$

3.1.3 *Biswal method*

Biswal and Marani (2014) make the hypothesis that parameter a can be described as a function of the maximum subsurface stream flow $Q_{s,m}$. Because the peak of the stream flow Q_m consists of both subsurface flow and storm flow it is not possible to approximate $Q_{s,m}$ based on Q_m.
In order to be able to define a as a function of the maximum subsurface stream flow $Q_{s,m}$ Biswal and Marani (2014) integrate equation 1 between Q_{sm}, t_0 and Q_n, t_n. This results in equation 8, where parameter n is defined as the nth day of a recession period. This integral is worked out in equation 9 and rewritten in equation 10.

$$-\int_{Q_{s,m}}^{Q_n} Q^{-b} \cdot dQ = \int_{t_0}^{t_n} a \cdot dt \tag{8}$$

$$Q_n^{-b+1} = Q_{s,m}^{-b+1} + (b-1) \cdot a \cdot t_n \tag{9}$$

$$\frac{Q_n}{Q_{s,m}} = \left[1 + Q_{s,m}^{-b+1} \cdot a \cdot t_n\right]^{\frac{1}{1-b}} \tag{10}$$

For large t_n equation 11 and subsequently equation 12 will apply. This will reduce equation 9 to equation 13, with parameter a depending on Q_n and b. Filling this relation for a back in to equation 1 will lead to equation 14.

$$Q_{s,m}^{-b+1} \cdot a \cdot t_n \gg 1 \tag{11}$$

$$(b-1) \cdot a \cdot t_n \gg Q_{s,m}^{-b+1} \tag{12}$$

$$a = \frac{1}{(b-1) \cdot t_n} \cdot Q_n^{1-b} \tag{13}$$

$$\frac{dQ}{dt} = -\frac{1}{(b-1) \cdot t_n} \cdot Q_n^{1-b} \cdot Q^b \tag{14}$$

A dimensionless flow is then defined by Biswal and Marani (2014) as $Q_n^* = Q/Q_n$, resulting in equation 15. It is good to notice that the value of Q_n varies with every individual recession and that $Q_n^*(n)$ is by definition equal to 1. Substituting $c = (b-1) \cdot t_n$ results in equation 16. Parameter c is a measure of the time it takes to reduce Q_n^* by a factor e, assuming Q_n^* is at Q_n.

$$\frac{dQ_n^*}{dt} = -\frac{1}{(b-1) \cdot t_n} \cdot {Q_n^*}^b \tag{15}$$

$$\frac{dQ_n^*}{dt} = -\frac{1}{c} \cdot {Q_n^*}^b \tag{16}$$

3.1.4 *Recessions graphs*

In order to give an impression what different values of parameters b and c mean, a plot of q versus t (the behaviour of Q or Q_n^* versus t will be roughly the same) is made for different values of b and c as shown in figure 3. It can be seen that recessions with a higher c-value recede always slower and that recession with higher b-values recede faster for values higher than $\overline{Q}$, but slower for values lower than $\overline{Q}$.

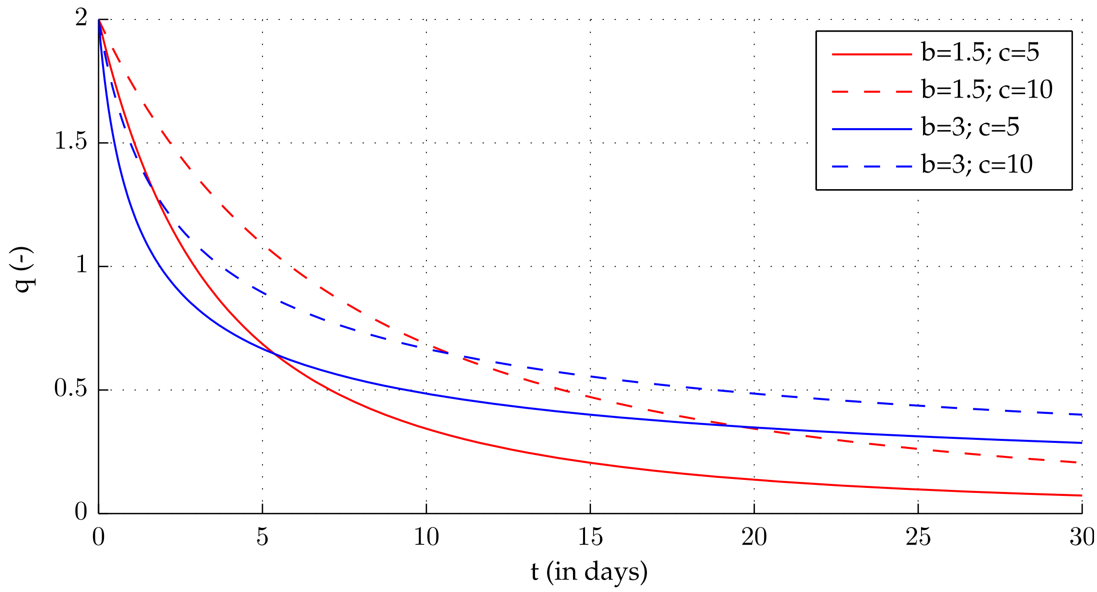


Figure 3: *Plot of dimensionless flow q versus t, for b=1.5 and c=5, b=1.5 and c=10, b=3 and c=5, and b=3 and c=10*

The four plots in figure 4 show a one year hydrograph for the four extremes for the combinations of parameters b and c. It can be seen that a low b results in a much broader peak, which is related to the slower receding behaviour for values higher than the mean of Q. The distinction between high and low values of c is most clearly visible in figures a and b, but is can also be seen in figure c and d, where q is roughly constant between June and December for plot d, but slowly declining in plot c.

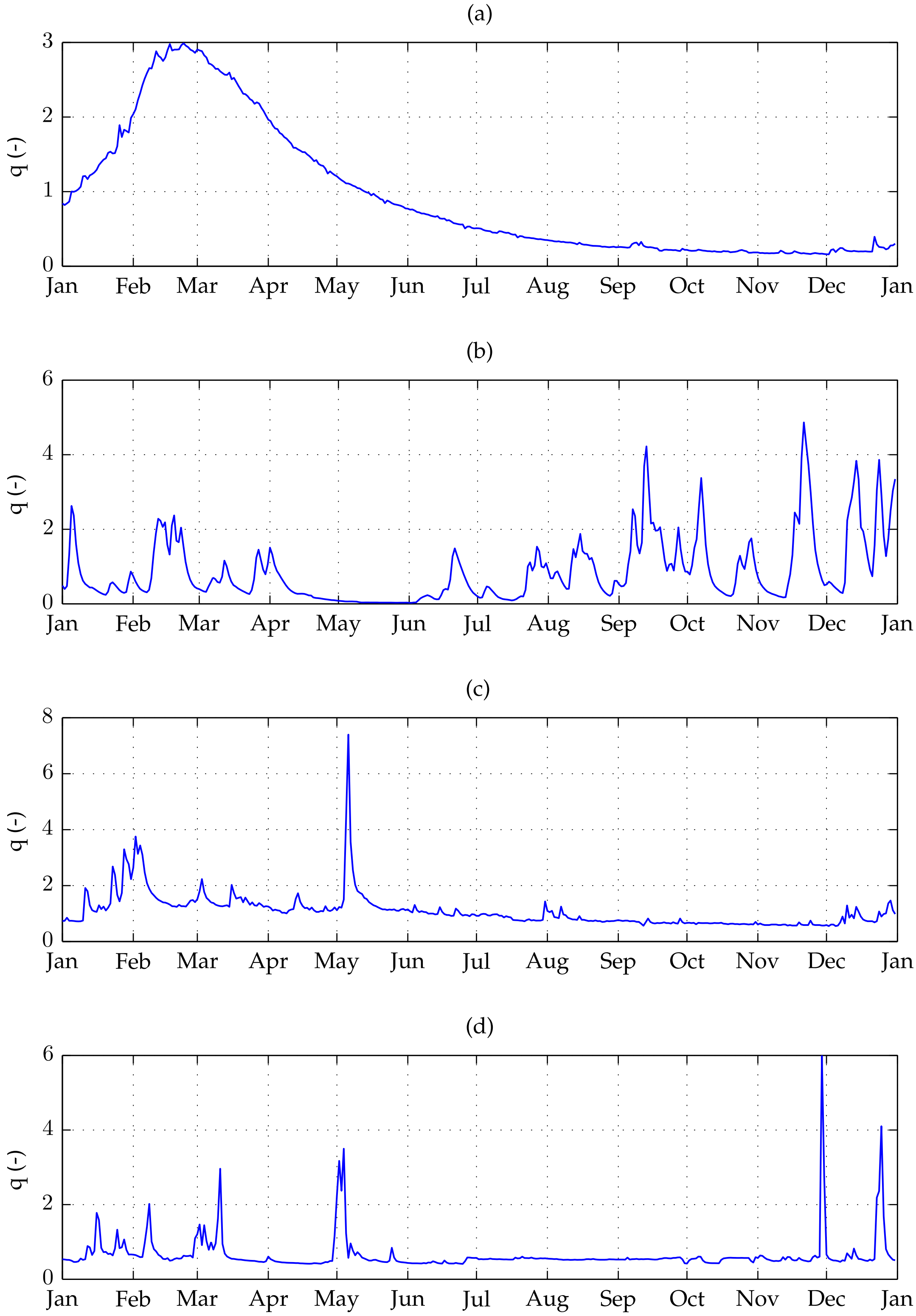


Figure 4: *Hydrographs (plot of dimensionless flow q against time) for a one year period for different catchments: (a) Hydrograph for the catchment Wansford Snakeholm Lock in 1995, low b, high c; (b) Hydrograph for the catchment Anie in 1980, low b, low c; (c) Hydrograph for the catchment Arlesey in 1978, high b, high c; (d) Hydrograph for the catchment Tromie Bridge in 1980, high b, low c.*

This section will explain the physical background of the different recession analysis methods, in order to gain insight in the underlying processes of recession behaviour. According to Mutzner et al. (2013) stream flow Q is assumed to depend on the discharge per unit length of active drainage network q_l (in day^{-1}) and the length of the active drainage network G (in mm) as described in equation 17. Taking the derivative of Q to t leads to equation 18.

$$Q(t) = q_l(t) \cdot G(t) \tag{17}$$

$$\frac{dQ}{dt} = q_l \cdot \frac{dG}{dt} + G \cdot \frac{dq_l}{dt} \tag{18}$$

Brutsaert and Nieber (1977) assume a constant G, where Biswal and Marani (2014) assume a constant q_l, leading to two different physical explanations for declining stream flow. These different theories are worked out in respectively section 3.2.1 and section 3.2.2.

