Technical Note: Defining prior probabilities for hydrologic model structures in UK catchments

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Abstract

Choosing a suitable model structure, i.e. a set of equations that represent the dominant hydrologic processes of interest, is the starting point for any modelling study. This model structure choice is often guided by experience with a particular model. More recently the focus has shifted to flexible modelling frameworks, which allow structures to be chosen based on the specific characteristics of the catchment under study. Little work has been done though on defining prior probabilities for different model structures based on physical catchment characteristics or climatic conditions. Here we combine two soil moisture accounting (SMA) modules used widely in the UK, PDM and Penman, in combination with three different routing modules, linear, parallel and leaky, and apply them to 89 UK catchments to define such prior probabilities. The 6 model structure combinations are applied in a Monte Carlo framework (10,000 parameter samples per structure) to each of the catchments and the fraction of parameter sets that are behavioural is estimated. Parameter sets are considered behavioural if they reach pre-defined thresholds regarding Nash-Sutcliffe Efficiency and Bias. We make the basic assumption that better model structures produce more behavioural parameter sets. We find that there is a clear distinction between model structures for different catchment types. A subsequent CART analysis quantifies how physical (baseflow index) and climatic (runoff coefficient) characteristics define which model structures are most likely.

We conclude that specific model structures work best for different catchments. We found that there is a certain classification of catchments possible per model structure combination. This classification can be determined by climate, topography, landuse and geology. Geology (BFI) in this case, determines which SMA module to use, while topography (DPSBAR), landuse and climate (Runoff Coefficient) determine which routing module to use.

Keywords: Model structure selection, prior probability

1. Introduction

The selection of a model structure is an essential part of the modelling process. It is important to select an appropriate model structure that gives a good representation of the hydrologic behaviour of the catchment. However, often model structures are chosen according to experience in the past with a particular model structure where the hydrologist is familiar with, or based on the simple availability of a particular model. Also, data availability often has an influence on the selection process (Mroczkowski et al., 1997; Uhlenbrook et al., 1999; Wagener and McIntyre, 2005; Sivakumar, 2008; Clark et al., 2011).

Recent studies suggest that different systems might be best modelled using specific model structures (Clark et al., 2008; 2011). Examples of flexible model structures that have been proposed are the Rainfall-Runoff Modelling Toolbox (RRMT) developed by Wagener et al. (2001). This toolbox splits models into soil moisture accounting (SMA) and routing components and therefore makes the assumption that that the rainfall-runoff process can be represented by these two components. Different model structures can then be selected for either of those components. The FUSE modelling framework (proposed by Clark et al., 2008) goes a step further by allowing even more flexibility than RRMT. The framework takes structural elements from several widely used hydrologic models (e.g. Topmodel) and allows the user to select any combination of these components. Different newer versions of this FUSE framework have been proposed such as the FLEX and the SUPERFLEX frameworks (Fenicia et al., 2007; Euser et al., 2013) The choice of the components are chosen by certain selection criteria. In this study we address the simple question: can we use a priori information to choose one or more model structures for a particular catchment?

Here we apply a combination of six different model structures made up of two different soil moisture accounting modules and three different routing modules. We assume that the chosen components are capable of representing the variability in physical characteristics that we expect to encounter within our dataset. We apply these models to 89 UK catchments to understand which model structure works better for different catchments.

In this paper, we first represent the variety in characteristics of the catchments to show that a wide range of catchments is used (chapter 2.1). We then show the different model structure combinations in detail (chapter 2.2). After that we introduce the methodology used for this research (chapter 3). The final results will be represented in figures and their physical interpretation will be discussed in detail (chapter 4). We finally conclude with some overall conclusions (chapter 5).

2. Data and Models

2.1 Catchment data

The used data from the catchments are respectively daily precipitation, potential evapotranspiration and discharge with a time series of 10 years. This data are from 89 catchments in Scotland, Wales and England with a surface area ranging from 0.9 km^2 to 9895 km^2 and with an average of 209 km^2. The catchments have a wide range in hydrologic characteristics. Some of these characteristics and the ranges of values found within the dataset are shown below:

- a base flow between 18% and 98%
- a runoff coefficient between 0.04 and 0.93
- a maximum elevation between 79 and 979 meters

This diversity in physical characteristics gives a good representation of the different types of catchments throughout the UK. An overview of the location of the catchments is shown in figure 1. In this figure, the colour of the catchment and its corresponding flow duration curve are determined by the value of the runoff coefficient. Figure 1(a) shows that the catchments are widely distributed within the UK and vary in size. Figure 1(b) shows that the catchments exhibit significantly different flow duration curves, suggesting significant differences in the response of the precipitation that becomes runoff.

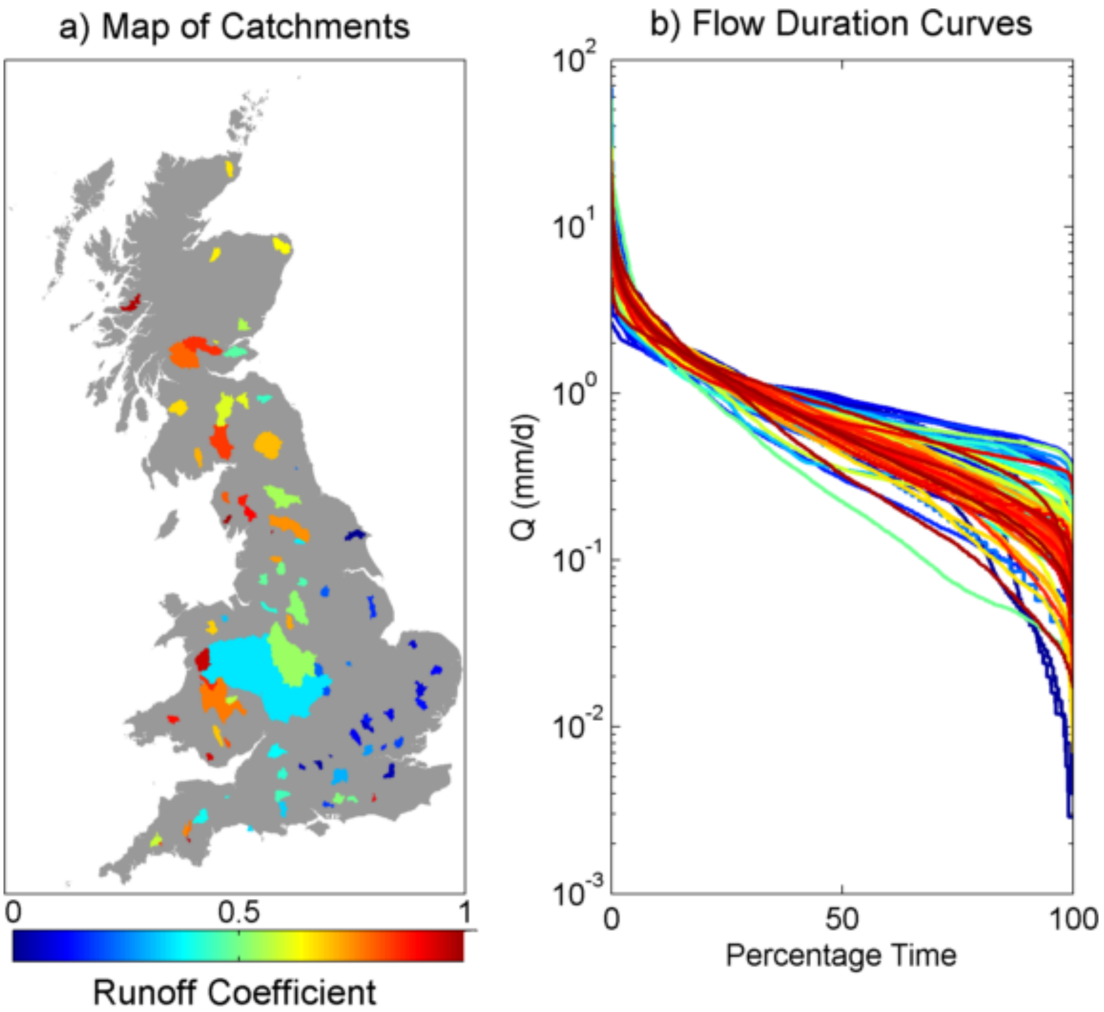

Figure 1; location of catchments used in this research and runoff coefficients(a) and their corresponding flow duration curves (b).

