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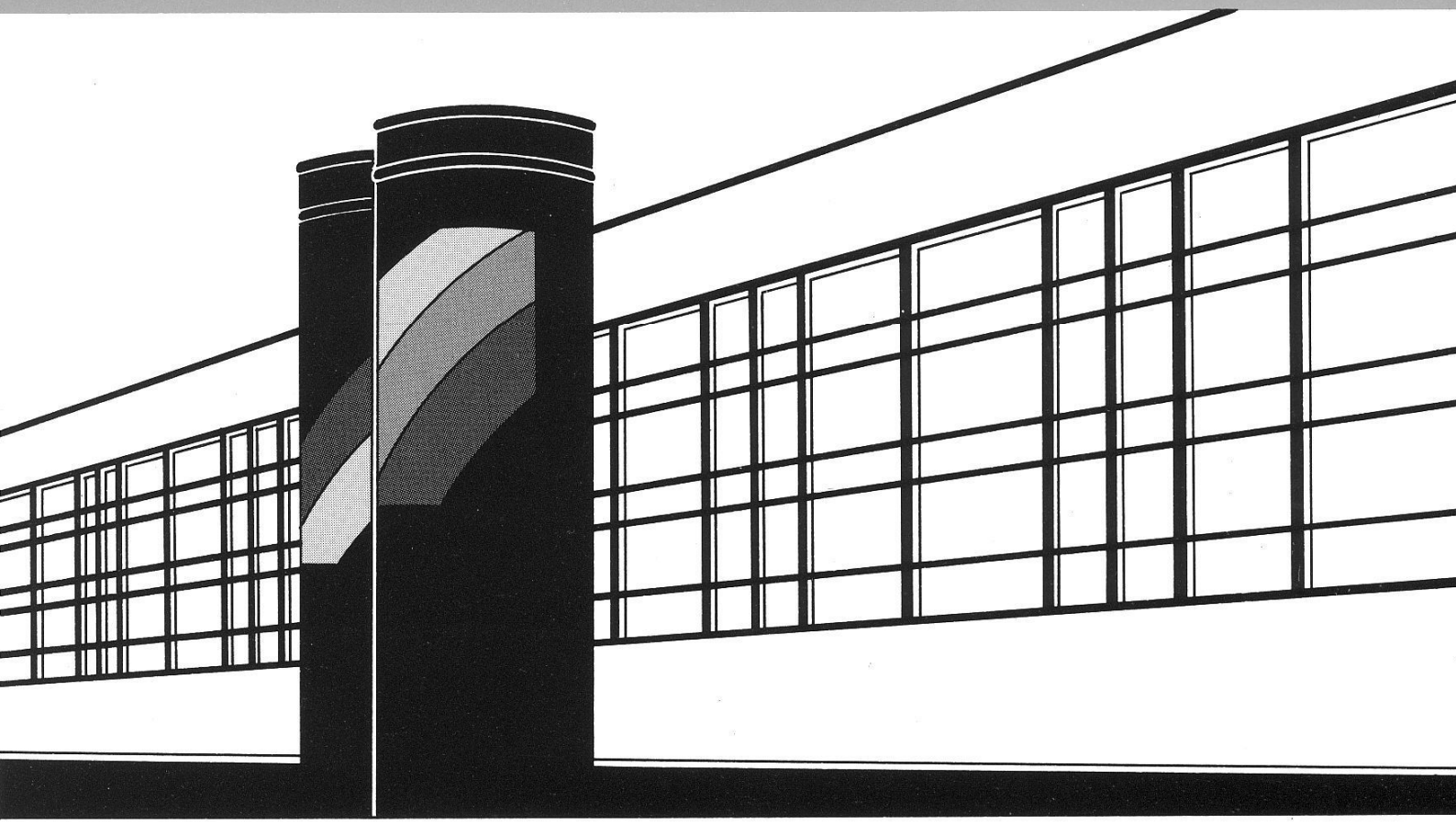

Heft 172 Yi He

Application of a Non-Parametric Classification Scheme to Catchment Hydrology

Application of a Non-Parametric Classification Scheme to Catchment Hydrology

Von der Fakultät Bau- und Umweltingenieurwissenschaften der Universität Stuttgart zur Erlangung der Würde eines Doktor-Ingenieurs (Dr.-Ing.) genehmigte Abhandlung

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Acronym

Acronym	Description
CC	Catchment Classification
CD	Catchment Descriptors
CMs	Conceptual Rainfall-Runoff Models
FAO	International Food and Agricultural Organization
FCC	Fertility Capability Classification
HBV	Hydrologiska Byråns Vattenbalansavdelning (water balance section of the hydrological bureau of the Swedish Meteorological and Hydrological Institute
HOST	Hydrology of Soil Types
ISRIC	International Soil Reference and Information Centre
IUSS	International Union of Soil Science
IWS	Institute of Hydraulic Engineering, Universitaet Stuttgart
LCC	Linnaean catchment classification
LVR	Local Variance Reduction
MDS	Multidimensional scaling
NS	Nash-Sutcliffe efficiency coefficient
PUB	Predictions in Ungauged Basins
SCC	Statistical catchment classification
SMHI	Swedish Meteorological and Hydrological Institute
VIC	Variable Infiltration Capacity Model
VIC-2L	two-layer Variable Infiltration Capacity
XAJ	Xinanjiang model
WRB	World Reference Base

Notation

The following table shows the symbols used in the HBV-IWS and XAJ-IWS models. Local notations are explained in the text.

Symbol	Definition	Dimension
HBV-IWS model:		
P	Precipitation	[L/T]
ET	Evapotranspiration	[L/T]
Q	Runoff	[L/T]
SP	Snow Pack	[L]
SM	Soil Moisture	[L]
UZ	Upper Groundwater Zone	[L]
LZ	Lower Groundwater Zone	[L]
$lakes$	Lake Volume	[L]
S_{melt}	Snow melt	[mm/day]
DD	Degree-day factor	[mm/ºC·day]
T	Average daily temperature	[ºC]
TT	Threshold temperature	[ºC]
D_{max}	Maximum limit to the degree-day factor	[mm/ºC·day]
DD_0	Degree-day factor when there is no rainfall	[mm/ºC·day]
k	Coefficient	[(ºC·day)$^{-1}$]
PE_A	Daily potential evapotranspiration	[mm/day]
T	Daily mean air temperature	[ºC]
C_{ET}	Model parameter	[(ºC)$^{-1}$]
T_M	Monthly long term mean temperature	[ºC]
PE_M	Monthly long term average evapotranspiration	[mm/month]
E_{int}	Evaporation from the interception storage	[mm/day]
I_{act}	Amount of water in the interception storage	[mm/day]
PWP	The minimum soil moisture at which a plant wilts	[mm]
β	Free model parameter	[-]
Q_1	Direct runoff generated from the upper reservoir	[mm/day]
Q_{perc}	Percolation generated from the upper reservoir	[mm/day]
Q_2	Slow runoff generated from the lower reservoir	[mm/day]
α	Model parameter for direct runoff	[-]

k_1	Recession coefficient of the upper reservoir	[day^{-1}]
k_{perc}	Percolation rate	[day^{-1}]
k_2	Recession coefficient of the lower reservoir	[day^{-1}]
h_1	The depth of water in the upper reservoir	[mm]
h_2	The depth of water in the lower reservoir	[mm]

XAJ-IWS model:

EU	Actual evapotranspiration in the upper layer	[mm/day]
EL	Actual evapotranspiration in the lower layer	[mm/day]
ED	Actual evapotranspiration in the deeper layer	[mm/day]
WU	Soil moisture in the upper layer	[mm/day]
WL	Soil moisture in the lower layer	[mm/day]
WD	Soil moisture in the deeper layer	[mm/day]
WMU	Tension water capacity in the upper layer	[mm/day]
WML	Tension water capacity in the lower layer	[mm/day]
WMD	Tension water capacity in the deeper layer	[mm/day]
K	Coefficient for the upper soil layer	[-]
C	Coefficient for the deeper soil layer	[-]
PE_A	Daily potential evapotranspiration	[mm/day]
P	Daily precipitation	[mm/day]
IM	Percentage of impervious area	[%]
RB	Runoff originated from impervious areas	[mm]
f/F	proportion of the pervious area of the catchment where tension water capacity $\leq$ the ordinate $W'M$	[%]
B	Exponent of the tension water capacity distribution curve	[-]
$S'M$	Free water storage capacity	[mm]
MS	Maximum free water storage capacity	[mm]
FR	the fraction of the area that is producing runoff	[-]
f/FR	Proportion of the area where free water storage is less than or equal to S'M	[%]
Ex	Exponent of the free water capacity distribution curve	[-]
KI	Model parameter related to interflow	[-]
KG	Model parameter related to groundwater	[-]
CI	Reservoir constant related to interflow	[-]
CG	Reservoir constant related to groundwater	[-]
QI	Streamflow generated from interflow	[mm]
QG	Streamflow generated from groundwater	[mm]
QT	Total streamflow/runoff	[mm]
t	Time step	[hour]

Abstract

Classification has been considered a fundamental step towards improved catchment hydrology science. Catchments classification has been traditionally carried out via Linnaeus-type cluster analysis, mainly represented by hierarchical approaches and methods based on partitioning of hydrological data set. This paper proposes a new scheme where the classification procedure is based on similarity interpreted as distances between catchments. The similarity or distance is defined under the following premises:

1. similar catchments behave similarly;
2. similarity can be described with catchments' characteristics; and
3. hydrological models are able to capture catchments' similarity.