3.2.1 *Subsurface storage*

The first theory assumes a constant G in equation 17, making it possible to relate Q directly to q_l. It can be assumed that q_l is a function of subsurface storage S, thus $q_l = f(S)$. Therefore Q is also a function of subsurface storage S, thus $Q = f(S)$, therein following Kirchner (2009). This makes it possible to define equation 19. It is further assumed that declining S only depends on Q, thus $dS/dt = -Q$. Substituting both this relation and equation 1 into equation 19 results in equation 20.

$$\frac{dQ}{dS} = \frac{dQ/dt}{dS/dt} \tag{19}$$

$$\frac{dQ}{dS} = \frac{-a \cdot Q^b}{-Q} = a \cdot Q^{b-1} \tag{20}$$

Solving equation 20 leads to a relation of Q depending on S, as shown in equations 21 and 22. S_0 will have a different meaning depending on the value of parameter b. If $b < 2$, S_0 is the lower limit of the storage, if $b = 2$, S_0 can be explained as a scaling coefficient and when $b > 2$, S_0 is the upper limit of the storage, as explained by Kirchner (2009).

$$Q(S) = [a \cdot (2-b) \cdot (S - S_0)]^{2-b} \qquad \text{if } b \neq 2 \tag{21}$$

$$Q(S) = e^{a \cdot (S - S_0)} \qquad \text{if } b = 2 \tag{22}$$

3.2.2 *Drainage density*

The second theory assumes a constant q_l in equation 17, which will relate Q directly to G as shown in equation 23. The length l is then defined as the length of the longest dried channel measured from an active source. $G(l)$ is now defined as the total length of all active channels at length l. Finally $N(l)$ is defined as the number of active sources at length l. Figure 5 shows a model of a catchment, which can clarify the meaning of G, l and N.
It is further assumed that channels are receding at a constant speed v_c, thus $v_c = dl/dt$, making $G(t)$ proportional to $G(l)$. A decline of G to l is simply the number of channels N that are receding, thus $dG/dl = N$. Applying this on equations 18 leads to equation 24.

$$Q(t) = q_l \cdot G(t) \tag{23}$$

$$\frac{dQ}{dt} = q_l \cdot \frac{dG}{dt} = q_l \cdot \frac{dG}{dl} \cdot \frac{dl}{dt} = q_l \cdot v_c \cdot \frac{dG}{dl} = q_l \cdot v_c \cdot N(l) \tag{24}$$

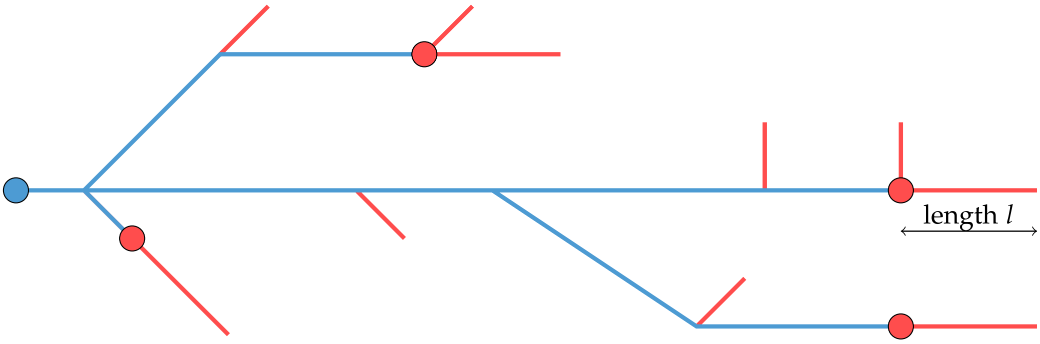


Figure 5: *Model of a catchment, where blue lines represents active channels, red lines represents dried channels, red dots represents active sources and the blue dot represent the outlet. Water is flowing from the sources to the outlet. The total length of the active channels is G, the number of active sources is N and the length of the longest dried channel measured from the source is l.*

Applying these relations on equation 1 makes it possible to find a relation of $N(l)$ and $G(l)$ as shown in equation 25. Because Biswal and Marani (2014) argue that parameter c is also a function of b, the relation between Q and dQ/dt can be based on equation 25.

$$N(l) \propto G(l)^b \tag{25}$$

3.3 EXTRACTING PROCEDURE

In the literature a number of criteria for finding periods of recession can be found, i.e., finding periods in which stream flow depends solely on subsurface flow. These criteria are listed below.

- A declining stream flow: $dQ/dt < 0$, which is a fundamental criterion for finding recession periods.
- A declining stream flow recession: $-d^2Q/dt^2 < 0$. This behaviour is expected in theory, but in practice a small influence of precipitation, evapotranspiration or measurement scatter can lead to a non declining stream flow recession.
- No significant precipitation during the whole period of the recession, as it can influence the stream flow. It is possible to define a threshold, being the maximum allowed precipitation on any day during a recession, P_{max}, or define a maximum relative to the stream flow: $P(t) < Q(t)/x$
- No significant potential evapotranspiration during the whole period of the recession, as it can influence the stream flow. It is possible to define a threshold, being the maximum allowed potential evapotranspiration on any day during a recession, E_{max}, or define a maximum relative to the stream flow: $E(t) < Q(t)/x$
- The recession period must have a minimum length T_{min} in order to expect the stream flow to be due to base flow. According to a review of Stoelzle et al. (2013) this minimum value varies for different publications from 2 to 10 days, and can depend on hydrological and climatological properties.
- Eliminate days at the start and the end of the recession, to lower the influence of storm flow at the start and the end of a recession period. A review by Stoelzle et al. (2013) shows that typically at least the first five days of a recession period are eliminated and that most studies do not eliminate days at the end of a recession. The number of days eliminated at the start of the recessions is defined as T_{start} and the number of days eliminated at the end of the recessions is T_{end}.

It will be determined which combination of criteria can be useful as an extraction procedure. This will be done by taking a declining stream flow for at least 7 days as a starting point, using all the

available data. After that the above mentioned criteria will be tested one by one, by varying the parameter of one criteria at a time, while keeping the other parameters constant. The different combinations of criteria will be evaluated by looking at the parameters c and b, the regression coefficient R^2, the number of recessions per catchments N_{rec} and the number of catchments with data N_{cat} to see which criteria are valuable for the extracting procedure.
Criteria which result in high values of R^2, N_{rec} and N_{cat}, will be determined as valuable criteria. Expected is that the value of parameter b will be around 1 to 3 (Stoelzle et al., 2013). Literature values of c are not available, however an estimate of 30 to 60 days can be made based on Brutsaert (2008). They however assume a linear storage, setting parameter b to a value of 1, where this research use b as a variable.

3.4 PARAMETER FITTING

This section will describe the different procedures for fitting a line to recession points. A combination of a regression procedure and individual recessions, the cloud of points or binning can be used as a parameter fitting procedure.

3.4.1 *Regression procedures*

Linear regression

Applying linear regression on the basic equation 1 can be done by log transforming it first, as shown in equation 26 for stream flow and in equation 27 for dimensionless flow. Using regression values for $ln(a)$ and b can be found. Taking the exponential of $ln(a)$ also gives parameter value a. The procedure for dimensionless flow is roughly the same, except for taking the inverse for finding c.

$$ln\left(-\frac{dQ}{dt}\right) = ln(a) + b \cdot ln(Q) \tag{26}$$

$$ln\left(-\frac{dq}{dt}\right) = ln(1/c) + b \cdot ln(q) \tag{27}$$

Quadratic regression

Using quadratic regression the basic relation from equation 1 will change into equation 28. The log transformed equation will change consequently, as shown in equation 29. Using regression parameters b and d are found directly, parameter a by taking an exponential. The same results hold again for dimensionless flow.

$$\frac{dQ(t)}{dt} = -a \cdot Q^{b+d \cdot ln(Q)} \tag{28}$$

$$ln\left(-\frac{dQ(t)}{dt}\right) = ln(a) + b \cdot ln(Q) + d \cdot ln^2(Q) \tag{29}$$

3.4.2 *Individual, cloud and binning*

Individual recessions

One procedure is to look at all the individual recessions separately. As the number of data points in a individual recession can be quite low, only linear regression is possible, as quadratic regression can lead to overfitting. It is possible to take the median of the parameters of the individual recession lines to end up with one representative result per catchment.

Cloud of all recession points

Another procedure is looking at all recession points at once. When looking at this cloud of points, linear and quadratic regression are possible. This procedure is suitable for both the Brutsaert-method and the Biswal-method.

Binned means

Scatter in the measurements will arise because of measurement precision and resolution. For high values of dQ/dt this scatter will not be significant, however for low values of dQ/dt there will be a significant effect. For low values of dQ/dt, negative scatter will have a bigger effect on a log scale than an equally large positive scatter, resulting in a bias towards lower values for dQ/dt for low values of Q. In order to remove the bias due to this scatter Kirchner (2009) introduced the method of binned means. This binning is done by sorting values of Q from low to high, and defining n bins, where every bin contains $1/n$ of all the sorted data points of Q and dQ/dt. After that the mean values of both Q and dQ/dt are taken for every bin, resulting in n values of Q and dQ/dt.

3.5 Variations

Based on the findings later in this report one of the methods will be selected for further analysis. This method will be used for further analysis on decadal, seasonal and regional variations. Variations in decades will be determined by looking at the 5 most recent decades, seasonal variations will be determined by looking at variations between the 12 months.

3.5.1 *Regional variation*

Regional variation will be shown in a map, showing the parameter values of b or c per catchment. These values will be interpolated in order to get a more smooth map for the United Kingdom, which can be used to make estimates for ungauged catchments. Outliers for both b and c are removed, taking into account that values of b range from 0 to 8 and values of c range from 0 to 100 days.
The interpolated values will be compared to the values for each catchment. This will be done by making an interpolated grid based on all catchments, except for one. The values of this catchment will be estimated using the grid and will be compared to the actual value. By doing this for all catchments one can estimate the errors in the interpolated map. Again a map and interpolated map can be made using found values of the errors.

3.6 Catchment characterizations

Results for different catchments will be related to geology, land use and the 22 catchment descriptors, as given in chapter 2.

For the 66 uninfluenced catchments, geology and land use will be compared to values of b and c. As this data is qualitative and often contain multiple sorts of geology and land use, only one predominant geology and land use will be used per catchment. Results will be presented using box plots, with values of b or c against common types of geology and land use. Not all the catchments with geological and land use data will be used, because it will be too time consuming and the smaller subset can already give a good estimation of the relations between recession behaviour and geology and land use.

The 22 catchment descriptors are quantitative and these can be compared to parameter b and c using linear regression and scatter plots. This will be done for all the 618 catchments containing catchment descriptors.

4 RESULTS

This chapter will describe the most important results of this study, starting with the results of the extraction procedure in section 4.1. Section 4.2 describes the results of the various methods and will conclude that the Brutsaert-method with the median of the individual recessions will be used for analysis in the following sections of this chapter.
Section 4.3 describes variations between 5 successive decades, section 4.4 describes seasonal variations by showing results for every month separately and section 4.5 describes the regional variations of the results in the United Kingdom. The errors in estimating the recession behaviour based upon interpolated grids are shown.
Section 4.6 relate recession behaviour to geology, land use and catchment descriptors and shows that correlation exists between parameter b and geology and parameter c and BFIHOST.

4.1 EXTRACTION PROCEDURE

The extraction procedure will result in defining a recession period as a period with declining stream flow for a minimum length T_{min} of 8 days, with T_{end} is 2 days and P_{max} is 1 mm/day. Evapotranspiration and declining stream flow are not taken into account and no days at the start of the recession are removed. More detailed information on the calibration of the extraction procedure can be found in appendix A.

4.2 DIFFERENCES BETWEEN METHODS

A selection of the used methods and regression techniques is shown in figure 6 to give a impression how the different methods look graphically. It can be seen that the slope of the Brutsaert-method (plot a) is lower than the slope of an average individual recession, where the slope of the Biswal-method (plot b) is quite consistent with the average individual slope. It is further good to notice that using quadratic regression the Brutsaert-method (plot c) has a positive second order behaviour, where the Biswal-method (plot d) has a negative second order behaviour.

Table 1 shows more detailed results for the Brutsaert-method using different parameter fitting methods. It can be seen that the value of parameter b is approximately 1 point higher for the median of the individual recessions than for the other four methods. A possible explanations is that there is a bias in taking the cloud of points, resulting in a lower value of b. This bias is also shown by Biswal and Marani (2010).
It is also shown that there is a significant quadratic behaviour. This behaviour is however not highly reliable, due to the bias that seems to exist for using the cloud of points.