2.2 Hydrologic models structures

The models used consist of two separate modules: a Soil Moisture Accounting (SMA) module and a Routing module. They are implemented within RRMT discussed in the introduction section. All these modules are lumped, relatively simple (in terms of number of parameters), and of conceptual or hybrid metric-conceptual type (Wheater *et al.*, 1993). The SMA module determines the actual moisture in the catchments. This results in an Effective Rainfall (ER). After the ER is calculated, the Routing module computes the amount of moisture that actual becomes runoff. In this study, two SMA modules and two routing modules are used. These will be described below, and an overview of these modules is shown in figure 2.

2.2.1 Soil Moisture Accounting model structures

Here we briefly explain the different model components used in this study. More details can be found in Wagener et al. (2001).

[1] The 'PD3 model structure', is a version of the Pareto Distribution (Moore, 1999). This structure can be used for heterogeneity in the catchment. For example, near stream zones could give a difference in response to the actual runoff than zones far away from

the stream. The Pareto Distribution will be used to take account for this response. The principle of this model is as follows: if rainfall is added to the component, the amount of moisture exceeding the critical capacity (c_{max}) will be the first contribution to the effective rainfall, u1. This amount will be calculated by the following formula:

$$u1_k = \max(r_k - (c_{max} - c_{k-1}))\,, 0)$$

Where:
r_k = amount of rainfall
c_{max} = maximum capacity
c_{k-1} = capacity on time step k-1
k = time step

The remaining rainfall will than be added to the soil moisture store and redistributed between the stores based on a Pareto distribution (Wagener et al, 2001):

$$s_k = s_{max} * (1 - \left(\left(1 - \left(\min\left(\left(\frac{c_k}{c_{max}}\right)\right), 1.0\right)\right)\right)^{b+1} \quad)$$

Where:
s_k= storage on time step k
s_{max} = maximum storage

In this case, $c_{max,}$ b and c(1) will be calibrated.

The stores that overflow produce the second part of the effective rainfall, u2. This part is computed by the following formula:

$$u2_k = \max(r_k - (s_k - s_{k-1}), 0)$$

In this case, the actual evapotranspiration is always equal to the potential evapotranspiration. A sketch of this structure is shown in figure 2(a).

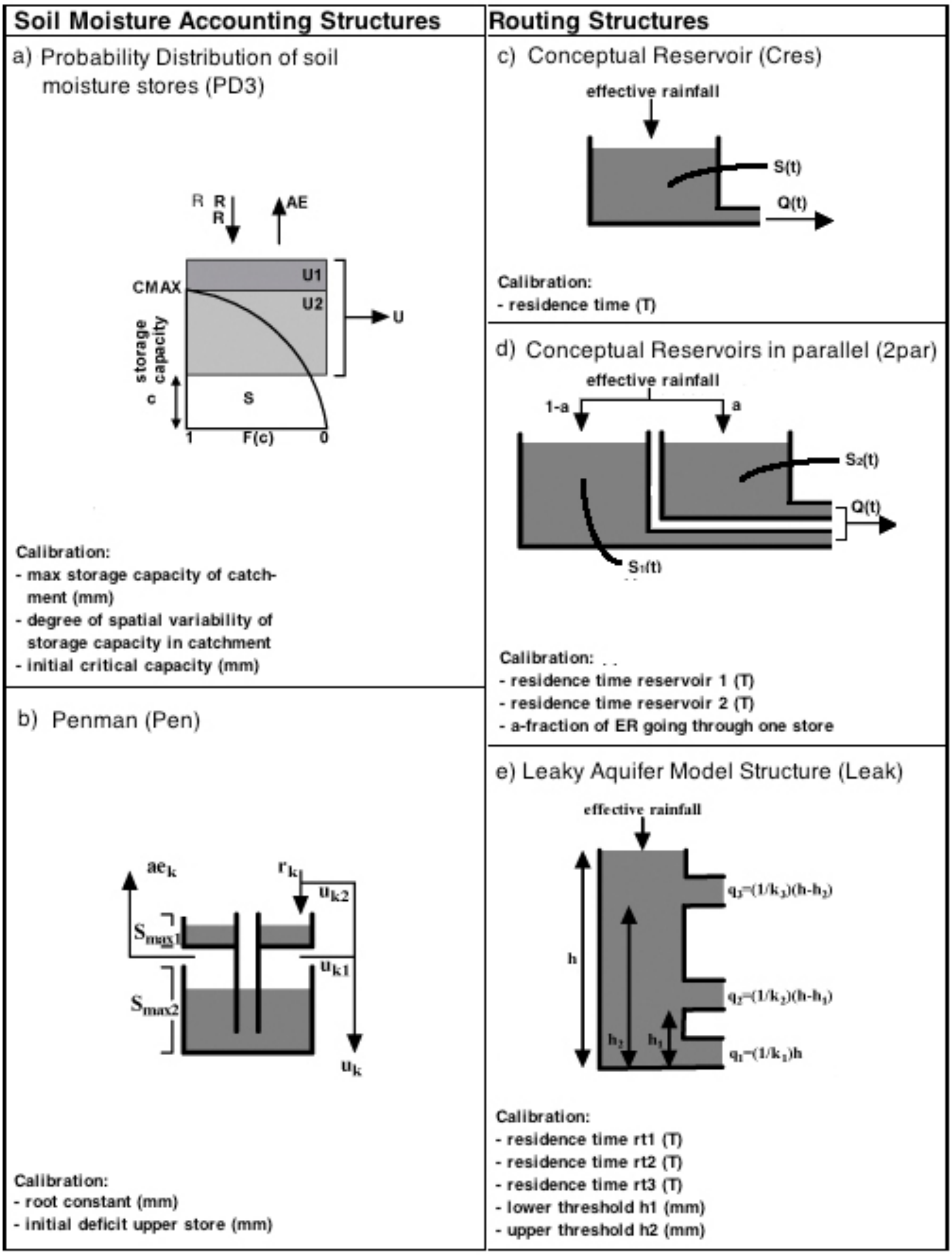

Figure 2; Five model structures components. The Routing structures are shown on the left; the Soil Moisture Accounting (SMA) structures are shown on the right. In this research, each routing structure is combined with both SMA structures. In this figure, also the parameters that are calibrated are shown underneath each drawing. Component a) is the Conceptual Reservoir structure, component b) is the parallel Conceptual reservoir structure, component c) is the Leaky structure, component d) is the Probability Distribution structure and component e) is the Penman structure

[2] The 'Pen model structure', which is based on an empirical drying curve developed by Penman (1949). This structure is a two-store concept. The upper store (S_{max}) is equal to the root constant and is calibrated. The other value that is calibrated is the initial deficit for the lower store. Beside these calibrated parameters, there are also parameters that

are fixed. This is firstly the value of the lower store. This has been fixed to 1000 mm and is recommended by Moore (1992) and Jolley (1995). The reason for this is to make sure that the store doesn't dry out.

The model structure also has a bypass mechanism. This accounts for the quick response of the catchment. This mechanism is fixed to 0.15 as recommended by Mander and Greenfield (1978, in Jolley 1995) and determines the precipitation that directly becomes runoff. There's also a parameter that that defines the rate of the depletion after the upper store is emptied. This value is 0.08 (following Penman, 1949, in Jolley, 1995) i.e. the actual evapotranspiration reduces to 1/12 of the potential evapotranspiration. Before the store is emptied, this rate is 1:1.