If many sets of model parameters lead to similar model performance for two catchments, they are considered as similar catchments. To implement the proposed scheme, two procedures, namely multidimensional scaling (MDS) and local variance reduction (LVR), are undertaken to construct a configuration of n catchments' characteristics in Euclidean space using information about similar performance between the catchments. The MDS is used to determine the appropriate dimension of the Euclidean space and the LVR is used to obtain the transformation matrix and the coordinates in the transformed Euclidean space. This scheme avoids the idea of parametric regression-based regionalization approaches where a regression function is pre-defined between model parameters and catchment descriptors. In the aforementioned approach, the function that is selected is usually subjective and arbitrary and one can also argue that a priori function is neither able to represent the highly complex hydrological processes nor consider the interdependences amongst model parameters.

The proposed scheme is initially tested with a research version of the HBV-IWS model on a number of catchments within the Rhine Basin. Additionally a modified Xinanjiang model is applied to the same catchments to check if the assumption of invariant catchment similarity holds true. Invariant catchment similarity here assumes the catchments genuinely carry their similarities independent of the model used for simulation. This test is also a backstop measure to determine if the models under consideration are capturing the underlying simplified hydrological processes in a rational manner. The scheme will be extended to regional calibration of rainfall runoff models as well as regional drought or flood studies once similarity within catchments has been established. The proposed scheme will eventually contribute to the PUB (Predictions in Ungauged Basins) initiative.

Kurzfassung

Klassifikationsverfahren sind ein fundamentaler Schritt in Richtung besserer Einzugsgebietshydrologie. Einzugsgebietsklassifikation wurde traditionell durch Linnaeus-Cluster Analysis, hauptsächlich basierend auf hierarchischen Ansätzen und Methoden der Partitionierung hydrologischer Datensätze, durchgeführt. Diese Arbeit schlägt ein neues Schema vor, bei dem die Klassifikation auf Ähnlichkeit, interpretiert als Abstand zwischen Einzugsgebieten, basiert. Die Ähnlichkeit oder Distanz wird unter den folgenden Voraussetzungen definiert:

1. Ähnliche Einzugsgebiete verhalten sich ähnlich.
2. Ähnlichkeit kann durch Gebietseigenschaften beschrieben werden.
3. Hydrologische Modelle können die Ähnlichkeit von Einzugsgebieten abbilden.

Wenn viele Parametersätze eines Modells bei zwei Einzugsgebieten zu gleicher Modelleffizienz führen, können sie als ähnliche Gebiete bezeichnet werden. Um das vorgeschlagene Schema zu implementieren, wurden zwei Verfahren, nämlich multidimensional scaling (MDS) und local variance reduction (LVR), angewandt, um eine Konfiguration von n Gebietseigenschaften im Euklidischen Raum, basierend auf Informationen über ähnliche Modelleffizienz, zu konstruieren. MDS wird benutzt, um die notwendige Dimension des Euklidischen Raums zu ermitteln und mit LVR werden die Transformationsmatrix und die Koordinaten im transformierten Euklidischen Raum bestimmt. Die Methode umgeht die Idee der parametrischen, regressionsbasierten Regionalisierungsansätze, bei denen eine Regressionsbeziehung zwischen Modellparametern und Gebietseigenschaften vorgegeben wird. Dabei wird die Form der Beziehung normalerweise subjektiv und willkürlich gewählt und man kann argumentieren, dass diese a proiri definierte Funktion weder die hochkomplexen hydrologischen Prozesse noch die Abhängigkeiten zwischen Modellparametern wiedergeben kann.

Die vorgestellte Methode wird zuerst mit einer Forschungsversion des HBV Modells und einigen Teileinzugsgebieten des Rheins getestet. Zusätzlich werden die Ergebnisse mit dem Resultat einer Anwendung des modifizierten Xinanjiang Modells der selben Einzugsgebiete verglichen, um zu überprüfen, ob die Annahme der invarianten Gebietsähnlichkeit gültig ist. Invariante Gebietsähnlichkeit nimmt in diesem Fall an, dass die Einzugsgebiete selbst, unabhängig vom gewählten Modell, ihre Ähnlichkeit in sich tragen. Dieser Test stellt auch sicher, dass die gewählten Modelle die zu Grunde liegenden hydrologischen Prozesse sinnvoll abbilden können. Die Methode soll auf die regionale Kalibrierung von hydrologischen Modellen und regionale Hoch- und Niedrigwasserstudien erweitert werden, sobald

die Ähnlichkeit von Einzugsgebieten erfasst ist. Damit könnte das Verfahren zukünftig zu der PUB Initiative (Predictions in Ungauged Basins) der IAHS (International Association of Hydrological Sciences) beitragen.

1 Introduction

Human existence is intrinsically linked to water. The issue of water assumes different dimensions when one considers worldwide millions of people are negatively affected in one way or the other by water related issues. Be it floods, lack of sanitation, disease or drought, water is and shall remain an integral part of human existence. Rainfall runoff models play a crucial role in the development of reliable water management frameworks. 'Evaluating river discharges from rainfall has stimulated the imagination and ingenuity of engineers for many years' (Shaw, 1998). Ever since the devotion of the Italian polymath, Leonardo da Vinci (1452-1519) to the recent advancement barely covered by the Primer (Beven, 2000), the development of these models has undergone a long way of being scientifically formed and shaped. This doctoral undertaking is perceived to be a rather tiny, nevertheless non-negligible fraction of the collective runoff in the field of catchment hydrology, in particular, catchment classification and regional calibration of rainfall runoff models.

1.1 Background and motivation

'The derivation of relationships between the rainfall over a catchment area and the resulting flow in a river is a fundamental problem for the hydrologist' (Shaw, 1998). Rainfall-runoff models of different types provide a means of quantitative extrapolation or prediction of discharge and estimation of water balance (Beven, 2000). These models can be classified into different types based on varied criteria (Hundecha, 2005). Two dominant categories of these models are physically-based and conceptual models. A plethora of literature is devoted to the comparison of the performance of physically-based and conceptual models, including debates associated with their data requirement and model complexity.

Physically based models, as presented by (Freeze and Harlan, 1969) describe distributed mechanics of hydrological processes. Such models are appropriate for studying the effects of land use changes, soil erosion, surface groundwater interactions (Todini, 1996) because their parameters are (or should be) reflected in the field measurements (Beven, 1989). In practice, however, they do not represent physical processes as they are purported to, especially in the reality of heterogeneity and complexity of water flows in the field (Bhaskar, 1989). Hydrological data at very fine resolution in a heterogeneous domain is currently neither available (at least, hard to achieve) nor desirable. Even if the hydrological processes

were accurately represented and data were to be obtained, the computing power that such simulations would require cannot be ignored. These problems have been discussed extensively in the literature (Beven, 1985, 1986, 1993; Beven and Binley, 1992; Bhaskar, 1989; Hornberger et al., 2003; Sokrut, 2004).

Current research, now more than ever, is moving towards simpler, more robust, more easily and quickly calibrated rainfall-runoff models, away from more complex, over-parameterized and 'data-greedy' models. Beven (1989) makes an interesting assertion on current distributed models arguing that they are in fact lumped conceptual models; even if they operate at the grid scale rather than at the catchment scale of more traditional lumped conceptual models.