It is expected that the binning procedure eliminates the influence of scatter, resulting in higher values of dQ/dt for low values of Q. This can be translated into lower values of b and c when using the binning procedure in comparison to the cloud of points. This behaviour can be seen in the table, but differences between the cloud and binning are however not very large. The value of R^2 is however much higher when using the binning procedure.

Table 2 shows results for the Biswal-method using different parameter fitting methods. It can be seen that increasing values of n lead to increasing values of b and c, but also in R^2, which is in accordance to Biswal and Marani (2014), who show that higher values of n give better results. Results for the binning procedure are comparable to the results obtained by using the Brutsaert-method. The quadratic behaviour is however much larger and much more varying than for the Brutsaert-method.

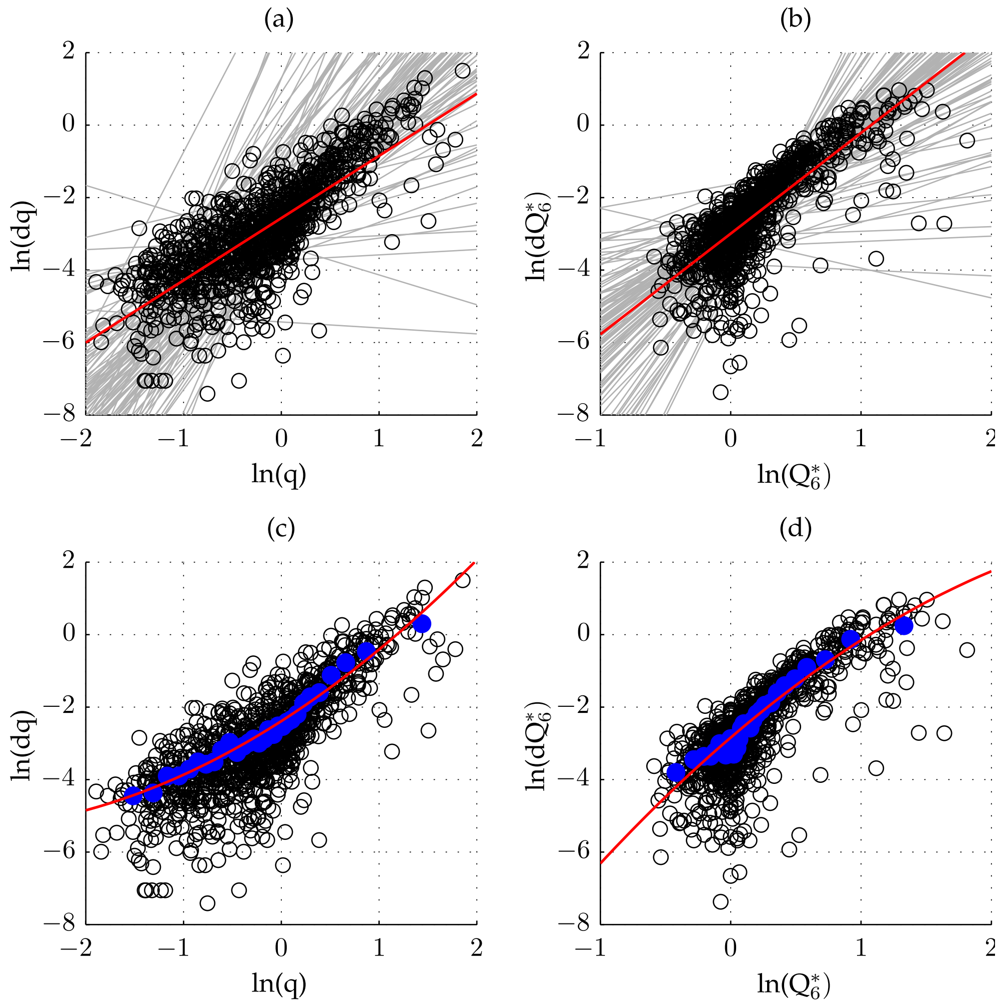


Figure 6: *Catchment considered is Roxton, with: (a) plot of $ln(q)$ against $ln(dq)$ for the Brutsaert-method, for both individual recessions, the grey lines (median b=2.8, c=11), and the cloud of points (b=1.7, c=13), the red line (b) plot of the Biswal-method (b=2.7, c=21), with $ln(Q_6)$ against $ln(dQ_6)$ (c) plot of the Brutsaert-method using the cloud of points with $ln(q)$ against $ln(dq)$, using binning and quadratic regression (b=1.7, c=11, d=0.3) (d.) plot of the Biswal-method with $ln(Q_6^*)$ against $ln(dQ_6^*)$, using binning and quadratic regression (b=3.1 c=17, d=-0.4)*

Table 1: *The Brutsaert-method, using respectively the cloud of points, binned means of the cloud of points, the median of individual recessions and linear and quadratic regression. The three values of b, c, d and R^2 are the 10th, 50th and 90th percentile.*

Method	c (*days*)			b			R^2			d		
Cloud, linear	3.4	9.3	33	1.3	1.8	2.4	0.42	0.69	0.81			
Binned, linear	3.0	7.5	26	1.3	1.7	2.4	0.77	0.96	0.99			
Individual, linear	1.3	5.9	33	1.9	2.9	4.9	0.43	0.80	0.90			
Cloud, quadratic	3.0	9.5	38	1.3	2.0	2.6	0.44	0.72	0.83	-0.1	0.1	0.5
Binned, quadratic	2.7	7.6	26	1.3	2.0	2.5	0.77	0.97	0.99	0.0	0.1	0.5

Table 2: *The Biswal-method, using respectively the cloud of points, binned means of the cloud of points, linear and quadratic regression and different values of n. The three values of b, c, d and* R^2 *are the 10th, 50th and 90th percentile.*

Method	n	c			b			R^2			d		
Cloud, linear	1	6.0	11	32	1.1	1.8	2.7	0.10	0.37	0.62			
Cloud, linear	2	7.1	12	33	1.4	2.2	3.5	0.15	0.47	0.69			
Cloud, linear	3	8.5	14	35	1.6	2.5	3.9	0.19	0.54	0.73			
Cloud, linear	4	9.5	16	39	1.8	2.6	4.1	0.23	0.59	0.75			
Cloud, linear	5	11	18	42	1.9	2.8	4.2	0.29	0.63	0.77			
Cloud, linear	6	12	20	47	2.0	2.8	4.3	0.32	0.66	0.79			
Binned, linear	6	11	17	39	2.0	2.7	4.2	0.67	0.92	0.97			
Cloud, quad	6	13	21	50	1.9	2.9	5.1	0.40	0.79	0.89	-1.0	0.0	1.5
Binned, quad	6	11	18	40	1.8	2.6	4.5	0.71	0.94	0.98	-0.7	0.0	2.0

Three methods are selected in order to compare them and gain insight in potential biases of these methods, which can help choosing one recession analysis method for further analysis. The Brutsaert-method using the cloud of points, binning and linear regression (hereafter called 'Brutsaert-method'), the Brutsaert-method using the median of individual recessions (hereafter called 'median of individual recessions') and the Biswal-method with n=6, binning and linear regression on the cloud of points (hereafter called 'Biswal-method') are therefore selected. The comparison is done by making a couple of scatter plots.

A scatter plot of b for one method against b for another method (figure 7) and, in the same way, c against c (figure 8) is made to analyze relations between the three different recession analysis method. The scatter plot of b against b (figure 7) shows that there is not much agreement for the Brutsaert-method and the Biswal-method (plot a) and the Brutsaert-method and the median of the individual recessions (plot b). Agreement between the Biswal-method and the median of the individual recessions (plot c) is however quite high. These results are consistent with the theory of a bias in the Brutsaert-method using the cloud of points. The Biswal-method is designed to overcome this bias, which seems to succeed, according to these scatter plots.

The scatter plot of c against c (figure 8) shows that there is quite a good agreement for the Brutsaert-method and the median of the individual recessions (plot b) and less good agreements for the Brutsaert-method and the Biswal-method (plot a) and the Biswal-method and the median of the individual recessions (plot c). A possible explanation is a bias in parameter c when using the Biswal-method.

Figure 9 shows a scatter plot of parameter b against parameter c is for the three methods. According to the theory behind the Biswal-method, parameters b and c should be related, which is shown in the plot, but with a regression coefficient of only 0.47. The Brutsaert-method and the median of individual recessions show no significant correlation between b and c. The idea of a bias in parameter c using the Biswal-method seem to strengthen, because the Biswal-method show a correlation between b and c, where the other methods do not find this relation.

It can be concluded that there is possibly a bias in parameter b when using the Brutsaert-method and in parameter c using the Biswal-method. Quadratic regression seems not to be reliable, because of this bias. For further analysis the Brutsaert-method using the median of individual recessions is used, because no bias is shown and it is therefore the best choice.

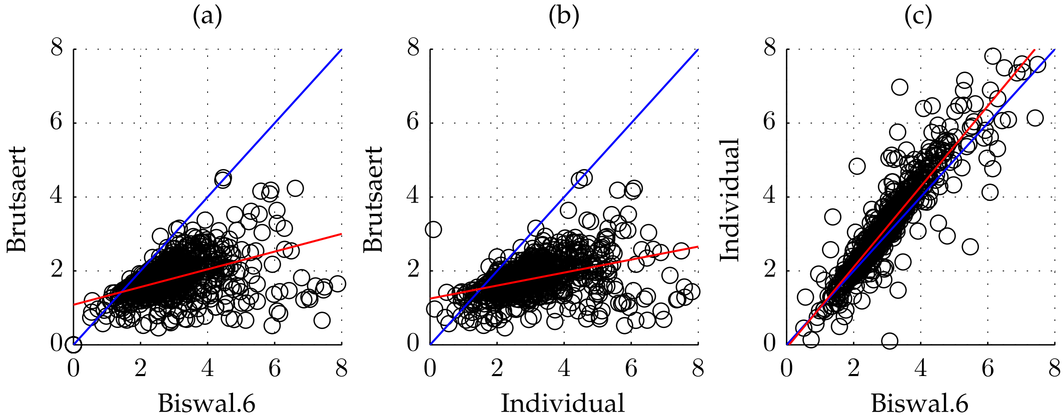


Figure 7: *Scatter plot of parameter b against parameter b, where the red line is the regression line, for (a) the Biswal-method against the Brutsaert-method, with* R^2*=0.22 (b) the median of the individual recessions against the Brutsaert-method, with* R^2*=0.18 (c) the median of the individual recessions against the Biswal-method, with* R^2*=0.85*

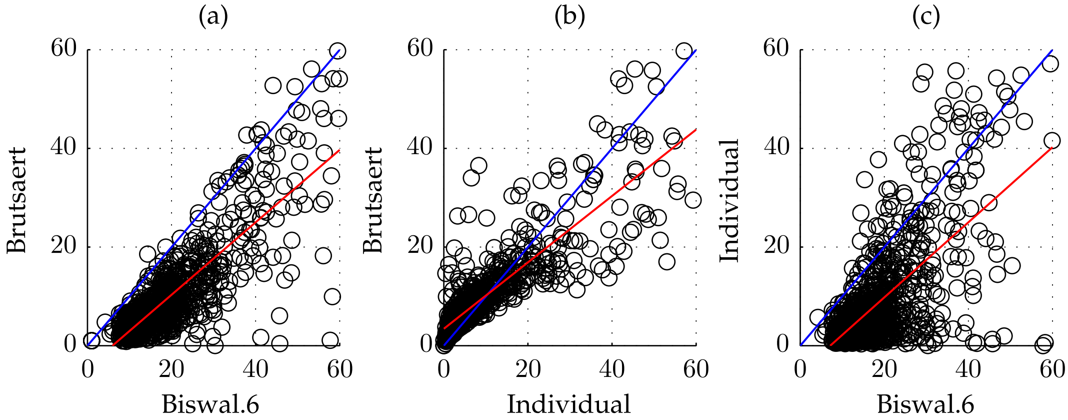


Figure 8: *Scatter plot of parameter c against parameter c, where the red line is the regression line, for (a) the Biswal-method against the Brutsaert-method, with* R^2*=0.67 (b) the median of the individual recessions against the Brutsaert-method, with* R^2*=0.74 (c) the median of the individual recessions against the Biswal-method, with* R^2*=0.42*