Thus, this model structure has two calibrated parameters and three fixed parameters. The reason for the three parameters being fixed is that these have been found reasonable for catchments in the UK. A sketch of this structure is shown in figure 2(b).

2.2.2 Routing model structures

The routing modules are as follows:

[1] The 'Cres' routing module is a single conceptual reservoir. A storage function is involved in the module, which describes the relationship between outflow of the reservoir and the amount of water stored,

$$S(t) = a * Q(t)$$

where *S(t)* is the storage [L] at time *t*, *a* is a storage coefficient [$L^{1-n} * T^n$], with *n* being the coefficient of non-linearity. In this module, the reservoir will be assumed to be linear, so *n*=1. *Q(t)* is the outflow [L/T]. The parameter that will be calibrated is the residence time [T]. This defines how long water is stored in the reservoir. The larger its value, the longer it takes for water to move through the reservoir and the more delay it produces. A sketch of this structure is shown in figure 2(c).

[2] The '2par' routing module is a combination of two conceptual reservoirs as described above, in a parallel manner. The additional calibrating parameter is 'alpha' which is the fraction of ER that is going through one store. The remaining part will be the amount of moisture that flows through the other store, and reflects the groundwater of the specific catchment. A sketch of this structure is shown in figure 2(d).

[3] The 'Leak' module represents a leaky aquifer. This module is based on Moore (1999) who used a similar structure to model snow. The parameters that are calibrated are the residence times for each type of runoff and a lower threshold for the lower part q_2 and an upper threshold for the upper part q_3 of the effective rainfall. The leakage from the catchment is described by q_1. In practice, this model represents catchments with a very slow water flow component. A sketch of this structure is shown in figure 2(e).

3. Methodology

The two SMA components are combined with the three routing components creating six different model structures. A uniform random sampling (URS) is used to select 10000 parameter sets randomly from the feasible parameter space. The ranges of the parameters are set according to the recommendations of Wagener et. al. (2001) which are also shown in table 1. We assume that we can define reasonable minimum and maximum values for each parameter and that the parameters follow a uniform distribution. We checked whether 10000 parameter samples is sufficient by repeating the sampling several. This made it visible whether the results were robust or not. The results were very similar, so an number of 10000 parameter samples is judged sufficiently reliable.

Furthermore, we selected some objective functions as basis for choosing acceptable models (chapter 3.1). With these objective functions we run the model structure combinations and consider the performance per catchment (chapter 3.2). In order to group different catchments we introduced some classifications (chapter 3.3). For a statistical reliable outcome we linked these groups of catchments a corresponding model structure combination with the use of Classification and Regression Tree analysis (chapter 3.4).

Table 1; Parameters are used during the calibration process. a) shows the ranges used for the routing structures and b) represents the ranges used for the SMA structures.

a) Routing structures				b) Soil Moisture Accounting structures			
Name	**Parameter**	**Description**	**Range**	**Name**	**Parameter**	**Description**	**Range**
Cres	k(q)	time constant	1:15	PD3	cmax	Max sotrage capacity	0:500
	n	Non-linearity coefficient	1		b	Shape of Pareto distribution	0:2.5
2par	k(q)	time constant first reservoir	1:15				
	k(s)	time constant second reservoir	15:100		c(1).	Initial critical capacity	0:0.2
	a(%)	percentage of flow going through first reservoir	0:1				
Leak	k1	Residence time 1	0:200	Pen	r	root constant	10:200
	k2	Residence time 2	0:100		in. Def.	initial deficiet upper store	0:0.25
	k3	Residence time 3	0:25				
	h1	Lower threshold	0:175				
	h2	Upper threshold	0:275				

3.1 objective functions

We selected two objective functions as basis for choosing acceptable models. The first is the Nash Sutcliffe Efficiency. This metric has been introduced by Nash and Sutcliffe (1970) to allow the comparison of models applied to different catchments and to assess the value of additional or improved model components. Its range is from minus infinity to one, where one is its optimum. This function is defined as:

$$NSE = 1.0 - \frac{\sum_{i=1}^{N} (o_i - c_i(\theta))^2}{\sum_{i=1}^{N} (o_i - \bar{o})^2}$$

Where

o	observed variable
c	calculated variable
i	time step

N total number of time steps
θ parameter set

In addition to the NSE metric, which is more focused on fitting the output variance, we add the absolute bias metric to account for the water balance fit. This value is at its optimum if it has the value 0. This metric is defined as follows:

$$ABIAS = \frac{\left|\sum_{i=1}^{N}(o_i - c_i(\theta))\right|}{\sum_{i=1}^{N} o_i}$$

We chose that parameter sets for a given model structure are considered acceptable ("behavioural") if the associated NSE is higher or equal to 0.6, and ABIAS is lower or equal to 0.1. Any parameter set that falls outside these two thresholds is rejected.

3.2 Performance of structure combinations

During the calibration, all parameter sets that satisfied these thresholds are counted per model structure combination for each catchment. We made the basic assumption that per catchment, the structure combination with the largest number of behavioural parameter sets, is most likely to be a suitable representation of that catchment. With this data we achieve a list per catchment with the behavioural parameter sets per model structure combination. It is then easily visible which model structure will be best applicable to for a certain catchment.

3.3 Classification of catchments

In order to determine whether there is a correlation between certain characteristics of the catchments and the best working model structure combinations, certain characteristics of the catchments are chosen. These characteristics with its classes are shown below (Marsh and Hannaford, 2008):

Geology

For the representation of geology, the BFI per catchment is used. This is measuring of the amount of the runoff of the river that derives from stored sources (Gustard et al, 1992). Catchments with high base flow indices are likely to have a slow response, whereas catchments with low base flow indices are likely to have a fast response.

Landuse

The distribution of different use types of land per catchment, divided in:
- Percentage of woodland
- Percentage of arable land
- Percentage of grassland

Each type of land will have its own behaviour in terms of runoff. Catchments with a high amount of woodland or grassland areas will generally have a slower response of the discharge.

Climate

In order to represent the climate per catchment, firstly the Runoff Coefficient (Q/P) is used. This metric compares the amount of precipitation (P) to the amount of runoff (Q) over a certain period, in this case 10 years. In fact it is an average of how much of the precipitation becomes at the end runoff over the long term. Another way of representing the climate is by the Aridity Index (PE/P). This metric compares the potential evapotranspiration (PE) with the precipitation, and is therefore in fact an average of how much of the precipitation becomes potential evapotranspiration.

Topography
A descriptor of the topography is the mean Drainage Path Slope (DPSBAR). It provides an index of overall catchment steepness. This index is computed using the mean of all inter-nodal slopes for the catchment. It is expressed in metres per kilometre. Values of >300 m/km means that it is a mountainous terrain and values of <25 m/km are catchments with the flattest planes.

An overview of specific values per classification for each catchment is shown in appendix A and B.

In order to make sure that these characteristics aren't strongly correlated, we plotted the values of the characteristics against each other. In these plots, there wasn't a clear correlation visible between the chosen characteristics and therefore these characteristics are useful for the research. In addition to these plots, also the values of the aforementioned characteristics are plotted per model structure combination. It is than visible for which values per characteristic a certain model structure combination is best applicable. We then selected only the graphs that gave a clear preference for a certain structure combination. This is because the reason of the graphs is just to show that a correlation is visible rather then the physical reason for a specific correlation. In order to determine which graphs represent this distinction best, we plotted all values of all characteristics against each other. After that, we visually selected the graphs with the clearest distinction.

3.4 CART-analysis

3.4.1 tree building process

In order to make a more clear and statistical acceptable distinction between the different catchments and their best applicable model structures, we used Classification and Regression Tree (CART) analysis. This is a method that recursively splits the data until ending points, or terminal nodes. This is achieved with pre-set criteria. It analyses the explanatory variables and determines which division of the introduced variables best reduces deviance in the response variable (Lawrence and Wright, 2001). In this case it will be used for a classification of catchment characteristics into model structure combinations. For this analysis, firstly the 'predictors' or 'independent outcomes' are necessary. These are in this case the aforementioned catchments characteristics, such as BFI and Aridity Index. Secondly, the categorical outcomes, or 'dependent' variables are necessary. These are the best working model structure combinations. This outcome is associated with a certain weight. This is the third necessary variable and is the number of behavioural parameter sets per combination per catchment. (Lawrence, 2001). An overview of this number is shown in appendix C.