Conceptual models (CMs), on the other hand, are well-known for their moderate data requirement. They provide "simplified representations of key hydrological processes using a perceived system" (Dawson and Wilby, 2001). They exhibit deficiencies when dealing with ungauged basins because the conceptual model parameters have to be obtained by calibration and validation. In addition, their conceptual basis reduces their ability to deal with climate/landuse change and other dynamic changes taking place in most catchments. This is due to the fact that they only perform well with calibration and validation based on the past hydrological data which does not necessarily reflect the future. The calibration-validation-dependent nature and static features associated with CMs highly constrain their application for prediction within ungauged basins and basins undergoing climate and/or physical changes. In a broad and practical sense, ungauged basins do not only refer to the basins without past stream flow observations but also those basins envisage potential changes in the future[1]. Regionalization methods are needed which relate easily measured watershed characteristics to watershed model parameters (Vogel, 2005). It is not only to enable predictions at past ungauged sites but also many more sites within the emerging context of climate change. Some attempts have been made at tackling the aforementioned problems including parameter estimation methods for both gauged and ungauged basins (Bloeschl, 2003); assessment of water balance related consequences of land-use/cover changes using regional characteristics (Samaniego, 2003); and parameter regionalization in modeling the effect of land use changes on the runoff generation of a river basin (Hundecha and Bárdossy, 2004). Many attempts have been made to establish a linkage between dynamic catchment characteristics and model parameters to diminish the aforementioned deficiencies of CMs. (Vogel, 2005) provides a comprehensive review of regional approaches.

[1]based on a discussion with Dr. Vladimir Smakhtin, IWMI

1.2 Objectives

Two conceptual rainfall-runoff models are chosen in this study to undertake investigations related to the research problems of predictions in ungauged or insufficiently gauged basins.

Estimates of hydrological parameters at ungauged sites have traditionally been obtained with regression-based approaches (Burn and Boorman, 1993; Vogel, 2005). Earlier on, a two-step approach was proposed. One needed to calibrate a model on individual catchments independently in the first step and obtain the relationship between the model parameters and the catchment descriptors in the second step. Examples of this approach could be found in Abdulla and Lettenmaier (1997b); Sefton and Howarth (1998). The two-step approach could not lead to a strong relationship and thus the performance of regional prediction was often limited (Hundecha, 2005). A one-step approach has been implemented to improve the weakness of the two-step approach. The calibration is performed without making any direct reference to the model parameters but to the coefficients of the predefined regression function (Hundecha, 2005). The one-step approach does not guarantee a unique set of optimum model parameters to be found although a constraint is imposed by the functional relationship. Considerable uncertainties are associated with the one-step regression approach, although much improvement is achieved compared to the two-step one. One may argue that a linear or non-linear regression function is not able to represent the highly complex and non-linear hydrological processes. Secondly, a priori function is fully subjective and arbitrary. There is no formal guideline as to what type of regression function should be employed.

Apart from main-stream regression-based regional calibration approaches, there exist a variety of other approaches applied to estimation of hydrological parameters within ungauged basins. Some of these methods and their corresponding examples are listed below:

- Kriging interpolation methods, e.g. Vandewiele and Elias (1995); Merz and Bloeschl (2004)
- Catchment pooling methods, e.g. Mosley (1981); Gottschalk (1985); Burn and Boorman (1993)

In general, the above-mentioned methods are based on the idea of homogeneity within a population where a pattern or behaviour is shared, hence the model parameters or explanatory variables of the model parameters can be transfered to other individuals in the same population cluster (Gottschalk, 1985). Chapter 2 will elaborate on these methods.

Many previous studies have achieved some progress but the problems of regional calibration and parameter estimation are far from solved (Xu and Singh, 2004). The relationships

between hydrology and physiography are regarded as the ultimate scientific goal by Gottschalk (1985). He further proposed areal classification as one proper tool to define hydrological regions and spatial variations.

This work is undertaken to further the catchment classification methods. The main objective of this work is to establish a non-parametric catchment classification scheme and the secondary objective is to explore its applications in catchment hydrology, in particular predictions in ungauged or insufficiently gauged basins.

2 The role of catchment classification in rainfall-runoff modelling

While "diversity is nature's principal theme" (Gould, 1989), human beings have been craving for the least variability and order (Wagener et al., 2007). There exists an order in any seemingly chaotic and turmoil process or system, which needs to be discovered or unveiled. One approach to discern order in a heterogeneous world is through the means of classification (Gould, 1989; Wagener et al., 2007). Classification systems such as taxonomy, nomenclature, categorization and organization all lead to name and organize entities or organisms into groups on the basis of properties or relationships they have in common (Grigg, 1965).

Classification has been considered a fundamental step towards improved catchment hydrology science (Gottschalk, 1985; McDonnell and Woods, 2004; Vogel, 2005; Wagener et al., 2007). "The need for classification" in the field of geography has been identified by Grigg (1965) as follows:

1. to give names to things;
2. to transmit information;
3. to make inductive generalization.

While geographers require names for similar features of the earth's surface that occur repeatedly (Grigg, 1965), hydrologists need names for catchments that have similar characteristics and can transmit similar knowledge or information.

Catchment classification has been traditionally carried out via Linnaeus-type (Linnaeus, 1766) analysis, mainly represented by hierarchical approaches. Similar to what has been implemented in the field of ecology, statistical classification has gradually seen its growth and become an essential component contributing to catchment classification.

This chapter is organized into two parts. Section 2.1 is a review of methods directly based on physiographic properties and climatic conditions over a catchment. These methods are regarded as Linnaean or natural classification. Section 2.2 provides an overview on the current numerical clustering and regionalization methods. They are regarded as statistical or arbitrary classification.

2.1 Linnaean catchment classification (LCC)

Classification is a necessary preliminary in most sciences as Grigg (1965) put it, "the state of classification is a measure of the maturity of a science". Hydrology, as a discipline of science, is still young if compared to biology. A scientific and globally agreed classification system in hydrology has yet to be delivered (Wagener et al., 2007).

Many hydrological regions have been delineated or divided based on administrative boundaries which may cut across geologic, climatic and topographic boundaries (Mosley, 1981). Simple division of areas cannot be of use for the purposes of hydrological prediction. Isolines were probably the earliest attempt to extract some similar features of an area and used as a common method of regionalization to classify regions into runoff zones (Gottschalk, 1985). An isoline joins points of the same value and forms a continuous line which can be of equal altitude (contour lines), temperature (isotherms), barometric pressure (isobars), wind speed (isotachs), wind direction (isogon) and so forth. An isoline map is therefore regarded as a sort of thematic map. In the case of hydrology, an isoline map is a prototype classification that is based on a continuous variation of landscape features. Grigg (1965) clearly points out the difference between the classification of objects and areas, where the former is based on not only the properties but also the functions and relationship that the objects have in common and the latter based only on the properties. Classification of objects that are based on function and relationship is most important for hydrologists since the ultimate goal of classification is to make inductive generalization of objects. An isoline map, apparently, cannot suffice such purpose.

Fortunately, hydrologists are by no means "the little frog" constrained in the dark and small well. Many wonderful systems already exist for hydrologists to make use of. Organism classification in biology, element classification in chemistry (periodic table), soil classification in pedology and regionalization in geography[1] have been recognized by many hydrologist as classification systems that can be adopted in hydrology, even though many of the established classification systems have been subject to criticism.

2.1.1 LCC - What's been done

Linnaean classification and nomenclature

Looking back into the great 18th century, Carl Linnaeus, a Swedish botanist, physician and zoologist, laid the foundations for the modern scheme of nomenclature. The original Linnaean system classified organisms within a hierarchy, starting with three kingdoms. **Kingdoms** were divided into **Classes** and they, in turn, into **Orders**, which were divided

[1] Ecology, a close relative of hydrology, has also seen growing advancement in classification. This review has not included this field.

into **Genera** (singular: genus), which were divided into **Species** (singular: species). Linnaeus also attempted to describe every species with a two-part name and adopted the so called binomial ("two-name") nomenclature after Jean Bauhin, a French physician. Linnaean nomenclature can identify every species with only two names without any ambiguity[2].

Systems of classification and binomial nomenclature have had a revolutionary effect on the study of all living organisms. Linnaean hierarchical classification system has become the basis for almost all subsequent system of classification and nomenclature and remained standard for over 200 years. It has contributed to eventual understanding of the morphological similarities among species while also providing powerful evidence for common origins.