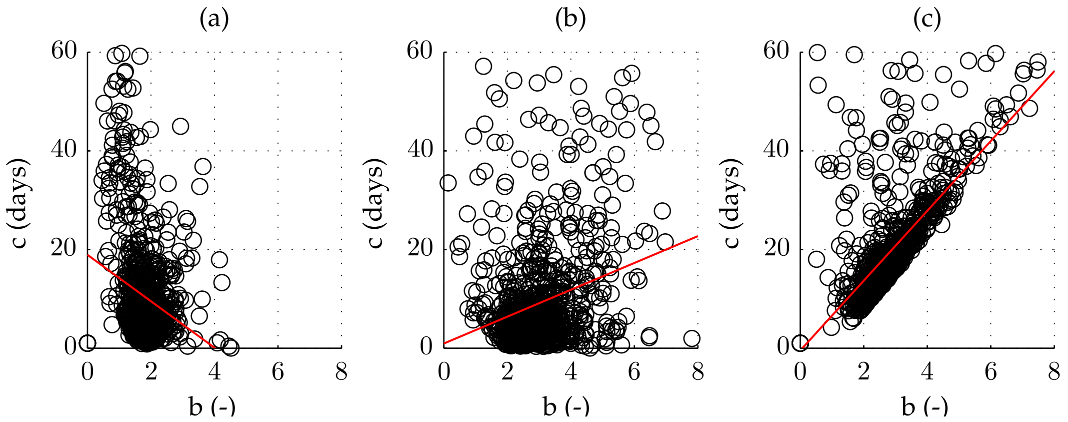


Figure 9: *Scatter plot of parameter b against parameter c, where the red line is the regression line, for (a) the Brutsaert-method, with* R^2*=0.06 (b) the median of the individual recessions, with* R^2*=0.07 (c) Biswal-method, with* R^2*=0.47*

Table 3 shows the values of parameters c and b, R^2, N_{rec} and N_{cat} for different decades. No large differences in results exists for parameter b and c between the different decades, only the decade from 1960-1969 seems to differ a bit from the other decades. In order to suppress a potential bias, caused by having more catchments with data in later decades, also a box plot is made consisting of only catchments with data for all the decades. Results are shown in figures 10, for parameter b, and figure 11, for parameter c, where four decades are compared with the results of the decade 2000-2009. The decade 1960-1969 show the largest differences for both b and c, but it does not seem to be significant.

Table 3: *Parameter values c and b, R^2, N_{rec} and N_{cat} for different decades, based on the median of individual recessions. The three values of c, b, R^2 and N_{rec} are respectively the 10th, 50th and 90th percentile.*

Decade	c (days)			b			R^2			N_{rec}			N_{cat}
1960-1969	11	17	33	1.9	2.6	3.9	0.42	0.68	0.83	16	89	256	439
1970-1979	12	21	46	2.0	2.9	4.1	0.35	0.64	0.79	32	152	370	712
1980-1989	13	21	47	2.0	2.8	4.1	0.34	0.64	0.78	43	198	430	863
1990-1999	12	21	45	2.0	2.9	4.1	0.33	0.66	0.81	56	235	492	938
2000-2009	11	20	46	2.0	2.9	4.2	0.35	0.70	0.84	76	238	403	955

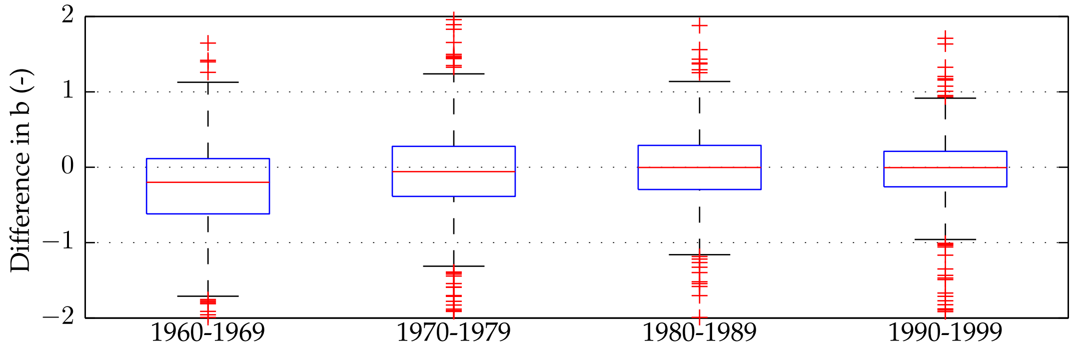


Figure 10: *Box plot of parameter b for different decades relative to the decade from 2000-2009, for 407 catchments using the median of individual recessions.*

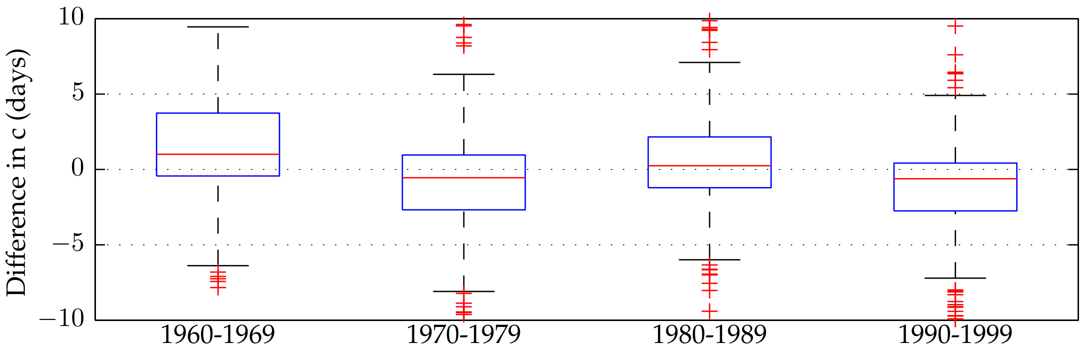


Figure 11: *Box plot of parameter c for different decades relative to the decade from 2000-2009, for 407 catchments using the median of individual recessions.*

4.4 SEASONAL VARIATION

Seasonal variations are measured by the median values for b and c for the different months. In order to compare values of c correctly, mean stream flow values, which are used for defining the dimensionless flow, are determined for every month separately. Results of the recession analysis for different months are shown in table 4.

It can be seen that both parameters b and c are higher during the summer months, varying from 2.5 to 3.3 for b and from 3.3 to 9.2 for c over the year. A possible explanations is the higher evapotranspiration in summer months than winter months. The value of R^2 is however higher during winter months. A possible explanation is that the variation in evapotranspiration is also larger in summer months than in winter months, resulting in a less good linear fitting.

Table 4: *Parameter values c and b, R^2, N_{rec} and N_{cat} for different months, based on the median of individual recessions. The three values of c, b, R^2 and N_{rec} are respectively the 10th, 50th and 90th percentile.*

Month	c (days)			b			R^2			N_{rec}			N_{cat}
January	1.2	3.9	15.1	1.6	2.5	4.1	0.50	0.82	0.93	21	86	159	927
February	1.7	5.3	23.4	1.7	2.7	4.7	0.46	0.81	0.92	18	81	173	954
March	1.4	5.1	21.9	1.8	2.7	4.7	0.45	0.79	0.92	24	100	198	938
April	1.9	6.2	31.3	1.9	2.9	4.8	0.34	0.77	0.91	24	102	226	943
May	2.5	8.1	36.5	1.7	2.9	5.3	0.27	0.73	0.90	18	80	186	930
June	1.8	9.2	47.9	1.7	3.1	6.0	0.25	0.67	0.89	14	60	168	897
July	1.4	7.1	46.9	1.7	3.2	6.2	0.22	0.73	0.91	9	50	141	879
August	0.9	7.7	57.7	1.7	3.3	6.3	0.31	0.76	0.92	9	38	121	835
September	0.9	6.1	61.1	1.8	3.2	6.5	0.35	0.81	0.95	8	40	111	801
October	0.8	4.4	29.8	1.9	2.9	5.1	0.55	0.85	0.95	14	55	130	907
November	1.0	4.2	23.3	1.9	2.7	4.9	0.47	0.81	0.93	11	52	107	878
December	1.1	3.3	14.0	1.8	2.7	4.7	0.55	0.86	0.95	16	55	118	921

4.5 REGIONAL VARIATION

There is quite a lot of regional variation for parameters b and c. Figure 12 shows a map of the UK with the value of b for the different catchments. Based on that a linearly interpolated map is made, which is shown in figure 13. It is clearly visible that values of b are generally lower for the western parts of the country than for the eastern parts.
Estimating b values based on the interpolated map results in the estimated relative errors as shown in the interpolated map in figure 14. In general errors tend to be under 20 percent for Wales, South East England and Southern Scotland, but at least 30 percent for large parts of the rest of the UK.

Variation of parameter c for the different catchments is given in figure 15. Based on that a linearly interpolated map of c is made, which is shown in figure 16. Values of c are mostly lower than 10 for Wales, Scotland and South West and North England, but for a large part of South East and East England values are 30 or higher.
The interpolated map of the relative errors for c is shown in figure 17. It shows us that the errors for c are in general larger than for b and that they are much more distributed over the United Kingdom.

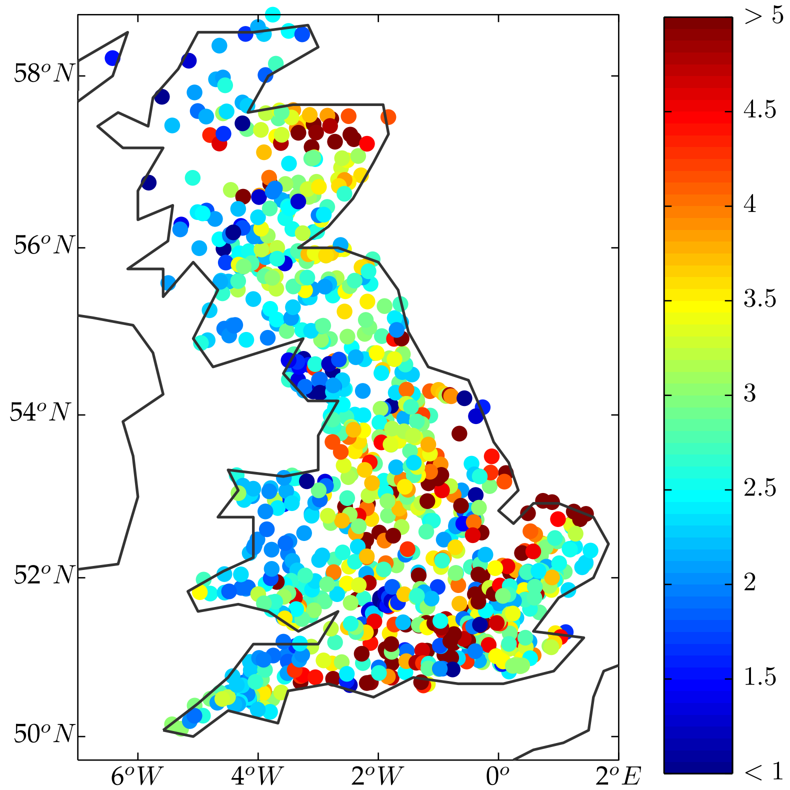


Figure 12: *Plot of parameter b for the United Kingdom using the median of individual recessions, containing 956 catchments with b values between 0 and 8.*