3.4.2 selection of a tree using Input Variable Selection

As aforementioned, CART produces a classification of the dependent variables (model structures in our case). This classification can be improved by an increase of the number of independent variables (catchment characteristics). In that case, the chance that data points will be misclassified will decrease, at least on the dataset used for the CART calibration. However, the fewer variables are used, the more robust the CART is likely to be over different datasets, and also the clearer its interpretation will be. It is therefore necessary to find its optimal number of variables that should be used. The problem with finding its optimal number is that it is impossible to select this number a priori. For that reason, automatic procedures of Input Variable Selection (IVS) is used. IVS has been used in modelling water resources systems mainly to choose input of hydrological models and thus avoid unnecessary model complexity and enhances model accuracy (Galelli and Casteletti, 2013, Hejazi and Cai, 2009). This is the same principle necessary in our case; the only difference is that it is used for regression rather than classification. For this research, we already selected some characteristics a priori. These are listed on page 8 and 9. However, for the IVS analysis we introduced some more variables in addition to the ones already selected. The reason is that we wanted to be sure that there is a clear distinction between the variables that are superfluous and not. These added characteristics with a short description are listened below (Marsh and Hannaford, 2008).

- BFIHOST (transformation of BFI with soil type considered in percentage)
- Elevation (Height descriptor calculated by 10h percentile of elevation subtracted from 90th percentile of elevation in m)
- Area (the surface of the catchment in km^2)

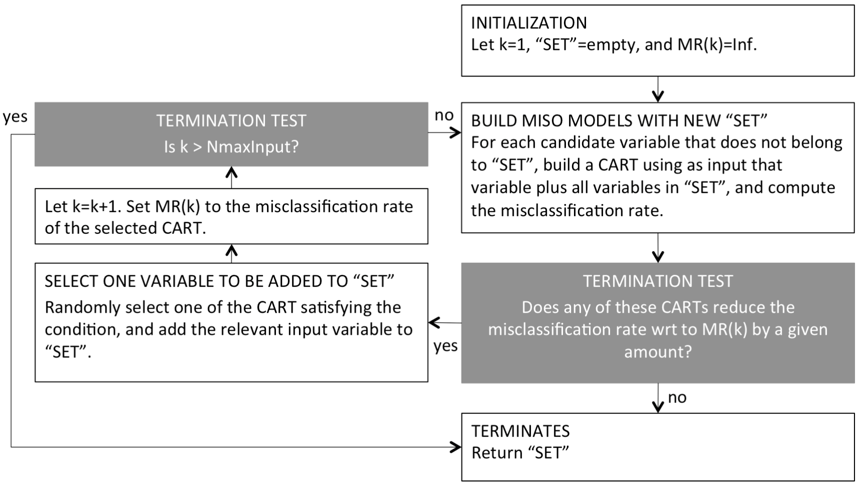

Figure 3; Illustration of the selection process for CART analysis. This process selects the best amount of variables necessary for the use of CART analysis

The IVS process works as follows. In the first stage, it builds a CART for each candidate variable. It then takes the variable with the smallest number of misclassified data points (variable 1). It then takes randomly the second variable (variable 2) and analyses this combination with CART. After this, it compares the misclassified data points of this combination with the misclassified data points of variable 1. If the misclassified data points with this combination are decreased, it includes the regarding variable in its 'best' set of variables. If the misclassified data points with this combination are increased, it excludes the regarding variable and tries another variable. If there are no variables anymore that give a better performance, the process will be terminated. An overview of this principle is given in figure 5.

3.4.2 the final tree

When the selected variables are implemented, CART software finds the best way of splitting the variables by checking all possibilities. After that, it creates a tree with one of the variables on each node. The branches represent certain criteria for each variable. By comparing these criteria to the values of a certain catchment, a certain 'route' on the tree can be followed. At the end of this 'route' the optimal model structure combination will appear.

3.4.2 advantages and disadvantages of CART

The advantage of CART is that it is inherently non-parametric in the first place. It is therefore applicable to a wide variety of analyses. Also, it can be used with many possible predictors. CART has a sophisticated system to deal with enormous numbers of different variables and is therefore also useful for this classification problem. Furthermore, it has clever methods for dealing with missing variables and a relatively little input is required from the analyst. Finally, the trees are relatively simple to interpret. A disadvantage is that it is an automated strategy, which depends on the choices made. However, for this research it has been very helpful and it also compares the classified with the misclassified data points, which makes it therefore a robust approach.

4. Results and Discussion

4.1 Results

In this section, we discuss the main results supported by the figures presented here. Some further details are shown in the appendix and are referred to as appropriate in the text.

4.1.1 Performance of structure combinations

The result of the performance of the structure combinations per catchments is plotted in six squares, each representing a certain model structure combination (figure 6). The darkness of each square represents the number of behavioural parameter sets relatively to the maximum number per catchment (darker colour means larger number). This maximum number is shown in the square of the regarding model structure combination. The station number of each catchment is represented on top of each square plot. This number and its corresponding catchment name are shown in appendix A and B.

In the figure we find that the model structure with the highest number of acceptable parameter sets varies across the catchments, therefore suggesting that model structure selection is important. The lowest number of acceptable parameter sets that defines the chosen model structure is 1, while the highest number is 9321. Furthermore, the structure combination most often chosen is PD3 & Cres, while the least often chosen structure combination is Pen & 2par. Also it is visible that, for the Soil Moisture Accounting structure, the Probability Distribution (PD3) structure is more often selected than the Penman model structure. From the routing model structure, the Leak structure is chosen least and the Cres structure is chosen most often. It is therefore clearly visible that there is a certain difference across the best working model structures.

4.1.2 Classification of catchments

In order to know whether there's a correlation between certain specific catchments and their best applicable model structure combination, some of the values of the characteristics are plot against each other. This is shown in figure 7.