Periodic table of chemical elements

Another celebrated classification system is the periodic table of chemical elements and the credit goes to Dmitri Mendeleev, a Russian chemist. Unlike the top-down hierarchical classification system in biology, the periodic table is based on the recurring trends of the properties of the elements. A group is a vertical column, while a period is a horizontal row in the periodic table of the elements. The elements in the same group usually have very similar properties and exhibit a clear trend in properties with increasing atomic number down the group. The first Mendeleev periodic table was left with a number of missing elements and he used his table to predict the properties of these "missing elements". Many of them were discovered later on and fit the predictions well. The periodic table has provided an extremely useful framework to classify, systematize and compare all the many different forms of chemical behavior [3].

Soil classification

Soil classification is another area where classification has played significant roles. Due to the complex nature of soil formation and texture and based on the purpose the classification is made, there exist several soil classification systems. Soil classification sees its most application in agriculture due to the fact that soil is the nature medium for the growth of land plants that supply food, fibers, drugs, and other needs of humans (USDA, 1999). Various purposes lead to a number of soil classification systems. According to Rossiter (2001), two types of soil classification are possible:

- **natural soil classifications** - soils are grouped by some intrinsic property, behaviour, or genesis of the soils themselves, without direct reference to use, e.g. the World Reference Base (WRB) jointly developed by the International Soil Reference and Information Centre (ISRIC), the International Union of Soil Science (IUSS) and the In-

[2]modified after `http://en.wikipedia.org/wiki/Carolus_Linnaeus`
[3]modified after `http://en.wikipedia.org/wiki/Periodic_table`

ternational Food and Agricultural Organization (FAO). The natural soil classification follows the same line along the Linnaean hierarchical classification system that the differentiating characteristics are used to formulate different levels or hierarchies to group soils.

- **technical soil classifications** - soils are grouped by some properties or functions that relate directly to a proposed use or group of uses, e.g. the HOST (Hydrology of Soil Types) classification system "makes use of the fact that the physical properties of soils have a major influence on catchment hydrology" [4] and groups all UK soil types into 29 hydrological classes; the FCC (Fertility Capability Classification) classification system identifies a number of soil properties essential to the specific requirement of growing crops and divides soils into groups with the critical thresholds of those identified properties (Sánchez et al., 1982).

Regionalization and classification in geography

If we, hydrologists, were to borrow ideas from geographers and use them in hydrology, we would first need to understand their purposes of regionalization. They are summarized from Grigg (1965) and numerated as follows:

1. for geographers to give widely accepted names or terms to similar features of the earth's surface which occur repeatedly;
2. for geographers to exchange knowledge and pass on to new students of the subject. If similar parts of the earth's surface can be grouped together, then statements can be made about that areal class which are applicable to all the smaller parts within the same class;
3. for geographers to make inductive generalization about the relationship of the regions under study.

There are three types of regions that have been commonly recognized by geographers (Berry and Hankins, 1976):

1. The "region" in the general sense in which the region is given a priori.
2. A homogeneous or uniform region; this is defined as an area within which the variations and covariations of one or more selected characteristics fall within some specified range of variability around a norm, in contrast with areas that fall outside the range. such a region, unlike that previously described, but like the functional region, is a result of the process of regionalization and is not given a priori.
3. A region of "coherent organization" or a "functional" region. this region is defined as one in which one or more selected phenomena of movement connect the localities within it into a functionally organized whole.

[4] from HOST introduction, available online: `http://www.macaulay.ac.uk/host/`

To throw additional light on regional systems, Grigg (1965) gave ten principles which would be useful in constructing a practical classification system. Amongst, two principles could be of particular interests to hydrologists:

1. a classification system should be designed for a clear and specific purpose, it hardly serves two or more different purposes equally well. A classification system would lose its precision as instruments of analysis if it attempts to cover a diverse range of goals;
2. a classification system is not absolute, i.e. it would be modified, updated or even completely changed as more knowledge is gained about the objects under study.

A ubiquitous and globally accepted hierarchical classification system or nomenclature in geography has, unfortunately, never been reached in light of many studies and endeavors. Herbertson was probably the first person who put together regions having the same physical characteristics into similar divisions on a world basis (Sum, 1970). Being deeply influenced by his doctoral work entitled "The Monthly Rainfall over the Land Surface of the Globe", he used mainly climate and relief as differentiating characteristics to divide the world into six natural regions, namely, polar regions, the cool temperature regions, the warm temperature regions, the west tropical deserts, lofty tropical or subtropical mountains and equatorial lowlands (Herbertson, 1905). He believed climate renders the physical earth's surface features and thus can represent various influence on the surface.

Regionalization and classification in hydrology

The regional system in geography has been popularized and adopted as a school of thought in hydrology. Isoline maps that are based on one single earth's surface feature have served as a primitive classification method to classify regions. The first work using an isoline map to formulate a classification scheme was accomplished by Herbertson (1912) in his paper of "The Thermal Regions of the Globe". The mean annual temperatures of 0°, 10° and 20° are represented with isotherm lines to classify the thermal regions of the World. The emphasis was laid on climate, in particular, temperature. It is a prototype of hydro-climatic classification leading to its development in hydrology.

Herbertson's first classification scheme (Herbertson, 1905) was criticized by (Roxby, 1907) who stated a region should be "an area throughout which a particular set of physical conditions prevail" but not one classified by only climate and relief. A set of landscape properties were then used as differentiating characteristics to classify physiographic regions in different parts of the world. Examples of them are listed below (developed from (Gottschalk, 1985)):

1. classify Finland into a number of physiographic regions (Granö, 1925-1928, 1952);
2. classify the former USSR with respect to both topographical and climatic information (Kuzin, 1960);

3. classify the entire Europe into a number of physiographic regions (Kondracki, 1968; Grimm, 1968a,b);
4. hydrological regionalization in New Zealand based on information about precipitation, vegetation, topography, soil types and geology (Toebes and Palmer, 1969).

The above-mentioned studies were undertaken separately and no one general approach was designed. Mosley (1981) moaned there was "surprisingly little guidance in the literature regarding the details of regionalization" in hydrology, whereas Sum (1970) delightfully named 1905-1937 "the golden age of regionlism, for it was during this period the regional concept underwent refinement and received its new images through the hands of Roxby, Unstead and Fleure." It certainly indicates again the maturity of geography and youthfulness of hydrology as a discipline of science in comparison with geography, not to mention biology. Despite of "little guidance in regionalization", Linsley et al. (1975) provided a short note on regionalization: "if the regional approach is used, considerable care should be taken to select streams as nearly similar in hydrologic characteristics as possible. They should have similar vegetal cover, land use, topographic conditions, and geologic characteristics, and large basins should not be grouped with very small basins. They should also have similar rainfall and evapotranspiration regimes". This had certainly pointed out a more comprehensive and practical direction for classification. Till then, regionalization strictly followed the footstep of the Linnaean classification system. Nevertheless, classification in geography and hydrology was no more than a game of mere identification of one and the other properties of the regions (Grigg, 1965). Insufficient attention was paid to the functions, relationships and co-varied behaviour among them. More questions had also been raised as what hydrologic characteristics should be taken into consideration and to what extent the interactions with each other affect the hydrological functions were not mentioned. One obvious reason that hinders the development of hydrologic classification is due to lack of data, in particular, spatially distributed data. The secondary reason lies in the understanding of the causal effects between catchment characteristics and hydrologic behaviour. Hydrologic regionalization surely has a long way to go.

So far, regionlization describes the procedure of grouping individuals into regions under the premise that all individuals that are similar are also contiguous, because a region cannot be formed if individuals are not contiguous (Grigg, 1965; Mosley, 1981). Early work of classification and regionalization was conducted within the context of geography. The actual meaning and usage of the terms of "classification" and "regionalization" have not been clearly defined in the specific field of hydrology. Regionlization having appeared in literature within the context of hydrology (reviewed in section 2.2) does not necessarily apply in one contiguous area. It refers to realization of proper model parameters by taking advantage of another gauged region or catchment that is similar to the one under study.

2.1.2 LCC - What's being done

A great deal of effort has recently been put into classification of catchments, especially in the last two decades. They have however been isolated and sometimes buried under vast amount of similar work. It is not until McDonnell and Woods (2004); Wagener et al. (2007) that "a commonly-agreed classification" scheme is officially being discussed within the PUB (Prediction of Ungauged Basins) initiative.