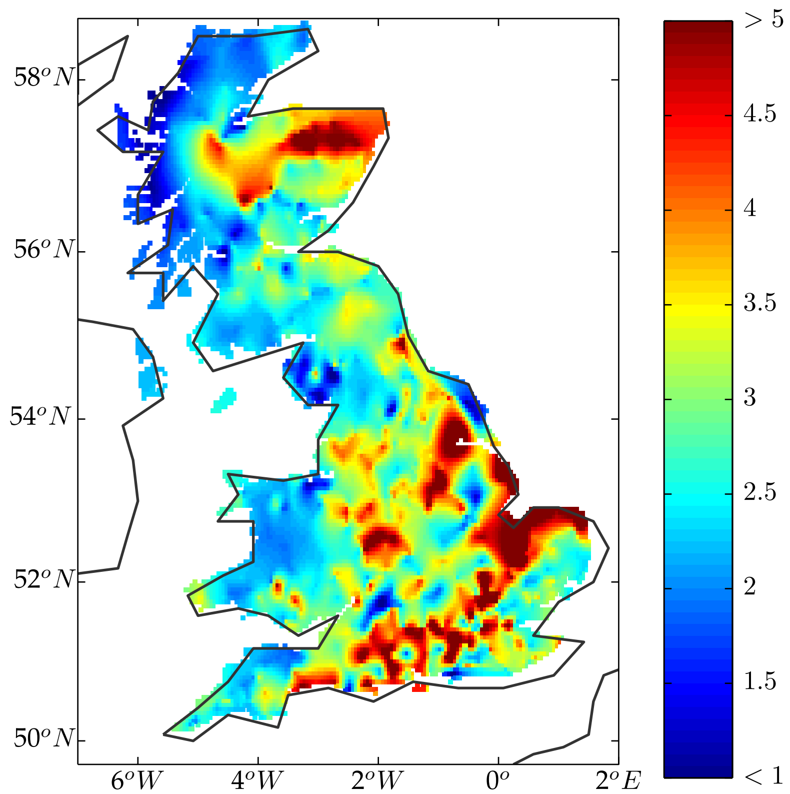


Figure 13: *Interpolated plot of parameter b for the United Kingdom using the median of individual recessions.*

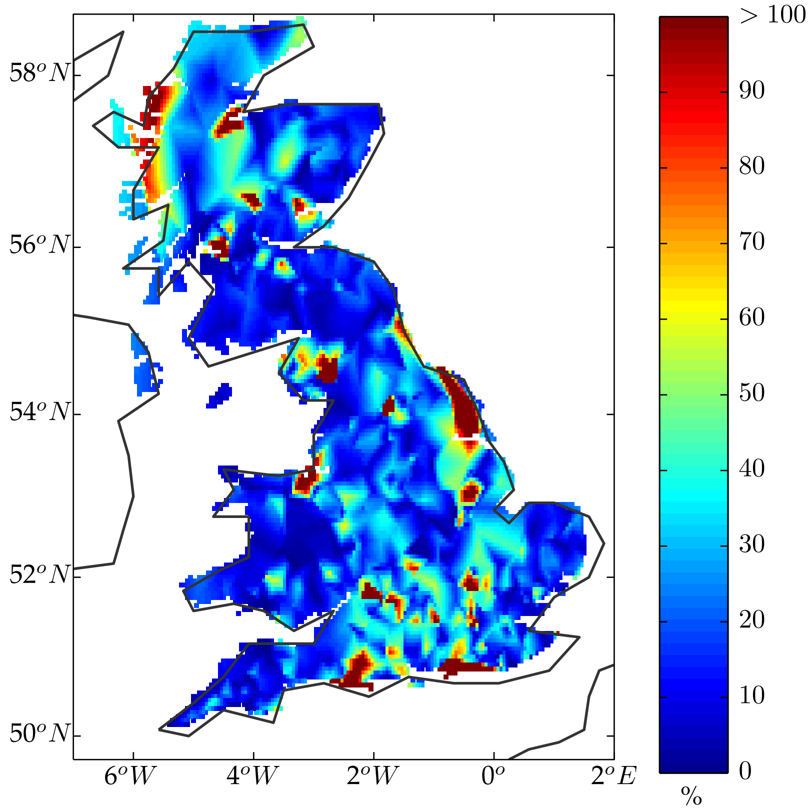


Figure 14: *Interpolated plot of the relative error for b for the United Kingdom, using the median of individual recessions.*

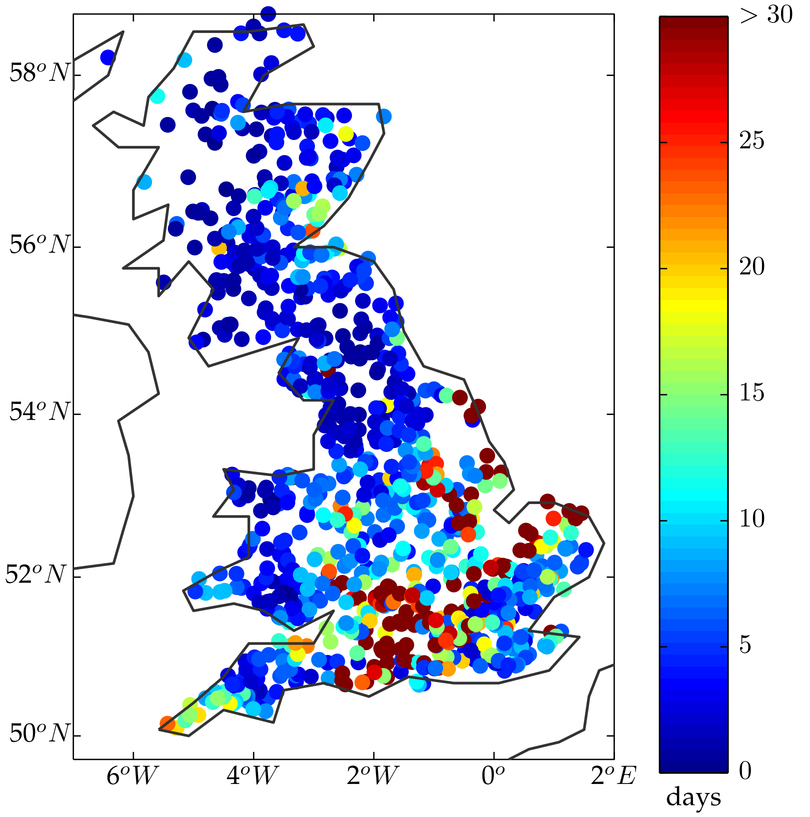


Figure 15: *Plot of parameter c for the United Kingdom using the median of individual recessions, containing 965 catchments with c values between 0 and 100.*

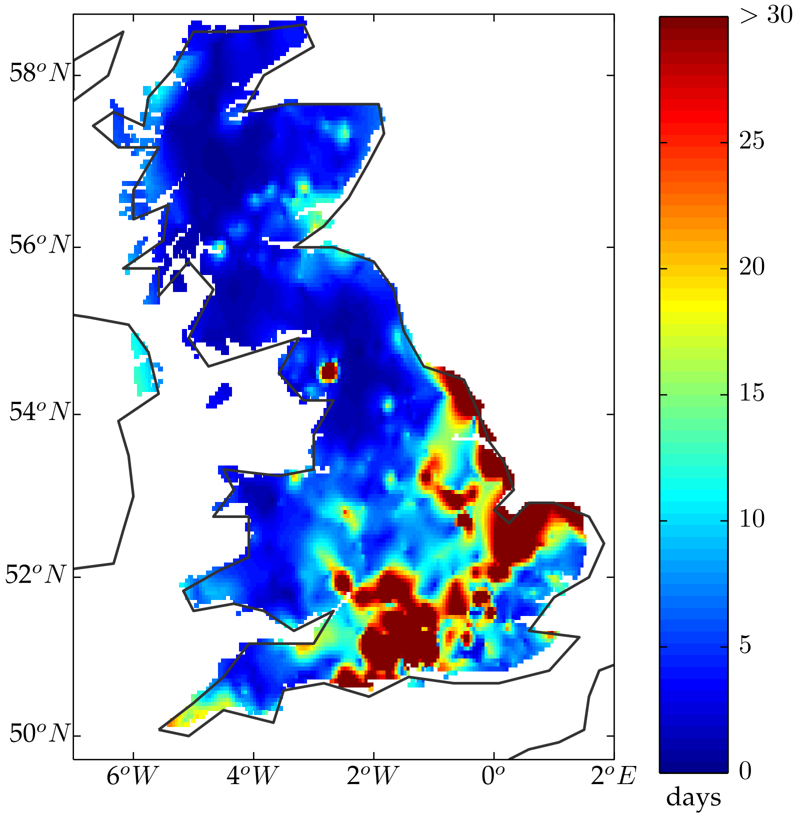


Figure 16: *Interpolated plot of parameter c for the United Kingdom using the median of individual recessions.*

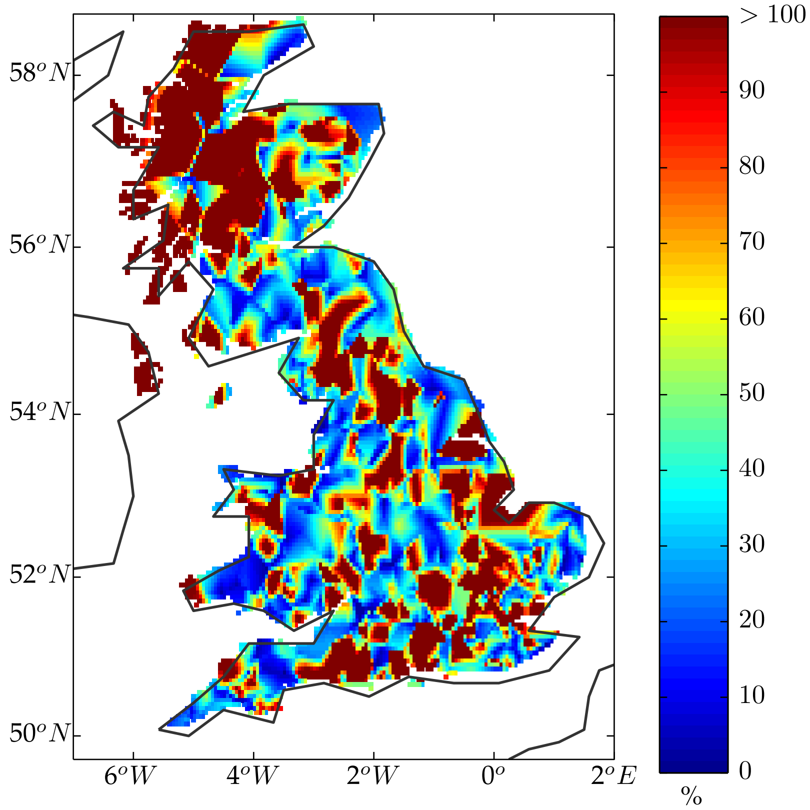


Figure 17: *Interpolated plot of the relative error for parameter c for the United Kingdom, using the median of individual recessions.*

4.6 CATCHMENT CHARACTERIZATION

In order to relate recession behaviour to catchment characteristics, recession behaviour is related to 22 catchments descriptors as well as to geology and land use.

4.6.1 *Catchment descriptors*

Catchment descriptors are related to values of b and c for 618 catchments. The scatter plots are shown in figure 18 for b and figure 19 for c.

The largest values of correlation for b are between b and BFIHOST, DPSBAR, PROPWET, RMED, SAAR and SPRHOST, however none of these being very strong correlations. BFIHOST and SPRHOST are both based on soil characteristics, suggesting that parameter b depends on soil type. The correlation with SAAR and RMED suggest a correlation between parameter b and precipitation. The correlation with DPSBAR suggest that flatter terrain is related to higher b values and the correlation with PROPWET suggest that wetter soil is related to lower values of b.