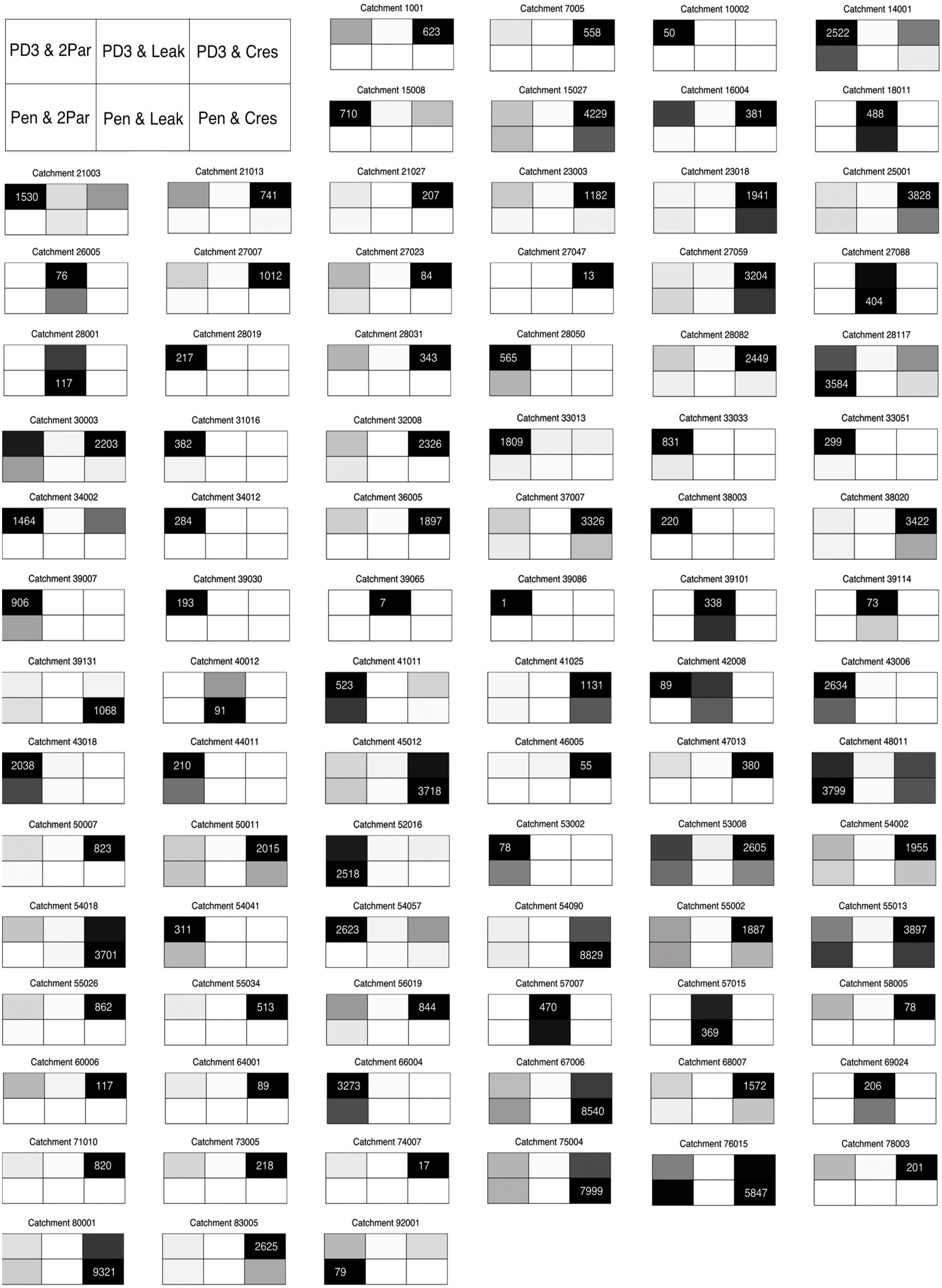

Figure 6; Performance for every model structure combination per catchment. Every square represents such a combination, with its location shown in the square plot on the far top left. The black square represents the best working model structure combination, and the number in it is the number of behavioural parameter sets (out of 10000). The grey colour in the other squares give an indication of the number of behavioural parameter sets of that specific structure combination, relative to the best model structure.

In the figure, every data point in the graph represents a catchment. The colour is determined by the best performing routing or SMA model structure. The size of the data point is proportional to the number of behavioural parameter sets. Fig. 7(a) shows the cases where PD3 is the chosen soil moisture accounting structure.

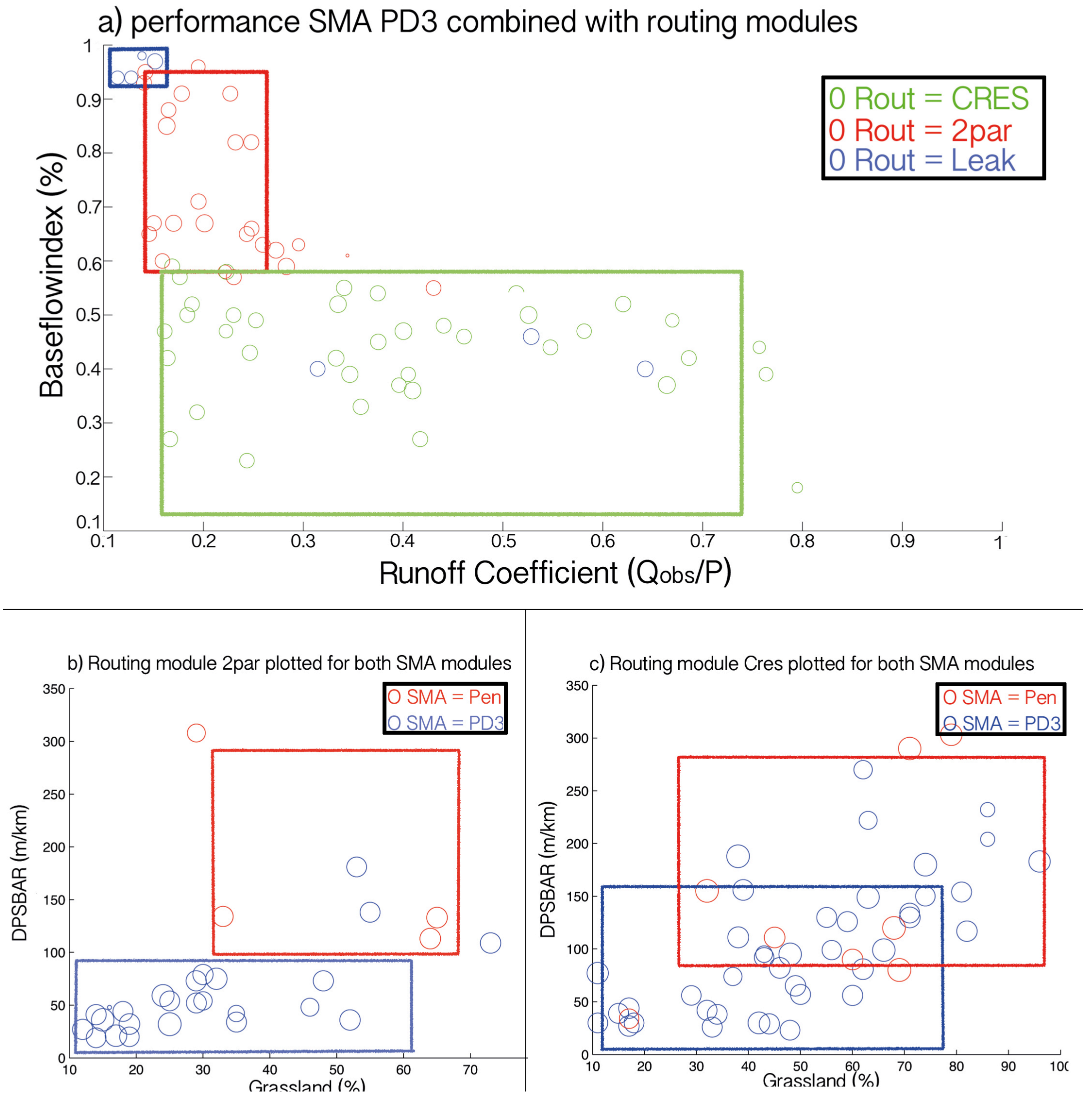

Figure 7; In all figures, each data point represents a catchment. The value of the specific characteristics (which are represented on the x- and y-axis) determines the location of the data point. The colour represents which structure is best working for that catchment. Graph a) shows this principle for the three routing structures combined with the soil moisture accounting structure 'PD3'. Graph b) shows this principle for the two SMA structures, combined with the routing module '2par'. Graph c) shows this principle for the two SMA structures combined with the routing module 'Cres'.

We find that the Leak routing structure is needed for catchments with a high baseflow index and a low runoff ratio, RR. Reducing the BFI (down to about 0.55) and increasing the RR up to about 1 leads to a patch in which the parallel routing structure is preferred (2par). Reducing the BFI value further leads to Cres being the preferred routing structure. Fig 7(b) shows the case where 2par is the chosen routing module and Pen and PD3 the soil moisture accounting modules. Fig. 7(c) shows the same combination, but

Cres as the chosen routing module rather then 2par. In both cases we find that the SMA structure PD3 is needed for low values of DPSBAR and percentages of grassland area, while for higher values of these descriptors Pen is the preferred SMA structure.

4.1.3 selection of a tree using Input Variable Selection

Table 2 shows the result of the IVS analysis.

For each attempt, the combination of characteristics that gave the best performance are coloured with grey squares. Also, the number of misclassified data points is shown for each attempt.