Wagener et al. (2007) has put a lot of effort collecting and reviewing most existing classification methods and concepts, which has provided a brilliant "kick-off" as a way forward (a way that avoids probable redundancy or repetition and hence is more straightforward). A summary based on their work is provided below. Additional work not covered in Wagener et al. (2007) is also reviewed in the following text.

Regionalization

Catchment classification in this dissertation has been given two categories. The Linnaean catchment classification refers to the systems more or less resembling the Linnaeus-type hierarchical approach using a number of physical catchment properties and climate as differentiating characteristics. It can also be regarded as a natural classification system which has been given the same terminology in the field of geography. The second category is refered to as statistical catchment classification which includes regionalization and statistical clustering methods. Regionalization is put in the second category because it is not directly based on the natural catchment characteristics but the catchment response and model parameters, which are synthetic characteristics fitted with regression procedure. The regional system is thus not reviewed in this section.

Catchment structural similarity

Similarity can be defined with catchment structural characteristics:

1. in the form of a **dimensionless number** such as **stream order** (a hierarchy of stream tributaries, initially developed by Horton (1945) and enhanced by Strahler (1957) to help describe relationships between stream and catchment, also used by biologist to relate species diversity Dorris (1967)); **bifurcation ratio** (originated by Horton (1945), the average ratio between the number of streams of order n and $n+1$, a low ratio indicates a low number of branches and high susceptibility to be flooded due to concentration); **drainage density** (the ratio between square of total length of all streams and total drainage area, the density value corresponds to the shape of a hydrograph); **hillslope Peclet number** Pe (a ratio between the characteristic advective time-scale and the characteristic diffusive time-scale (Berne et al., 2005), it provides estimation of the similarity between hillslopes with respect to the subsurface groundwater flow); **storm speed parameter** (proposed by Ogden et al. (1995). The parameter is obtained by dividing the product of U - the storm speed and t_e - the runoff plane kinematic time to equilibrium by Lp - the length of the runoff plane. It is of particular interest when

storm motions play a major role in catchment response and when spatial variability of runoff generation is concerned. The former situation has a strong impact on the shape of the hydrograph and the timing the peak.); ***G* parameter** (refer to (Gilfedder et al., 2003), a ratio between t_H - the time factors related to the lateral draining and t_V - the time factors related to the vertical filling of an aquifer. It integrates transmissivity, specific yield, recharge, length and head into one number in order to determine how well a system is likely to cope with a given rate of recharge without discharge to the surface. Hydrogeologically similar catchments in southern Australia were identified using this parameter to handle the dryland salinisation problem.);

2. in the form of **curves of distributions** such as a **hypsometric curve** (first introduced by (Langbein, 1947), an empirical cumulative height frequency curve for the Earth's surface or a catchment. The curve can be shown in non-dimensional or standardized form by scaling elevation and area by the maximum values. The non-dimensional hypsometric curve provides hydrologist and geomorphologist with a way to assess the similarity of catchments.); **topographic index curve** (the topographic index is conceptualized by (Kirkby, 1975). The index $(\alpha/tan\beta)$ is a ratio between α - the drained area per unit contour length and tanβ - the slope of the ground surface at the specific location. The locations with the same index value can respond in a hydrologically similar way.);
3. in the form of a **conceptual model** defined as a simplified schematic representation of the subsurface hydrological processes. An example is the HOST (Hydrology of Soil Types) classification system (Boorman et al., 1995) which has been used to group all UK soils into 29 classes and further regionalized a baseflow index;
4. in the form of a **mathematical model** which provides a direct link between structure and response behavior. An example is the study conducted by De Felice et al. (1993) who applied a simple conceptual model to classify catchments. The model uses a variation of the Thornthwaite-Mather method which represents the catchment as two reservoirs in series. His study clearly demonstrated one model parameter β (not fixed as a priori) could encompass the complex geological and morphological characteristics and differentiate catchments from low, medium to high permeability. Within each class, a surrogate value of β could be transfered to a catchment with similar geological and morphological features. The similar catchments identified by β is independent from climatic conditions.;
5. in other forms such as wavelet **spectral analysis**. Schaefli et al. (2006) has proposed a way to study hydrological landscape similarity by analysing spectral properties of observed hydrological time series. The information extracted from frequency domain can be considered as a signature of the catchment response. Prior to its application in hydrology, spectral analysis has been used in ecology for pattern description (Hill, 1973; Usher, 1975; Ripley, 1978).

Hydro-climatic similar regions

It is not only geographers who have used climate to divide similar regions, hydrologists have also attempted to apply climatic factors to catchment classification. Catchment

similarity can be defined based on climate due to the fact that climate has prevailing impact on catchment's hydrologic behaviour. Budyko (1974) proposed a climatic classification based on energy balance and described the climatic condition of each area with a 3-symbol combination (Court, 1976). Budyko's climatic classification is suitable on a large spatial scale as it is based on the balance in the long-term. The climatic dryness index defined as a ratio between average annual potential evaporation and average annual precipitation was used to classify arid regions of the world (UNESCO, 1979). It is only a rough division of regions based on water balance and cannot be used for practical purposes with respect to catchment response. To take into consideration of the seasonal variability, a combination of dimensionless variables including soil and climate properties are advanced by Woods (2006). He proposed three family indices to identify the dominant state of stored water including pore water, frozen water and open water, as the state of dominant storage impacts and is in turn affected by catchment processes and climatic conditions. The limitations to these indices lie in the heavy data demand of soil attributes and the simplifying assumptions the indices are based on.

2.1.3 LCC - What's to be done

A catchment is an indissoluble bond of landscape, soil, climate as well as human factors. No classification system so far has been designed with all possible characteristics of a catchment, whether it is in a form of hierarchy or a conceptual model. One catchment could be similar to another catchment in some properties, but not all properties. A hierarchical classification system analogous to the biological one is almost impossible as a catchment is such a vital entity, a symbiosis on a multidimensional scale that is more than an association of plants or animals.

It is meaningless to place a catchment in a class if it does not help to understand the one in question, bearing in mind that "a classification system should be designed for a clear and specific purpose". Nonetheless, a general-purpose hierarchy of catchments is the ultimate goal, regardless of its possibility. It could be used for pedagogical purposes to teach and pass the knowledge on as well as to make inductive generalization of a catchment with easy. McDonnell and Woods (2004) believe "a broad-scale catchment hydrology classification system would provide an important organizing principle, complementing the concept of the hydrological cycle and the principle of mass conservation".

A catchment classification system will not be absolute as more knowledge about the hydrological processes are understood. Any existing system will be subject to change.

Grigg (1965) makes pessimistic comment that "Even if (a system of hierarchy and classification) logically possible it is still a formidable task". The statement was perhaps valid in the "punch cards" era, today the reality is different. A distant goal can only be reached with many small and even trivial steps. Perhaps the proper manner to handle it, is to start

with the basic process components such as evapotranspiration and baseflow and move gradually to discharge which is the holistic composite response of all processes.

2.2 Statistical catchment classification (SCC)

Nature disguises itself by its diversity, however, it will not take long before we realize that "nature repeats itself similarly for the same configuration", Bárdossy (2003) Geo-statistics lecture note. The similar nature configuration has formed the bases for hydrological regionalization where similar catchments are taken to make inductive generalization of knowledge or information transmission about the other catchments not well documented.

In statistical theory, Gordon (1981) has interpreted classification as a collection of methods for the exploratory analysis of multivariate data. Statistical classification is by no means unique in the field of catchment hydrology, many other fields have explored it in much details. In geography, Grigg (1965) expressed his opinion with regards to the theory of numerical taxonomy "a return to the principles of classification put forward by Michael Adanson before Linnaean. He assumed that all characters are of equal weight and that affinity, the basis of grouping individuals into the same class, is a function of the proportion of features (properties or characters or elements) in common. There is no assumption made about origin." Ludwig and Reynolds (1988) defines statistical ecology as quantitative methodologies to explore patterns in biotic communities. A classification procedure can be viewed as a reduction of a data matrix of S rows (species) and N columns (SUs-sampling units of variables) into g groups ($g < N$), where the SUs within each of the g groups are more similar to each other than SUs between groups (Green, 1980).

Statistical catchment classification can facilitate extending frequency distribution from information rich to poor catchments (Riggs, 1973). The information refers to streamflow records in the past as well as non-stationary streamflow records in the future within the context of climate change. Transfering the parameters of a hydrological model at an ungauged site is similar to the problem of estimating a streamflow frequency distribution at an ungauged site (Vogel, 2005) and hence could be tackled by statistical catchment classification as well.