By far the largest values of correlation between c and recession behaviour are shown between c and BFIHOST and SPRHOST, with an R^2 of respectively 0.52 and 0.47. This suggest that parameter c depends for a large part on soil characteristics. Smaller correlations are shown between c and ALTBAR, DPSBAR, PROPWET, RMED and SAAR.

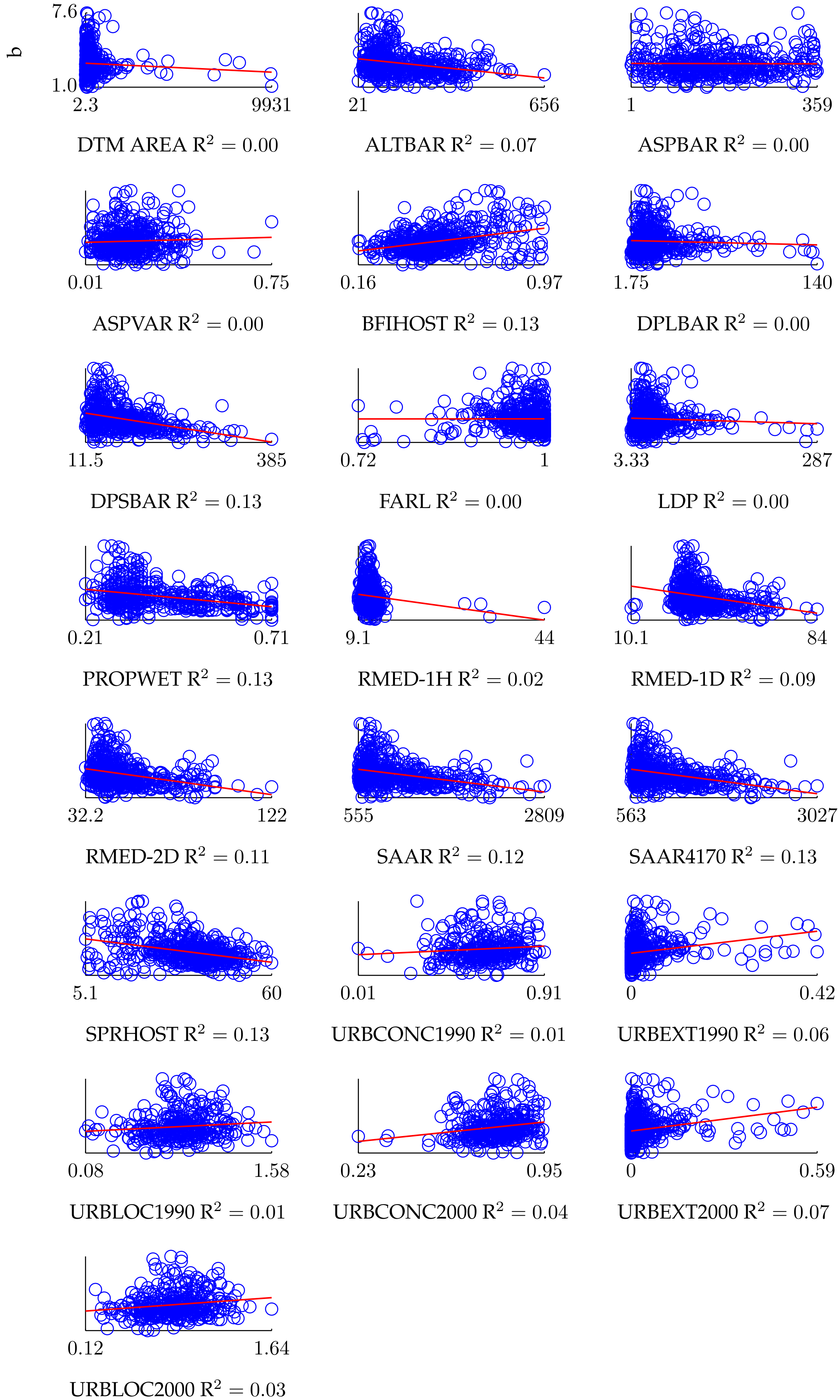


Figure 18: *Scatter plot of 22 catchment descriptors against b, with values of R^2 given in plot*

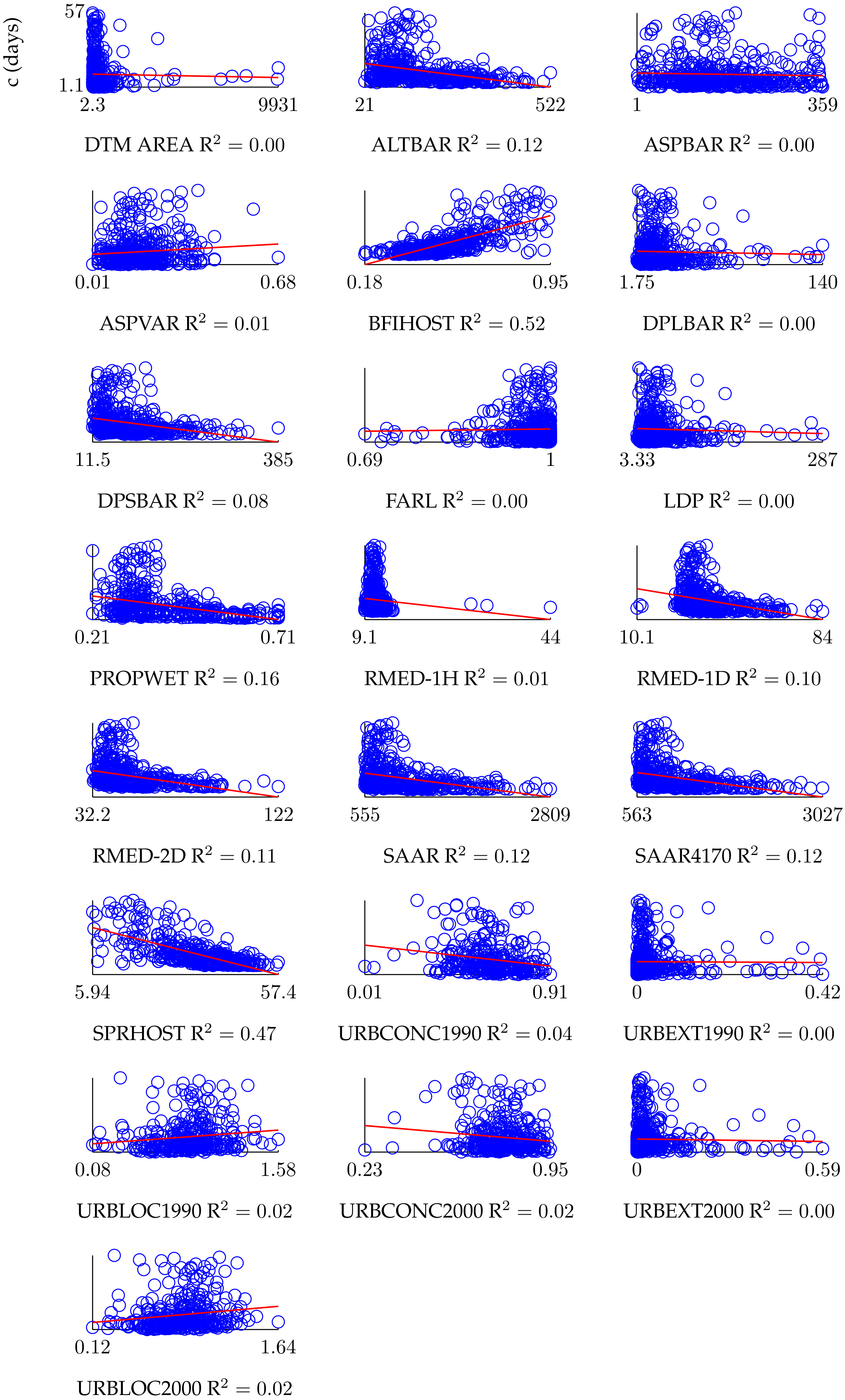


Figure 19: *Scatter plot of 22 catchment descriptors against c, with values of R^2 given in plot*

4.6.2 *Geology*

Geology is related to 66 selected, relatively uninfluenced, catchments. The results can be seen in box plots for different sorts of geology related to b, figure 20 and c, figure 21. Values of b seem to be of decreasing order for respectively chalk, sandstone, limestone and clay. It is also noteworthy that there is a large deviation in results in b values for catchments with chalk. It is also interesting to notice that regions with chalk can be recognized on a map, because of the higher values of b, see figure 22, where the region with chalk is based on data from the British Geological Survey.
Values of c seem to vary extremely for chalk, but also for limestone, were values for sandstone and clay do not have big variations and seem to stay under 10 in general.

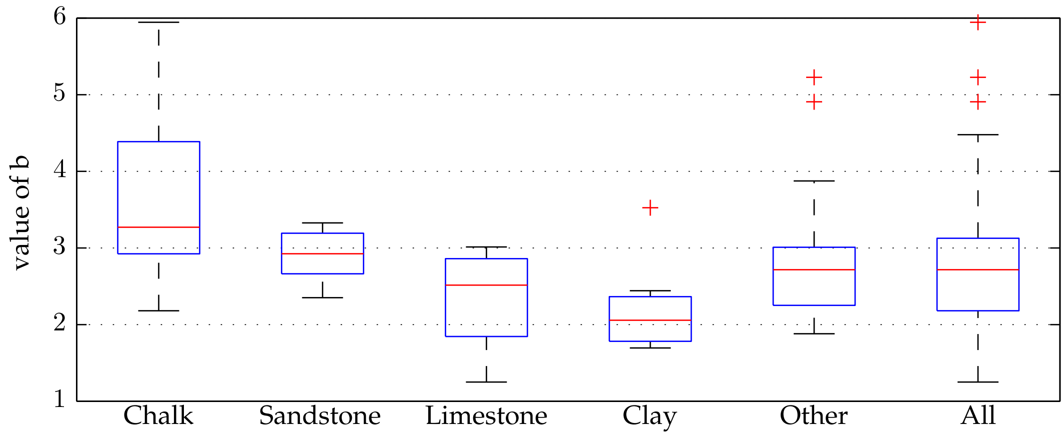


Figure 20: *Box plot of b with different sorts of geology.*

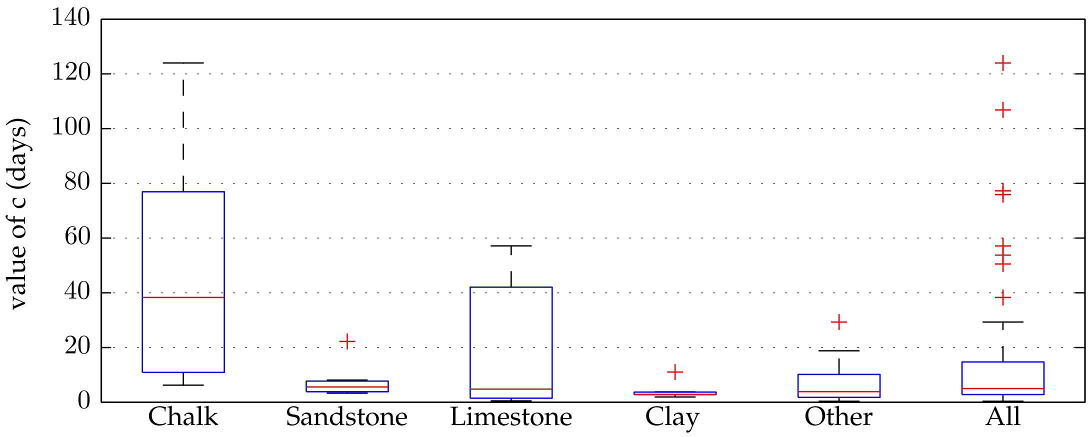


Figure 21: *Box plot of c with different sorts of geology.*

4.6.3 *Land use*

Land use is also related to parameters b and c for the 66 selected, relatively uninfluenced, catchments. Results are shown in figure 23 (for b) and figure 24 (for c).
The values of b seem to be roughly constant for the different types of land use. Noteworthy is to see that more general descriptions as agricultural and rural have larger variations, than a less general description as forest.
Forest and moorlands tend to have values of c under 15, where rural and grazing catchments have much larger values and variations.