Table 2; Performance of a certain combination of different characteristics. In this analysis a number of 20 attempts is chosen. During each attempt, it combines with IVS the best possible combination of characteristics. These regarding characteristics are given a grey colour. Also, the number of misclassified datapoints is represented in the table. The attemtps with the least misclassified datapoints are 4 and 14, which is a selection of the characteristics 'BFI', 'DPSBAR', 'Grassland', 'Runoff Coefficient', and 'Woodland'.

Results IVS analysis Attempt	Arable	Area	Aridity	BFI	BFIHOST	DPSBAR	Elevation	Grassland	Run. Coeff.	Woodland	# Misclassified Datapoints
1	▨			▨	▨	▨	▨		▨		12
2			▨	▨	▨	▨			▨	▨	9
3			▨	▨		▨	▨		▨	▨	10
4				▨		▨		▨	▨	▨	7
5		▨					▨		▨	▨	12
6	▨	▨			▨	▨	▨		▨		13
7	▨	▨	▨		▨			▨	▨		13
8	▨	▨		▨	▨	▨		▨			13
9	▨				▨		▨		▨		13
10	▨					▨	▨	▨	▨	▨	14
11			▨	▨	▨	▨			▨	▨	9
12			▨	▨		▨	▨		▨	▨	10
13			▨	▨		▨	▨	▨	▨		10
14				▨		▨		▨	▨	▨	7
15	▨	▨		▨		▨			▨	▨	8
16		▨	▨	▨		▨			▨		10
17	▨		▨	▨	▨		▨		▨		10
18		▨	▨	▨							10
19	▨		▨	▨			▨		▨	▨	11
20	▨				▨	▨	▨	▨	▨		13

The variables that led to the least misclassified data points in the tree were attempt 4 and 14. The corresponding combination consists of the following characteristics: the baseflowindex, area of grassland, DPSBAR, area of woodland and the runoff coefficient. This means that to achieve the best balance between the complexity and robustness of the tree, the selection made before the use of CART was a good selection. The only difference is that the aridity index and the surface of arable land were not necessary.

4.1.4 the final tree

Figure 8 shows the final decision tree that is created with CART analysis. In this tree it is visible that geology, land-use, climate and topography are represented.

In the tree, there is also the percentage of classified and misclassified data points is presented. This is done by a bar plot. In this plot the tallest bar is the model structure combination that is chosen by CART. In some cases, some lower bars are plotted in the same graph. These smaller bars represent the number of misclassified data points relatively to the chosen structure combination. It is now visible how robust the choice for a certain structure combination is.

The baseflow index in this case is mainly responsible for the choice of the type of routing module. In the first stage, BFI splits into three parts with each part leading to a different type of routing module. It is also visible that catchments with a high baseflow index but a low runoff coefficient will best perform if a Leak structure will be used. If there is a higher baseflow index and a high runoff coefficient, routing module 2par will be best applicable. Furthermore, catchments with a lower baseflow index will be best represented with the routing module Cres. This was already visible in figure 7(a), where the baseflow index was plotted against the runoff coefficient.

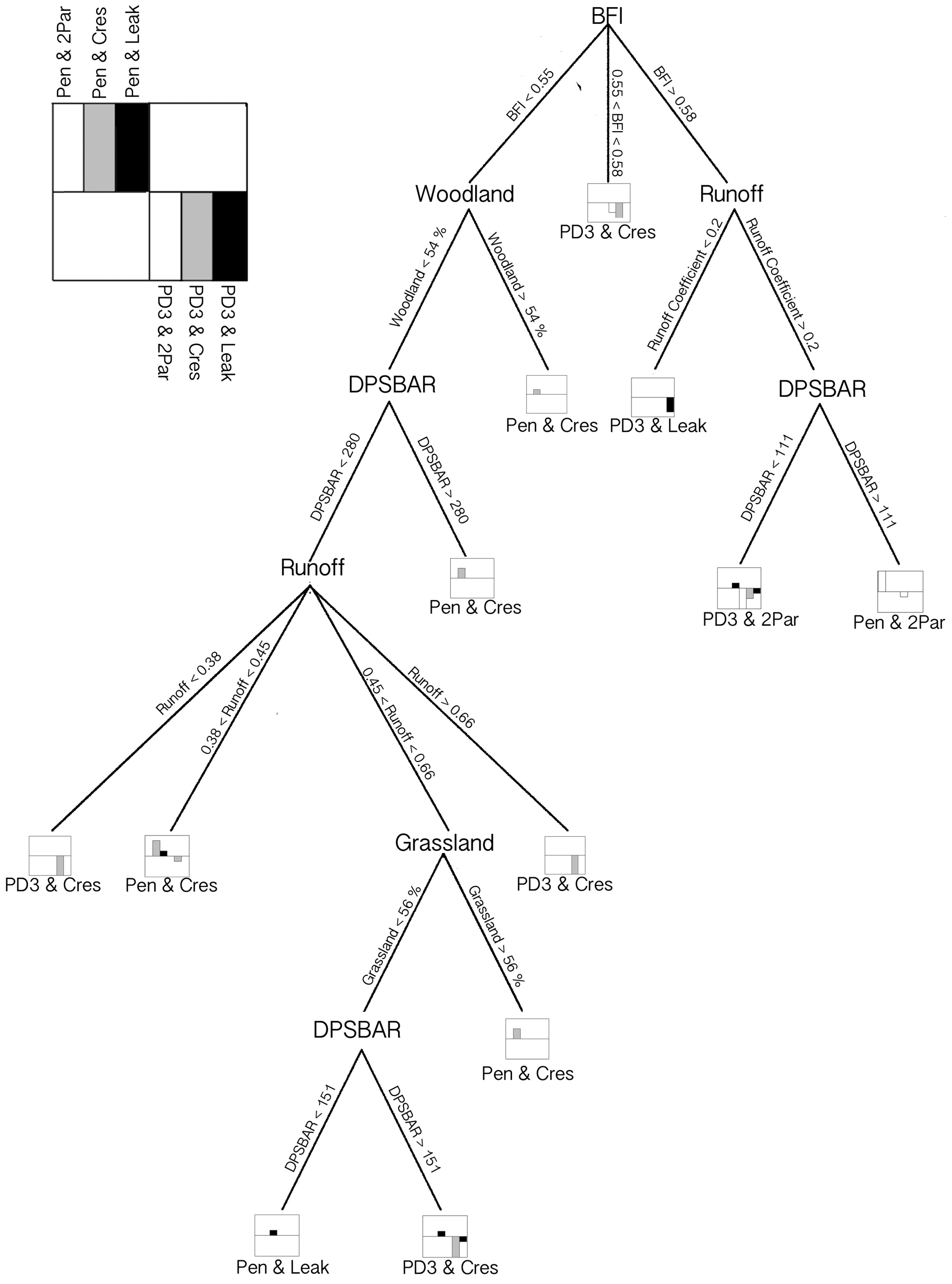

Figure 8; The decision tree that is created with the CART analysis. With this tree a decision can be made about the best model structure combination that could be used, depending of the characteristics of a specific catchment. This can be done by following a route by selecting the applicable values of the characteristics of a certain catchment. Also, in the bar plots the reliability of the choice for a certain model structure combination is shown.

Hence it is visible that topography will determine which soil moisture accounting module should be used. In general, catchments with high values of DPSBAR will be best represented with the Penman model structure, while catchments with low values of DPSBAR will work with the Probability function. This was already visible in the 7ures 7(b) and 7(c).

Landuse also has an influence on the choice of the soil moisture accounting module. The Penman model structure will work best with catchments that are mainly covered with woodland. Also when the catchment is mainly covered with grassland, the Penman structure will work best.

4.2 Discussion

In this section we discuss why the different modules can be used best. We determined this by the use of the tree in figure 8 and figure 7. However, in this section we only discuss the results of the tree as this is a more extended and robust presentation of figure 8 and it shows in principle the same.