2.2.1 SCC - What's been done

Information is transfered within similar catchments which can be classified via the methods introduced in section 2.1. In addition, methods formulated by numerical clustering and regionalization are alternative solutions to information transfer.

Numerical clustering

Numerical clustering is a collection of statistical measures to account for the variability displayed in a data set. Pattern recognition is usually achieved by numerical clustering. From automated speech recognition, text categorization, DNA sequence identification, to catchment classification, numerical clustering has been successfully applied in various areas. Two approaches are commonly used in cluster analysis: (1) supervised and (2) unsupervised clustering. A few examples applied in fields relevant to hydrology are discussed below.

1) Supervised clustering

Supervised clustering, as its name implies, is a procedure under a specific guidance or supervision. The so called 'supervisors' or 'teachers' provide labeled samples as training sets. The 'students' evaluate the objects in the data sets on the basis of the labeled samples. The objects that demonstrate similar features as the training sets will be labeled the same category as the training sets provided by 'supervisors' or 'teachers'.

Supervised clustering is often used for spatial classification (e.g. land cover) from remotely sensed images. A standard procedure for land cover classification would start with a few selected training sets. They are the cells with given land cover types (provided by 'teachers'). Spectral signatures containing multivariate statistics of each cluster are then derived from these specified cells in the image. The cell to classify is assigned to the class with the maximum probability. This procedure is referred to as maximum likelihood. The resulted classification can be reliable if the training cells and the image are both relatively homogeneous (without many mixed cells) (Bárdossy and Samaniego, 2002). A large amount of literature on supervised land cover classification can be readily accessible. Other examples of spatial classification can be found in Fetterer et al. (1994) who assessed sea ice type maps from Alaska Synthetic Aperture Radar Facility imagery, Ustin et al. (2002) who mapped different plant species, and Bokuniewicz et al. (2003) who used a typological approach to identify locations prone to submarine groundwater discharge.

2) Unsupervised clustering

In contrary, unsupervised clustering has no explicit 'teacher' or 'supervisor'. According to Duda et al. (2000), unsupervised clustering is an attempt to categorize samples when all we have is a collection of them without being told their category. There are instances when unsupervised clustering is particularly useful. They are summarized after Duda et al. (2000):

- collecting and labeling a large set of sample patterns following supervised clustering procedure can be at times extremely costly and/or time consuming;

- if only a few particular groups of samples are of interest, there is no necessity to label all sample patterns (could be the case of data mining). Supervision is provided to label only the groups of interests;
- for patterns that have inherent temporal variation (patterns slowly change with time);
- to find patterns and sub-patterns we may otherwise ignore under a supervised mode, major departures from expected characteristics may suggest we alter our prior knowledge of particular features or patterns.

Three types of unsupervised methods are discussed below:

2.1) Hierarchical approach

A cluster of similar catchments consists of catchments with close distances. The distance is measured in the space of catchment characteristics with a specific distance metric such as Euclidean and Mahalanobis distances. In this sense, the location of a catchment is identified by its characteristics and the distance from one to another represents their hydrological similarity. Examples include Mosley (1981) and Gottschalk (1985) who identified hydrologically similar regions in New Zealand and Sweden respectively.

Correlation coefficient (see Equation 2.1) and Euclidean distance (see Equation 2.2) were used as distance metrics in Gottschalk (1985).

$$\rho_{jk} = \frac{\sum_{i=1}^{p}(x_{ij} - \overline{x}_{ij})(x_{ik} - \overline{x}_{ik})}{[\sum_{i=1}^{p}(x_{ij} - \overline{x}_{ij})^2 \sum_{i=1}^{p}(x_{ik} - \overline{x}_{ik})^2]^{\frac{1}{2}}} \tag{2.1}$$

$$d_{jk} = \frac{[\sum_{i=1}^{p}(x_{ij} - x_{ik})^2]^{\frac{1}{2}}}{p} \tag{2.2}$$

where: ρ_{jk} = correlation coefficient between catchment *j* and *k*
d_{jk} = Euclidean distance between catchment *j* and *k*
i = index number of the catchment descriptor (*i=1,. . .,p*)
x = catchment descriptor

Catchment pair *j* and *k* can be put in one cluster if the distance metric (e.g. ρ_{jk}) is the highest among all pairs and considered as one element in the next step. Recalculation of clusters can be performed again and new clusters can be identified. The procedure continues till all clusters are put together. To treat a cluster of catchments as one element, Gottschalk (1985) used arithmetic averaging. A common way of displaying the results of clustering

is to construct a dendrogram. A dendrogram is a tree-looking diagram to illustrate the arrangement of clusters from the lowest to the highest level.

2.2) Data partitioning or K-means

Burn and Boorman (1992) applied K-means algorithm to divide catchments in the UK into K clusters based on their characteristics. The objective is to minimize the variability in K clusters expressed in Equation 2.3.

$$O_K = \sum_{k=1}^{K} \sum_{i=1}^{I} \sum_{m=1}^{M} w_m (x_{mi} - C_{mk})^2 \tag{2.3}$$

where:
O_K = objective function
w_m = weight assigned to each catchment descriptor
k = index number of the cluster (k=1,. . .,K)
i = index number of the catchment (i=1,. . .,I)
m = index number of the catchment descriptor (m=1,. . .,M)
x = catchment descriptor
C = centroid coordinate for the catchment descriptor m within the cluster k

The K-means algorithm involves three subjective judgments with respect to (1) the identification of global minima, (2) determination of an appropriate number of clusters, and (3) selection of catchment descriptors and associated weights (Burn and Boorman, 1992).

2.3) Hybrid clustering

Rao and Srinivas (2006b) tested three hybrid clustering algorithms for estimation of regional flood frequency. The clusters are initially established by hierarchical clustering using single linkage, complete linkage and Ward's algorithm. These clusters are further refined by using the K-means algorithm. The overall performance of the three hybrid algorithms was found to be better than either the hierarchical clustering or the K-means used alone. The combination of Ward's algorithm and K-means was reported to consistently provide good initial estimates of groups of catchments with similar flood responses. Rao and Srinivas (2006b) noted in the conclusion of his study that hierarchical clustering may not always be the best option to initialize K-means algorithm. He also pointed out non-stationarity present in hydrologic time series has made regional flood frequency estimation more complex and uncertain.

The clustering methods mentioned above all assume objects can be divided into 'non-overlapping clusters with well-defined boundaries between them' (Rao and Srinivas,

2006a). They are usually referred to as 'hard' classification because they do not allow any degree of ambiguity. It is often the case that one object may partially belong to more than one clusters with a certain degree of membership or probability. As a consequence of a vague boundary and a degree of membership, the fuzzy set theory (Zadeh, 1965) provides an option to define a 'soft' classifier that can be flexible to cope with 'ambiguity'. A large amount of fuzzy classification studies can be found in literature. Their major differences lie in the way 'they handle the data in the training and validating stages as well as the algorithms employed for the allocation phase' (Bárdossy and Samaniego, 2002).

Numerical clustering, as described above, is one way to approach pattern recognition and feature classification. Almost all clustering methods are distance based. An important issue is therefore the selection of a proper metric or distance measure. Worth also noting here is that a 'hard' homogeneous region is one that all individuals are similar and contiguous, while a 'soft' one based on fuzzy set theory can encompass individuals belonging to the region with a degree of membership. Homogeneous regions can be identified and hydrological responses are assumed to be more similar among the catchments within the region than similar to another catchment outside the region. Physiographic characteristics are often used as catchments' attributes to form regions of similar catchments, however, that similarity does not necessarily result in similar catchments' response, which was argued by Burn (1997) with regards to regional flood frequency analysis. Climatic attributes should not be neglected in forming a region of similar flood response. The representativeness of the resulted homogeneous region is highly dependent on the selection of meaningful catchment characteristics.

Parametric regional analysis

In hydrology, the procedure of transferring information in space (catchment-wise) is usually regarded as regional analysis (Riggs, 1973). It is clear that numerical clustering discussed above can be used for regional analysis, although identification of a homogeneous region isn't an easy task. Being an alternative solution to remediate the situation of missing streamflow data, parametric regional approaches have been thought of to transfer model variables from gauged to ungauged catchments. Parametric regional approaches, unlike numerical clustering, relate model variables to catchment characteristics with a or a few parametric function(s).