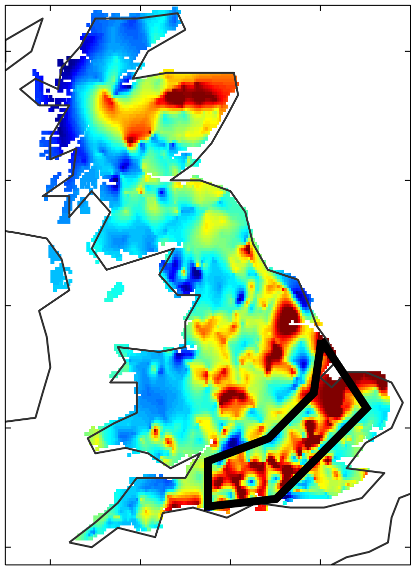


Figure 22: *Same figure as figure 14, with inside the black drawing the mayor regions with chalk.*

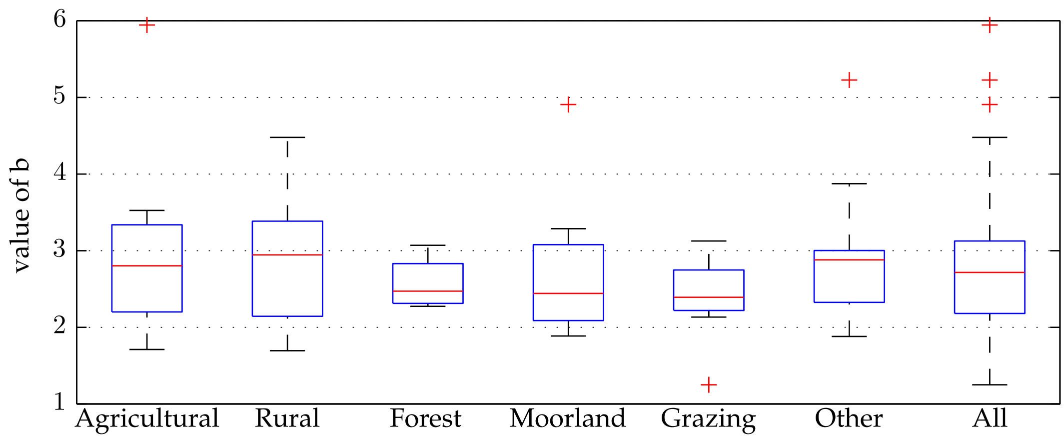


Figure 23: *Box plot of b with different sorts of land use.*

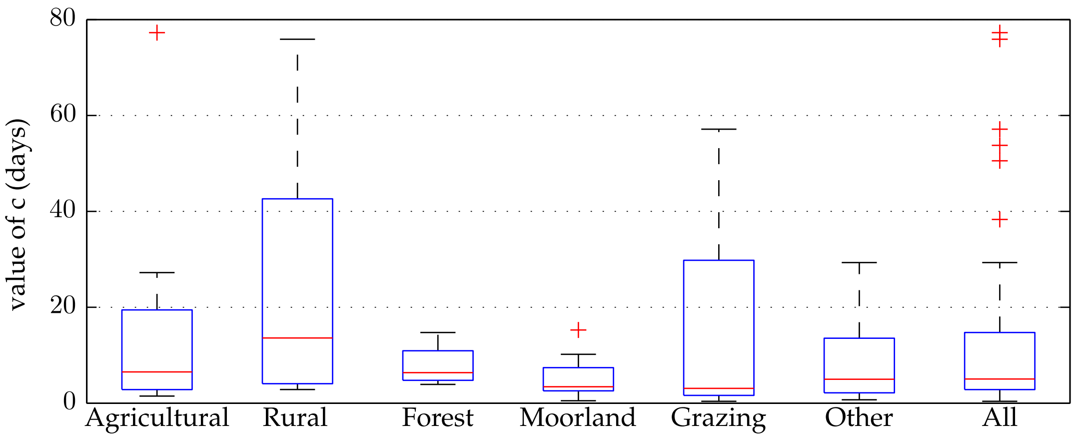


Figure 24: *Box plot of c with different sorts of land use.*

5 DISCUSSION

A discussion of the main results will be done in this chapter. First the extraction procedure will be discussed in section 5.1, followed by a discussing on the different methods, their results, also compared to literature, and their reliability in section 5.2.
Section 5.3 will follow by discussing decadal and seasonal variations and possible explanations for it. Then the regional variation and the interpolating procedure will be discussed. The last part of the discussion, section 5.4, is about relating recession behaviour to catchment characteristics and possible ways to achieve better results in further research.

5.1 EXTRACTION PROCEDURE

As there is no objective definition for extraction recession periods out of a stream flow time series, defining the extraction procedure is done by calibration. This calibration process is based on multiple indicators, making it possible to interpret results in multiple ways.
A review by Stoelzle et al. (2013) shows that there are large differences in results for different extraction procedures. They show strong correlation between the methods based on ranking 20 catchments in order of recession parameters, i.e., catchments with the highest parameters using one method, are very likely to have the highest parameters using the other methods. Using a consistent extraction procedure for different catchments lead thus to results which are at least reliable relative to each other.
Using different extraction procedures for every catchment separately, would however have some advantages too. Take for example some differences per catchment in the height of precipitation which is not effecting the stream flow directly. Using the same extraction procedure for every catchment would then lead to biases, but it was already shown that using different procedures would also lead to biases.

5.2 METHODS AND PARAMETER FITTING

Results for the Brutsaert-method show that values of b are in general lower when using the cloud of points than when using the median of individual recessions. This result can be explained as a bias of using the cloud of points, as shown by Biswal and Marani (2010). They illustrate it with a figure containing only recession lines with b values higher than 2, leading to a trend line (cloud of points) with a b value of 1.19. Research by Mutzner et al. (2013) show comparable results.
The Biswal-method seem to overcome the large differences between individual recessions and the cloud of points, giving comparable results for the b value for both methods. The Biswal-method fix however the relation between b and c values, i.e., values of c are linearly related to values of b. This relation is however not visible using the median of the individual recessions, in fact b and c are totally uncorrelated, questioning the reliability of the linear relation between values of b and c.
The bias in using the cloud of points can also give doubt about the procedure of quadratic regression, because quadratic regression is only used in combination with the cloud of points. Large variations for the second order term between the Brutsaert-method and the Biswal-method and lack of theoretical background for a second order relation further weaken the basis for quadratic regression as proposed by Kirchner (2009).

The physically reasonable range for values of b is traditionally defined as being between 1 and 3, according to Brutsaert and Nieber (1977) and Stoelzle et al. (2013). These values are indeed found using the Brutsaert-method with the cloud of points. Individual recessions and the Biswal-method give however values in a much larger range, suggesting that values of b between 1 and 8 are acceptable.

A physically reasonable range for values of c is not yet defined in literature, but an estimation was made ranging from 30 to 60 days (Brutsaert, 2008). All three methods used in this research find however values for c in the range of 1 to 60 days, suggesting that acceptable values can be much lower than 30 days.

At the moment quite some research is going on about explaining the physical background for recession behaviour, for example by Mutzner et al. (2013) and Biswal and Marani (2014). Gaining more knowledge about the physical background could help gaining insight in advantages and disadvantages of the different methods. An example would be the linear relation between b and c, which is based on the physical background, but which does only show up using the Biswal-method.

5.3 DECADAL, SEASONAL AND REGIONAL VARIATIONS

There are no large variations in results between different decades, suggesting that recession behaviour in general, i.e., without drastically changes in water management, is not really changing over a time period up to 50 years.

There is also quite some variation between results of the individual recessions of a catchment. Seasonal variability is shown to be part of this variability, giving higher values of both b and c in summer months, but that could not explain all the existing variability.
Other variability can be due to precipitation, evapotranspiration and measurement scatter. Including both precipitation and evapotranspiration in the model can lower this variability, but does this of course at the cost of a more extensive model. Lowering threshold values could also lower variability, but results in less recessions, reducing the reliability of the results.

Interpolated plots give lower b values for westerns part of the UK than for eastern parts and give lower values of c for Scotland, Wales and Northern England compared to the other parts. The interpolated plots are based upon results for over 950 catchments and seem to be quite consistent. The interpolated plot of errors, especially for parameter c, shows however large errors for almost every part of the United Kingdom. A first source of errors is of course the uncertainty in the found parameter values for every catchment.
Another potential source of errors is the assumption that values can be linearly interpolated, thus suggesting that catchment properties, as geology or land use, are changing perfectly linear in space, which might not be true. If catchment properties are not changing linearly, the parameter values are not changing linearly either.
A third source of errors, is taking the coordinates of the stream gauge as reference point for a catchment. An alternative, as taking the catchment centroid as reference point, would probably give a better representation of the characteristics around this reference point.

Last two problems were recognized by Skøien et al. (2006) who suggested a method of topological kriging, taking into account the nested nature of a catchment. If for example two catchment are both part of the same larger catchment, they probably have a better agreement than two catchment which are geographical closer but are not part of the same larger catchment.

5.4 CATCHMENT CHARACTERIZATION

Catchment characterization for the 22 catchment descriptors is done using data from 618 catchments. For a scatter plot between recession parameters and catchment descriptors this can be considered as an acceptable value.
Catchment characterization for geology and land use is however done using a smaller subset of 66 relative uninfluenced catchments. Using this data set with box plots, as done for geology and land use, results in around 10 catchments per box plot, reducing the reliability of the results. A possible way to achieve higher reliability of the results, is using quantitative data for geology and land use, thus having for example percentages of each type of geology per catchment. In that

way it is possible to compare parameter values to the percentage of a certain type of geology using a scatter plot and linear regression. An example of this is done by Beck et al. (2013) using percentages of clay, sand, silt and gravel in its research.

Although there seems to be reliable correlations between parameter *b* and geology and between parameter *c* and BFIHOST, is seems that it is not enough to give a reliable prediction of recession characteristics for ungauged catchments. This is because of the catchment characteristics, except for the relations mentioned, not having high correlations with both the recession parameters. The relations with geology and land use are also too qualitative and therefore less reliable and useful.
In order to make characterization of ungauged catchments possible, one can think of quantifying geology and land use, using percentage of certain types of geology or land use in a catchment. But quantifying can also be done in another way, instead of using geology, one can for example look at permeability. And instead of looking at land use, the Normalized Difference Vegetation Index (Deering et al., 1975) can be used, being an indicator of the amount of living vegetation. This data was not available for this research, but would help finding stronger correlations between recession behaviour and geology and land use.
This study also used an inhomogeneous data set, thus for example with both varying geology and land use. Using a more homogeneous data set, with for example a more constant geology, could results in more clear results for another variable as land use.