In the first place, it is clearly visible that the baseflow index in combination with the runoff coefficient makes the distinction between which routing module to use.
The reason that the routing module Cres works best for catchments with a low baseflow index is that the response of the precipitation is very much related to the discharge. In order to describe this behaviour, just a conceptual reservoir is necessary as it just computes the residence time that defines how long the water is stored in the reservoir. However, if this response is not that quick, an extra conceptual reservoir component is necessary. This computes two different residence times for each reservoir, where one reservoir is for quick responses whereas the other is for less quick responses. This principle is necessary for catchments with moderate baseflow indices. If there are catchments with a very slow response, even a third component with a third residence time is necessary. In that case, the Leak component will work best. This is the case for catchments with very high baseflow indices, or very low runoff coefficients. In these catchments there is always a discharge in the river, even in the driest periods. In that situation, the water comes from deep flows. The Leak structure also allows for losses, i.e. it allows for some of the precipitation leaving the catchment through subsurface pathways, rather than through the river and the catchment outlet.

In the second place, it is also clearly visible which SMA modules to use. This is mainly determined by the DPSBAR and the different types of landuse.
The Penmen structure allows for different types of vegetation cover (reflected in the size of the upper store) to be represented and to have an impact on the amount of actual evapotranspiration that occurs. It therefore reflects relatively homogeneous areas very well. This is also visible in the tree as Penman is the chosen model structure for high catchments with high values of altitudes (DPSBAR) and high values of different types of landuse. It also has a bypass component that allows for quick contributions to runoff. The PD3 model allows for spatial variability in response within a catchment due to its probability distribution of soil moisture depths. Hence it reflects more heterogeneous catchments better, which is visible in the tree by low values of altitudes and different types of landuse. This is likely more often the case than a homogeneous land use as the PD3 structure is chosen more often.

5 Conclusions

In this research, we have shown that specific model structures work best for different catchments. We also found that there is a certain classification of catchments possible per model structure combination. This classification can be determined by climate, topography, landuse and geology. Geology (BFI) in this case, determines which soil moisture module to use, while topography (DPSBAR), landuse and climate (Runoff Coefficient) determine which routing module to use. We can therefore conclude that it is indeed possible to use a priori information to choose one or more model structures for a particular catchment.

However, there are a few subjects that can be considered in further research. Firstly, we only used a selection of structures that are applicable to the UK. In further research, this subject can be extended by the use of more structure combinations. Secondly, the Penmen model structure provided good results less often than expected. Further research could get into more detail why a distribution function works better than a function that basically is adapted to the physical characteristics of catchments. Also, in this research the RRMT user manual is used which allows the choice of different model structure combination. However, in further research this can be extended by the use of the FUSE (with its extensions FLEX and SUPERFLEX) that allows even more flexibility.

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Appendix A; Physical characteristics of used catchments i.e. river name, station name, area and DPSBAR.

Station number	River name	Station name	Catchment Area (km^2)	DPSBAR (m/km)
1001	Wick	Tarroul	161,9	30
7005	Divie	Dunphail	165	77
10002	Ugie	Inverugie	325	42
14001	Eden	Kemback	307,4	73
15008	Dean Water	Cookston	177,1	59
15027	Garry Burn	Loakmill	20	111
16004	Earn	Forteviot Bridge	782,2	156
18011	Forth	Craigforth	1036	(-)
21003	Tweed	Peebles	694	181
21013	Gala Water	Galashiels	207	149
21027	Blackadder Water	Mouth Bridge	159	57
23003	North Tyne	Reaverhill	1007,5	92
23018	Ouse Burn	Woolsington	9	30
25001	Tees	Broken Scar	818,4	82
26005	Gypsey Race	Boynton	240	51
27007	Ure	Westwick Lock	914,6	99
27023	Dearne	Barnsley Weir	118,9	74
27047	Snaizeholme Beck	Low Houses	10,2	204
27059	Laver	Ripon	87,5	65
27088	Calder	Mytholmroyd	171,7	144
28001	Derwent	Yorkshire Bridge	126	191
28019	Trent	Drakelow Park	3072	34
28031	Manifold	Ilam	148,5	117
28050	Torne	Auckley	135,5	21
28082	Soar	Littlethorpe	183,9	26
28117	Derwent	Whatstandwell	755	133
30003	Bain	Fulsby Lock	197,1	39
31016	North Brook	Empingham	36,5	32
32008	Nene/Kislingbury	Dodford	107	42
33013	Sapiston	Rectory Bridge	205,9	19
33033	Hiz	Arlesey	108	36
33051	Cam	Chesterford	141	41
34002	Tas	Shotesham	146,5	20
34012	Burn	Burnham Overy	80	27
36005	Brett	Hadleigh	156	30
37007	Wid	Writtle	136,3	27
38003	Mimram	Panshanger Park	133,9	44
38020	Cobbins Brook	Sewardstone Road	38,4	44

Station number	River name	Station name	Catchment Area (km^2)	DPSBAR (m/km)
39007	Blackwater	Swallowfield	354,8	32
39030	Gade	Croxley Green	184	54
39065	Ewelme Brook	Ewelme	13,4	78
39086	Gatwick Stream	Gatwick Link	33,6	48
39101	Aldbourne	Ramsbury	53,1	89
39114	Pang	Frilsham	89,8	56
39131	Brent	Costons Lane Greenford	146,2	34
40012	Darent	Hawley	191,4	71
41011	Rother	Iping Mill	154	75
41025	Loxwood Stream	Drungewick	91,6	56
42008	Cheriton Stream	Sewards Bridge	75,1	54
43006	Nadder	Wilton	220,6	79
43018	Allen	Walford Mill	176,5	52
44011	Asker	East Bridge Bridport	48,5	138
45012	Creedy	Cowley	261,6	111
46005	East Dart	Bellever	21,5	95
47013	Withey Brook	Bastreet	16,2	81
48011	Fowey	Restormel	169,1	113
50007	Taw	Taw Bridge	71,4	95
50011	Okement	Jacobstowe	82,1	130
52016	Currypool Stream	Currypool Farm	15,7	134
53002	Semington Brook	Semington	157,7	48
53008	Avon	Great Somerford	303	29
54002	Avon	Evesham	2210	38
54018	Rea Brook	Hookagate	178	90
54041	Tern	Eaton On Tern	192	36
54057	Severn	Haw Bridge	9895	73
54090	Tanllwyth	Tanllwyth Flume	0,9	155
55002	Wye	Belmont	1895,9	134
55013	Arrow	Titley Mill	126,4	130
55026	Wye	Ddol Farm	174	180
55034	Cyff	Cyff flume	3,1	183
56019	Ebbw	Brynithel	71,7	188
57007	Taff	Fiddlers Elbow	194,5	153
57015	Taff	Merthyr Tydfil	104,1	157
58005	Ogmore	Brynmenyn	74,3	222
60006	Gwili	Glangwili	129,5	150
64001	Dyfi	Dyfi Bridge	471,3	270

Station number	River name	Station name	Catchment Area (km^2)	DPSBAR (m/km)
66004	Wheeler	Bodfari	62,9	109
67006	Alwen	Druid	184,7	120
68007	Wincham Brook	Lostock Gralam	148	23
69024	Croal	Farnworth Weir	145	80
71010	Pendle Water	Barden Lane	108	99
73005	Kent	Sedgwick	209	154
74007	Esk	Cropple How	70,2	232
75004	Cocker	Southwaite Bridge	116,6	290
76015	Eamont	Pooley Bridge	145	303
78003	Annan	Brydekirk	925	126
80001	Urr	Dalbeattie	199	80
83005	Irvine	Shewalton	380,7	56
92001	Shiel	Shielfoot	256	308

Appendix B; Physical characteristics of used catchments i.e. area of woodland, area of grassland, baseflowindex and runoff coefficient.