An early regional study was conducted by (Nash, 1960). Two parameter values of the instantaneous unit hydrograph (Nash, 1957) were estimated for an ungauged catchment by using regressional relationship obtained from 60 other gauged catchments in the UK. The parameters were expressed as linear functions of a number of topographic characteristics such as catchment area and slope and length and slope of the main channel. His results were not encouraging as the streamflow prediction at the ungauged catchment was rather poor. In contrary, James (1972) demonstrated significant correlations between certain model parameters and basin characteristics using the Kentucky Fortran Version of the Stanford

Watershed Model IV (Crawford and Linsley, 1966). He further proposed a similar linear regression based approach to be used on an ungauged catchment, that is to relate the values of parameters to measurable catchment characteristics with a regression function. In his study, however, he did not engage in predicting streamflow using the parameters assessed from the regressions. A similar study was performed earlier by Ross (1970) who estimated a number of parameters of the Stanford Watershed Model using catchment characteristics. Along the same line, Manley (1978) opted for the physically based 17-parameter HYSIM model to simulate flows in the ungauged catchments of the Severn River basin. He favored a physically based model for prediction in ungauged basins over the conceptual models due to the fact that "most of the (HYSIM model) parameters were based on field observations, or could be related to field observation". In addition to the ability to model an ungauged basin, he also argued that a physically based model is able to (i) use climate data to simulate events which are more extreme than those in the flow records on which the model is calibrated, provided the dominant hydrological processes are realistically defined; (ii) utilize data on basin type and topography to fix many of the parameters; and (iii) produce good starting estimates for the calibration process, if values of the parameters can be obtained from field measurements. Manley (1978) worked with a great deal of energy and determination although the time and cost invested are unproportional to the outcome and hence far from practical.

Regardless of physically based or conceptual models, the essence of a regional approach is premised on the deterministic relationship between model parameters and catchment characteristics in a certain region (James, 1972). The same applies to regional streamflow distribution as it is believed that distribution function is closely related to the catchment characteristics such as size, topography, surficial geology and climate (Riggs, 1973).

Regional analysis of streamflow can be implemented in two different regression-based procedures. The first one is used to estimate discharge with a certain return interval Q_T. It is calculated by a product of the catchment characteristics to a certain extent expressed by their power functions.

$$Q_T = a_0 \cdot C_1^{a_1} \cdot C_2^{a_2} \cdots C_n^{a_n} \tag{2.4}$$

$$log(Q_T) = log(a_0) + a_1 log(C_1) + a_2 log(C_2) + \cdots + a_n log(C_n) \tag{2.5}$$

where: $a_0 \cdots a_n$ = regression coefficients
$C_1 \cdots C_n$ = catchment characteristics

An early application of this procedure can be found from Benson (1962, 1964). A very comprehensive study on different regions across the US was performed by Thomas and Benson (1970). Over 20 catchment characteristics were considered to regionalize high,

medium and low flows. Results of the regression analyses indicate that streamflow can be defined more accurately in the humid Eastern and Southern regions than in the more arid Western and Central regions, that medium flows can be more accurately defined than high flows, and that low flows can be only weakly defined. Standard deviations of monthly and annual flows were found to be significantly related to catchment characteristics (Thomas and Benson, 1970).

The relevant catchment characteristics need to be selected according to their significance relevant to the flow characteristics (Riggs, 1973). Riggs (1973) collected 10 published regional flood frequency regressions and found that 4 catchment characteristics were the most commonly used ones, namely, (1) **drainage area** (10/10 times), (2) **main-channel slope** (5/10 times), (3) **percentage of basin area covered by lakes and swamps** (5/10 times) and (4) **mean annual precipitation** (4/10 times). The characteristics that were used in two out of the 10 studies of regional flood frequency are **T-year 24-hour rainfall**, **elevation**, **number of thunderstorm days** and **geographical factor**. The characteristics that appeared in only one study are **mean annual runoff**, **average degrees below freezing in January**, **orographic factor**, **main channel length**, **ratio of runoff to precipitation**, **mean annual snowfall**, **average number of wet days per year** and **shape factor**. All these catchment characteristics are, to some extent, "crude indices" and should be selected on the basis of prior knowledge or the system (Riggs, 1973). It is perhaps more appropriate to call the catchment characteristics as catchment descriptors (CDs). Pandey and Nguyen (1999) provides a comparative study on nine parameter estimation methods including *ordinary least square*, *weighted least squares using variance as weight*, *weighted least squares using Taster's weight*, *least absolute value regression*, *robust regression*, *generalized least squares*, *nonlinear optimization minimizing the sum of the squared errors*, *nonlinear optimization minimizing the relative errors* and *nonlinear optimization minimizing the least absolute deviations*.

The first procedure is of little interest since only a limited number of Q_T can be estimated. In many cases, a regional peak flow frequency curve is needed. The second procedure is established to estimate the parameters of a pre-defined distribution curve (mean and variance for a 2-parameter distribution and skewness in addition for a 3-parameter distribution to specify the location, scale and shape of a curve). The same catchment characteristics are used to formulate the regression function of the two or three distribution function parameters. A flow frequency curve can be obtained in this way.

Either with frequency study or prediction of streamflow, application of regional analysis to low flow was reported as least successful (Riggs, 1973). He suspected it is due to the greater dependence of low flows on catchment characteristics that are imperfectly known and that cannot be described by simple indices.

All methods so far have attempted to figure out this relationship no matter how it is formulated, physically or conceptually, and in a linear or non-linear form. It is interesting to see that the focus has never been shifted from what James (1972) pointed out: "The

question of how to interpret the relation between characteristics and parameters to estimate parameter values for the larger watershed is left open by this research design." Section 2.2.2 provides a brief review on many studies recently conducted following this direction.

2.2.2 SCC - What's being done

A large number of regional studies have been undertaken since 1970's and numbers have been on the rise in the last decade due to the increasing demand to estimate the impact of rapid climate and land use change. The reviewed studies below are arranged by the year of publication. Many interesting studies could not be reviewed here due to their unavailability or inaccessibility to the author, e.g. material published in languages outside the author's linguistic competence.

Abdulla and Lettenmaier (1997a,b): VIC-2L - a two-layer Variable Infiltration Capacity land surface hydrologic model for prediction of monthly discharge, 40 catchments ranging from 160 to 7000 km^2 distributed throughout the Arkansas–Red River basin of the south central U.S. Values of nine model parameters were first obtained by using two optimization methods. These optimal parameter values were then related to 10 distributed land surface characteristics and 12 meteorological variables. The method was tested by comparing simulations using the regional (regression equation) parameters for six catchments not in the parameter estimation set. The model performance using the regional parameters was good for most of the calibration and validation catchments, which were humid and semi-humid. The model did not perform as well for the arid to semi-arid catchments. A grid network version of the VIC-2L model was used in the second study to simulate monthly flow. In the first application, gridded parameter fields were linearly interpolated from locally estimated parameters at a set of the same 40 catchments. In the second application, the model was run using the parameters transferred to the large area grid from the gaged catchments via regression of the locally estimated parameters on catchment soils, topographic and climatological characteristics. Generally, the simulations based on the regional regression transfer scheme performed significantly better than those based on the interpolated parameters. However, the predicted actual evapotranspiration and its seasonal cycle were relatively insensitive to the regional parameter estimation schemes.

Post and Jakeman (1999): IHACRES - a lumped conceptual rainfall-runoff model, based on unit hydrograph principles (Jakeman et al., 1990). for prediction of daily discharge, 16 small (less than 1 km^2) catchments in the Maroondah region of Victoria, Australia. Six catchment descriptors were found to be important in defining catchment hydrologic response. They are area, drainage density, elongation, gradient of the channel, slope and wetted area. The model was calibrated first. Afterwards, six most appropriate regression functions were obtained to quantify the relationships and predict the daily streamflow of each catchment, as if it were ungauged for streamflow. The most appropriate regression functions were searched by trial and error from combinations of different catchment descriptors and

function forms such as square root, square, *ln*, and inverse transformations. Some of the relationships between the model parameters and landscape attributes are well defined, while others are poor (R^2 ranges from 0.37 to 0.94). As a result, the predictions of daily streamflow also vary in quality. Improvement of these results can be obtained through better understanding of the controls on hydrologic response as well as inclusion of a large number of catchments representing a broad range of features.