6 CONCLUSIONS AND RECOMMENDATIONS

The objective of this study was to characterize recession behaviour for ungauged catchments in the United Kingdom by relating recession behaviour to catchment properties. It can be concluded that characterizing recession behaviour for gauged catchments is possible. It was however not feasible to reliable characterize recession behaviour for ungauged catchments, because of the lack of clear relations between recession behaviour and catchment properties. More specific conclusions, sorted by research questions, are shown in section 6.1 and recommendations are shown in section 6.2

6.1 CONCLUSIONS

1. Which methods for analyzing recession behaviour can be useful for predicting recession behaviour for gauged catchments in the United Kingdom?

- It can be concluded that looking at the median of individual recessions seems to give the most reliable results. The Brutsaert-method using the cloud of points lead to a bias in parameter b and the Biswal-method lead to a bias in parameter c.
- There is lack of evidence for quadratic regression. Large (seasonal) variability in individual recessions show however also shortcomings in the linear model.
- For the extraction procedure no objective right definition can be found. Both using the same extraction procedure for different catchments as using different extraction procedures for different catchments will lead to biases.

2. How well can recession behaviour be characterized for gauged catchments in the United Kingdom?

- Results over the different decades seem to be consistent, suggesting that recession behaviour is not changing over a longer period of time.
- There is large variability between individual recessions, which can only partially be explained by seasonal variations.
- The traditionally reasonable range for values of b from 1 to 3 seem to be an underestimation, based on a bias in using the cloud of points. Based on this study, a reasonable range would be from 1 to 8 for parameter b and from 1 to 60 days for parameter c.

3. Which catchment properties relate to variations in recession behaviour?

- Correlations between recession behaviour and catchment properties are shown, most strongly between parameter c and BFIHOST and between parameter b and catchment geology. This study does not show correlation between recession behaviour and land use.
- Correlation between geographical location and recession behaviour is shown. Western parts of the UK have in general lower values of b than Eastern parts. Values of c stay mostly under 10 days for Wales, Scotland and South West and North England, but are higher than 30 days for large part of South East and East England.

4. Are correlations between catchment properties and recession behaviour strong enough to characterize recession behaviour for ungauged catchments in the United Kingdom?

- This study lacks enough strong correlations between recession behaviour and catchment properties to reliable characterize recession behaviour for ungauged catchments.

6.2 RECOMMENDATIONS

The recommendations of this research are listed below:

- Further research on the physical background of recession behaviour is important. It can be helpful in both validating the different recession analysis methods and explaining the variations between individual recession of the same catchment.
- Using more quantitative data for geology and land use. This can be helpful for finding more clear relations between geology and land use and recession behaviour and thus better possibilities for characterizing recession behaviour in ungauged catchments.

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A

EXTRACTION PROCEDURE

This appendix will give the calibration process for the extraction procedure, which will results in using a declining stream flow with T_{min} is 8 days, T_{end} is 2 days and P_{max} is 1 mm/day.

MAXIMUM ALLOWED PRECIPITATION

Table 5 shows the values of parameters c and b, R^2, N_{rec} and N_{cat} for different values of P_{max}. The table shows that the parameter values c and b are roughly constant for different values of P_{max} and that R^2, N_{rec} and N_{cat} are increasing with increasing values of P_{max}. P_{max} will be set to 1 mm/day, as it still has good values of R^2, N_{rec} and N_{cat} and it is low enough in order to expect that precipitation does not contribute directly to the stream flow.

Table 5: *Parameters c and b, R^2, N_{rec} and N_{cat} against P_{max}. The three values of c, b, R^2 and N_{rec} are the 10th, 50th and 90th percentile. T_{min} is 7 days, T_{end} is 0 days and T_{start} is 0 days.*

P_{max} (mm/day)	c $(days)$			b			R^2			N_{rec}			N_{cat}
0	0.4	5.4	59	1.2	2.7	5.7	0.12	0.50	0.83	9	45	157	820
0.25	1.1	5.5	36	1.9	2.9	4.9	0.33	0.73	0.88	153	609	1369	986
0.5	1.2	5.6	34	2.0	2.9	4.7	0.38	0.75	0.88	221	841	1790	987
1	**1.3**	**5.9**	**32**	**2.0**	**2.9**	**4.7**	**0.39**	**0.76**	**0.88**	**307**	**1167**	**2369**	**989**
2	1.6	6.3	30	1.9	2.8	4.3	0.37	0.76	0.87	428	1554	3086	990
$Q/5$	1.4	6.5	43	1.8	2.8	4.5	0.32	0.76	0.90	114	463	1317	986
$Q/10$	1.3	6.5	45	1.8	2.8	4.6	0.29	0.74	0.90	83	339	1011	978

MAXIMUM ALLOWED EVAPOTRANSPIRATION

Table 6 shows the values of parameters c and b, R^2, N_{rec} and N_{cat} for different values of E_{max}. For increasing values of E_{max} parameter values b and R^2 are increasing and especially N_{rec} and N_{cat} increase rapidly. Even a quite high value of E_{max} of 2 mm results in a relatively low value of N_{rec}. In summer it would be logical to have recessions with high values of the evapotranspiration, thus adding a maximum allowed value for evapotranspiration would lead to a bias towards recessions which contains more data from winter months than for summer months. Based on that and on the increasing values of N_{rec} and N_{cat} it is decided not to use evapotranspiration as a criterion.

Table 6: *Parameters c and b, R^2, N_{rec} and N_{cat} against E_{max}. The three values of c, b, R^2 and N_{rec} are the 10th, 50th and 90th percentile. T_{min} is 7 days, T_{end} is 0 days, T_{start} is 0 days and P_{max} is 1 mm.*

E_{max} (mm/day)	c $(days)$			b			R^2			N_{rec}			N_{cat}
0	1.0	6.8	14	1.6	2.5	5.0	0.43	0.67	0.91	8	8	8	8
0.25	1.7	8.6	42	1.0	2.5	4.4	0.12	0.66	0.93	8	11	34	513
0.5	2.6	9.2	44	1.5	2.6	4.6	0.30	0.71	0.88	13	62	177	885
1	2.5	8.9	48	1.8	2.6	4.3	0.36	0.75	0.87	36	223	750	957
2	2.2	7.7	40	1.8	2.6	4.3	0.40	0.76	0.87	62	412	1416	974
$Q/5$	3.4	9.4	57	1.1	2.2	4.0	0.27	0.78	0.96	8	18	64	493
$Q/10$	2.8	7.8	27	0.9	2.1	3.9	0.25	0.71	0.96	8	9	34	187

DECLINING STREAM FLOW RECESSION

Table 7 shows the values of parameters c and b, R^2, N_{rec} and N_{cat} for declining stream flow recession. This criterion seems to give very high quality data, i.e., high values of R^2, but also has lower values of N_{rec} and N_{cat}. It is therefore decided not to make use of this criterion.

Table 7: *Parameters c and b, R^2, N_{rec} and N_{cat} for declining stream flow recession. The three values of c, b, R^2 and N_{rec} are the 10th, 50th and 90th percentile. T_{min} is 7 days, T_{start} is 0 days, T_{start} is 0 days and P_{max} is 1 mm.*

c (days)			b			R^2			N_{rec}			N_{cat}
1.2	5.7	21	2.0	2.8	4.5	0.88	0.96	0.98	16	76	294	824

ELIMINATING DAYS AT THE START OF A RECESSION

Table 8 shows the values of parameters c and b, R^2, N_{rec} and N_{cat} for different values of T_{start}. It seems that parameter c is slightly increasing, parameter b slightly decreasing and R^2 and N_{rec} are decreasing with increasing T_{start}. Removing storm flow at the start of a recession is expected to lead to a decrease in parameter b, which does occur, but only slightly. Because R^2 is decreasing much faster than parameter b it is decided not to eliminate days at the start of a recession.

Table 8: *Parameters c and b, R^2, N_{rec} and N_{cat} against T_{start}. The three values of c, b, R^2 and N_{rec} are the 10th, 50th and 90th percentile. T_{min} is 7 days, T_{end} is 0 days and P_{max} is 1 mm.*

T_{start} (days)	c (days)			b			R^2			N_{rec}			N_{cat}
0	**1.3**	**5.9**	**32**	**2.0**	**2.9**	**4.7**	**0.39**	**0.76**	**0.88**	**307**	**1167**	**2369**	**989**
1	1.2	6.1	36	1.8	2.9	4.7	0.30	0.67	0.83	276	1057	2165	989
2	1.3	6.6	36	1.7	2.8	4.6	0.24	0.57	0.77	246	943	1954	989
3	1.3	7.1	38	1.7	2.7	4.4	0.22	0.49	0.71	216	833	1734	989
4	1.4	7.4	40	1.5	2.6	4.2	0.22	0.44	0.66	185	719	1518	989

ELIMINATING DAYS AT THE END OF A RECESSION

Table 9 shows the values of parameters c and b, R^2, N_{rec} and N_{cat} for different values of T_{end}. It seems that there is only a slightly increasing R^2 and a slightly decreasing N_{rec} for increasing T_{end}. A possible explanation can be that the stream flow at the end of a recession is more likely to be influenced by some precipitation, but it is not reasonable that this happens for a period longer than 1 or 2 days. It is decided to remove 2 days at the end of a recession to eliminate this influence and get a slightly better R^2.

Table 9: *Parameters c and b, R^2, N_{rec} and N_{cat} against T_{end}. The three values of c, b, R^2 and N_{rec} are the 10th, 50th and 90th percentile. T_{min} is 7 days, T_{start} is 0 days and P_{max} is 1 mm.*

T_{end} (days)	c (days)			b			R^2			N_{rec}			N_{cat}
0	1.3	5.9	32	2.0	2.9	4.7	0.39	0.76	0.88	307	1167	2369	989
1	1.3	5.8	31	2.0	2.9	4.8	0.40	0.78	0.89	276	1057	2165	989
2	**1.4**	**5.7**	**29**	**2.0**	**2.9**	**4.9**	**0.41**	**0.79**	**0.90**	**246**	**943**	**1954**	**989**
3	1.3	5.6	29	2.0	2.9	4.9	0.43	0.81	0.92	216	833	1734	989
4	1.3	5.4	27	2.0	2.9	5.0	0.47	0.84	0.93	185	719	1518	989

Table 10 shows the values of parameters c and b, R^2, N_{rec} and N_{cat} for different values of T_{min}. With increasing T_{min} recession parameter b and N_{cat} slightly decrease, parameter c increase a bit and N_{rec} decrease quite fast. There seems to be a small increase in R^2 with increasing T_{min}, except for a minimum period of 4 and 5 days. This can be explained, because linear regression with less points leads to a higher R^2, but does this at the cost of a higher uncertainty. Every choice for T_{min} in the range from 6 to 10 days seems to be reasonable, and therefore a period of 8 days is chosen for T_{min}.

Table 10: *Parameters c and b, R^2, N_{rec} and N_{cat} against T_{min}. The three values of c, b, R^2 and N_{rec} are the 10th, 50th and 90th percentile. T_{start} is 0 days, T_{end} is 2 days and P_{max} is 1 mm.*

T_{min} (days)	c (days)			b			R^2			N_{rec}			N_{cat}
4	1.2	4.3	20	2.0	3.0	5.3	0.53	0.82	0.92	585	1719	2939	996
5	1.3	4.7	25	2.0	3.0	5.2	0.45	0.80	0.91	475	1420	2592	995
6	1.3	5.2	26	2.0	2.9	5.0	0.44	0.79	0.91	343	1157	2250	992
7	1.4	5.7	29	2.0	2.9	4.9	0.41	0.79	0.90	246	943	1954	989
8	**1.3**	**5.9**	**33**	**1.9**	**2.9**	**4.9**	**0.43**	**0.80**	**0.90**	**188**	**755**	**1660**	**987**
9	1.4	6.2	37	1.9	2.9	4.6	0.44	0.80	0.90	143	613	1403	977
10	1.5	6.6	37	1.9	2.8	4.5	0.45	0.80	0.90	104	480	1164	968