Station number	Woodland (%)	Grassland (%)	Baseflowindex (-)	Runoff Coeff. (P/Q)
1001	10	42	0,39	1,2335
7005	11	11	0,42	1,1651
10002	11	35	0,63	0,9772
14001	12	29	0,63	0,7976
15008	10	24	0,59	0,9154
15027	19	38	0,45	1,3762
16004	14	39	0,52	2,6014
18011	(-)	(-)	0,4	2,7122
21003	15	53	0,55	1,6527
21013	9	63	0,52	1,1743
21027	11	50	0,49	0,7638
23003	33	43	0,37	1,4794
23018	1	18	0,32	0,4684
25001	4	46	0,33	1,2886
26005	2	16	0,94	0,0704
27007	8	56	0,39	1,5258
27023	18	37	0,47	0,6129
27047	13	86	0,18	3,4737
27059	12	49	0,43	0,7330
27088	10	47	0,35	1,2934
28001	14	33	0,47	1,0488
28019	8	35	0,66	0,7410
28031	6	82	0,54	1,3729
28050	12	17	0,67	0,3518
28082	7	33	0,5	0,4192
28117	11	65	0,66	1,0924
30003	4	15	0,59	0,3443
31016	14	19	0,91	0,3922
32008	8	32	0,57	0,3825
33013	8	14	0,65	0,2289
33033	8	15	0,85	0,3169
33051	10	14	0,67	0,2521
34002	7	19	0,6	0,2949
34012	4	12	0,95	0,2098
36005	5	11	0,47	0,3067
37007	11	17	0,42	0,3214
38003	13	18	0,93	0,2032
38020	12	17	0,27	0,3333

Station number	Woodland (%)	Grassland (%)	Baseflowindex (-)	Runoff Coeff. (P/Q)
39007	22	25	0,67	0,5065
39030	17	25	0,88	0,3260
39065	9	49	0,98	0,1933
39086	42	16	0,61	1,2217
39101	11	34	0,97	0,2585
39114	7	28	0,94	0,1394
39131	8	17	0,3	0,4038
40012	23	30	0,73	0,2254
41011	24	32	0,62	0,8631
41025	44	29	0,23	0,7189
42008	13	30	0,96	0,4753
43006	16	30	0,82	0,7402
43018	9	29	0,91	0,6351
44011	13	55	0,65	0,7175
45012	12	45	0,46	0,6829
46005	9	43	0,44	3,2836
47013	24	62	0,54	2,0671
48011	18	64	0,62	1,3506
50007	10	48	0,47	1,5017
50011	13	55	0,48	1,7030
52016	46	33	0,71	0,7060
53002	9	46	0,58	0,6088
53008	8	44	0,58	0,6153
54002	11	34	0,52	0,4434
54018	9	60	0,51	0,5807
54041	8	52	0,71	0,4760
54057	12	48	0,57	0,6526
54090	63	32	0,31	4,7629
55002	13	71	0,46	1,8053
55013	11	71	0,55	1,2049
55026	14	74	0,37	2,8203
55034	0	96	0,29	4,4039
56019	9	38	0,5	2,1281
57007	14	55	0,46	2,1414
57015	12	58	0,38	2,2225
58005	19	63	0,49	2,8475
60006	19	74	0,47	2,4068
64001	29	62	0,39	3,3167

Station number	Woodland (%)	Grassland (%)	Baseflowindex (-)	Runoff Coeff. (P/Q)
66004	19	73	0,82	0,6608
67006	18	68	0,48	1,7346
68007	12	48	0,5	0,6512
69024	14	46	0,4	1,0724
71010	8	66	0,36	1,5475
73005	6	81	0,42	2,9304
74007	6	86	0,29	3,8687
75004	8	71	0,44	2,9764
76015	8	79	0,54	3,5025
78003	25	59	0,44	2,2372
80001	21	69	0,36	1,8227
83005	13	60	0,27	1,5857
92001	17	29	0,61	5,7336

Appendix C; number of behavioural parameter sets per model structure combination.

	Penman (SMA) combined with			Distr. function (SMA) combined with		
	2par (R)	Leak (R)	Cres (R)	2par (R)	Leak (R)	Cres (R)
Station number:						
1001	0	0	0	287	16	623
7005	0	0	0	68	4	558
10002	0	0	0	50	0	0
14001	1987	10	245	2522	65	1609
15008	8	0	1	710	26	238
15027	1463	5	3296	1304	71	4229
16004	7	0	0	322	7	381
18011	0	453	0	0	488	0
21003	0	194	0	1530	304	804
21013	11	0	26	369	13	741
21027	8	0	0	22	2	207
23003	56	0	110	346	12	1182
23018	191	16	1703	127	40	1941
25001	710	55	2475	619	97	3828
26005	0	49	0	0	76	0
27007	14	0	1	255	12	1012
27023	13	0	0	31	1	84
27047	0	0	0	0	0	13
27059	704	64	2844	421	107	3204
27088	0	404	0	0	392	0
28001	0	117	0	0	102	0
28019	0	0	0	217	0	0
28031	0	0	0	132	5	343
28050	222	0	0	565	0	0
28082	205	5	200	663	25	2449
28117	3584	18	664	2834	134	1989
30003	1113	40	196	2078	114	2203
31016	23	0	0	382	0	0
32008	282	0	17	770	13	2326
33013	136	35	0	1809	152	132
33033	98	5	0	831	0	0
33051	14	0	0	299	2	0
34002	354	0	0	1464	38	1038
34012	0	0	0	284	0	0
36005	171	1	0	494	26	1897
37007	369	4	1093	893	21	3326

SMA structure:	Penman (SMA) combined with			Distr. function (SMA) combined with		
Routing:	2par (R)	Leak (R)	2par (R)	Leak (R)	2par (R)	Leak (R)
Station number:						
38003	0	2	0	220	0	0
38020	198	16	1535	301	49	3422
39007	436	0	0	906	0	0
39030	0	0	0	193	0	0
39065	0	0	0	0	7	0
39086	0	0	0	1	0	0
39101	0	305	0	0	338	0
39114	0	20	0	0	73	0
39131	180	7	1068	102	0	63
40012	0	91	0	0	48	0
41011	461	1	17	523	0	132
41025	43	6	876	44	4	1131
42008	0	68	0	89	79	0
43006	1941	13	0	2634	53	0
43018	1696	20	0	2038	96	0
44011	144	0	0	210	0	0
45012	1087	97	3718	860	221	3594
46005	0	0	0	2	3	55
47013	2	0	0	66	9	380
48011	3799	94	2999	3457	240	3144
50007	25	0	0	152	9	823
50011	609	0	916	551	52	2015
52016	2518	46	0	2366	104	198
53002	49	0	0	78	0	0
53008	1825	41	1569	2204	219	2605
54002	484	5	607	721	28	1955
54018	1981	148	3701	1141	171	3552
54041	118	0	0	311	0	0
54057	2122	32	141	2623	169	1390
54090	920	14	8829	773	25	7085
55002	931	0	759	921	44	1887
55013	3384	17	3381	2446	144	3897
55026	17	0	0	178	17	862
55034	1	0	0	51	3	513
56019	112	0	0	431	23	844
57007	0	450	0	0	470	0

SMA structure:	Penman (SMA) combined with			Distr. function (SMA) combined with		
Routing:	2par (R)	Leak (R)	2par (R)	Leak (R)	2par (R)	Leak (R)
Station number:						
57015	0	369	0	0	343	0
58005	0	0	0	30	2	78
60006	0	0	0	44	7	117
64001	0	0	0	10	1	89
66004	2665	9	0	3273	70	0
67006	4451	22	8540	3081	119	7379
68007	131	0	490	391	13	1572
69024	0	136	0	0	206	0
71010	0	0	0	84	20	820
73005	0	0	0	49	5	218
74007	0	0	0	2	0	17
75004	3406	22	7999	3189	89	6598
76015	5769	0	5847	3709	25	5773
78003	0	0	0	73	6	201
80001	2561	8	9321	1602	63	8138
83005	162	1	1162	248	23	2625
92001	79	0	0	29	1	15