Seibert (1999): HBV model for prediction of daily discharge, 11 catchments ranging from 7 to 950 km^2 located in the NOPEX area in central Sweden. A fuzzy measure, which allowed to combine different objective functions, was used to determine optimised parameter sets. Four widely available characteristics are selected, namely, drainage area (km^2), forest area (%), area of field or meadow (%) and lake area (%). Four different two-parametric regression functions (linear, exponential, power and log) were fitted to the relationships. 6 out of 13 model parameters could be well related to catchment descriptors. Some relationships that had been expected were found only partly or contrary. Loose or unexpected relationships could be partly explained by parameter uncertainty due to interrelations between model parameters. This is the so called "equifinality" problem that complicates the regionalisation of model parameters because optimised parameter values may vary by chance between a range of values. Reduction of uncertainty could potentially improve the relationships. One method was proposed to reduce parameter uncertainty is to include additional data beyond observed runoff into the calibration procedure.

Merz and Bloeschl (2004): 11-parameter lumped conceptual model for prediction of daily flows, 308 Austrian catchments ranging from 3 to 5000 km^2. The model is calibrated using a 5-term compound objective function. Afterwards, a linear regression function is obtained for each parameter and catchment descriptor. Using the preset or globally averaged parameters produces the worse regionalization results. Using multiple regressions improves the results, which suggests catchment descriptors do contain valuable information, in particular, spatial variability, that can be used to improve parameter estimates (with median Nash-Sutcliffe efficiency of 0.53 for both calibration and validation using optimised local regression). However, they note that there is no tight relationship between the parameters and any of the descriptors and the underlying hydrological relationship seems to be weak (the coefficients of determination R^2 is only up to 0.27, most of them are less than 0.10). Using the averaged parameter values of immediate upstream and downstream (nested) neighbors performs best (with median Nash-Sutcliffe efficiency of 0.57 for calibration and 0.56 for validation). In addition, they tested kriging methods which perform slightly poorer than the averaging method using immediate neighbors. They further conclude that catchment descriptors are not representative of the real physical controls on the water balance dynamics, instead, spatial proximity may be a good surrogate. In general, the relatively low Nash-Sutcliffe model efficiency could due to some low-quality data and insufficiently optimised model structures for individual catchments.

Many more regional studies with varying success and experiences have been reported,

including: **Servat and Dezetter (1993)** developed multiple non-linear regression equations for two models to assess daily flow in 20 catchments in the northwestern Ivory Coast; **Sefton and Howarth (1998)** calibrated IHACRES model on 60 catchments in England and Wales, and then related a set of dynamic response characteristics (DRCs) to physical catchment descriptors (PCDs) indices (topography, soil type, climate and land cover); **Xu (1999)** performed a regional study with multiple linear regression using MWB-6 (Xu et al., 1996) (a monthly water and snow balance model) on 26 Swedish and 24 Belgian catchments.

The regional studies mentioned above all follow a two-step procedure, that is to calibrate the hydrological model and obtain optimal parameter values in the first step and formulate the regression functions between catchment descriptors and model parameters and obtain the relationship in the second step. They all focus upon selection of an appropriate objective function, an efficient optimization procedure as well as a suitable regression form. Gradually, the focus has shifted and a one-step multiple regression approach has evolved. The one-step multiple regression approach acknowledges the fact that many equally good parameter sets lead to equivalent model performance and therefore does not separate the two steps of model calibration and multiple regression. It can help reduce the number of feasible parameter space and hence strengthen the relationships. The one-step approach is made possible thanks to rapid development in computing.

Fernandez et al. (2000): abcd model - a 4-parameter monthly water balance model, 33 catchments in the Southeastern US ranging from 155 to 39847 km^2. The model performance is evaluated with the objective function described in Equation 2.6. The model is not calibrated independently from the catchment descriptors but with an integrated objective function (see Equation 2.7) simultaneously taking into consideration of both the performance of the multiple regression and the predicted discharge.

$$R_i^2 = \sum_{t=1}^{n} (ln(Q_t) - ln(\hat{Q}_t))^2 \tag{2.6}$$

$$O_F = \frac{1}{N} \sum_{i=1}^{N} R_i^2 + \frac{1}{4}(R_a^2 + R_b^2 + R_c^2 + R_d^2) \tag{2.7}$$

where:

O_F	=	objective function
i	=	index number of a catchment, *i=1,. . .,N*
R_x^2	=	coefficient of determination of the regression function of the model parameter *a,b,c,d*
R_i^2	=	a measure of goodness of fit
t	=	time step, *t=1,. . .,n*
Q_t	=	observed discharge at time step *t*
$\hat{Q}_t$	=	modeled discharge at time step *t*

The generalized reduced gradient nonlinear algorithm is used to optimize $30 \times 4 = 120$ variables (30 catchments used for calibration). The regression relationships are found to be nearly perfect. These optimized relationships are tested with 3 other catchments. The results do not show any improvement from the traditional 2-step approach. The loss of model performance from calibration to validation catchments with the proposed one-step approach is almost the same as with the two-step approach. It must be pointed out that their study uses several catchment descriptors which require analysis of discharge data. The study is intended on formulation of the one-step approach but not its implementation at ungauged catchments. Based on these results, they believe multivariate regression analysis is not able to uncover basic physical laws and therefore regional studies will not advance unless the basic relationships between catchment characteristics and model parameters are formulated correctly. They also point out one way to tighten the relationships is to reduce model uncertainty and very broad feasible parameter space.

Hundecha and Bárdossy (2004): HBV-IWS model, 45 catchments selected from the Rhine River Basin ranging from 400 to 2100 km^2. An aggregated objective function is established to maximize the model performance in the form of the Nash-Suctliffe efficiency coefficient (see Equation 2.8) for all catchments and punish the individual catchment with the worst model performance (see Equation 2.9).

$$R_i^2 = 1 - \frac{\sum_{t=1}^{n} Q_t(\hat{Q}_t - (Q_t))^2}{\sum_{t=1}^{n} Q_t(\hat{Q}_t - (\overline{Q}))^2} \tag{2.8}$$

$$O_H = \sum_{i=1}^{N} R_i^2 + N \cdot min(R_i^2) \tag{2.9}$$

where:
- O_H = objective function
- i = index number of a catchment, *i=1,. . .,N*
- R_i^2 = the weighted (using observed discharge) Nach-Sutcliffe coefficient for catchment *i*
- t = time step, *t=1,. . .,n*
- Q_t = observed discharge at time step *t*
- $\overline{Q}$ = the mean observed discharge
- $\hat{Q}_t$ = modeled discharge at time step *t*

Soil properties and land use are related to the model parameters according to their relevance to the processes of runoff generation and runoff response. Instead of calibrating the model parameters, the linear coefficients relating the model parameters and catchment descriptors are calibrated. In comparison with the number of variables in search to maximize O_F for the same number of model parameters, this study requires to search less number of variables to maximize O_H. The generalized reduced gradient nonlinear algorithm is used

to find the optimal solution. In this way, the regional study can be performed in one step. The relationships established with 30 catchments are tested with up to 15 other catchments. Most of them obtain a Nash-Suctliffe efficiency above 0.8. With these relationships, the method is further implemented to study the impact on streamflow under three different future land use scenarios.

The choice of using the two-step or one-step approach is very much dependent on the perspectives of the modeler, although one-step approach appears to be more straightforward. The two-step approach allows careful selection of different forms of multiple regression and related model parameters with less computing burden. More studies in various regions and with a broad range of models using the one-step approach would be needed to compare its performance with the two-step one.

Based on the specific application and spatial and temporal resolutions required, regression-based regional analysis can be directly applied to model runoff processes with a simple parametric model. Similar to the formulation mentioned earlier in subsection 2.2.1 (refer to Equation 2.4), Samaniego (2003) tested and selected best models for modelling the long-term mean of the annual specific discharge. The same formulation of models were also applied to study the impact of changed land use and climatic variables such as precipitation, seasonal mean temperature on annual and seasonal specific discharges. Two other formulations of models were also tested. They are linear and non-linear (multiplication of a power function) descendants of the generalized form presented by Samaniego (2003) that was developed based on formal work of Chow (1974); Rodriguez-Iturbe (1969); Raudkivi (1979); Clarke (1994); Abdulla and Lettenmaier (1997b).

$$Q_i^t = \beta_0 \prod_j \left(x_{ij}^t\right)^{\beta_j} + \epsilon_i^t \tag{2.10}$$

where:
- Q_i^t = the specific discharge for the ith spatial unit and time duration t
- i = index number of the spatial unit, *i=1,. . .,n*
- j = index number of the input variable, *j=1,. . .,J*
- t = index number of the time duration, *t=1,. . .,T*
- x_{ij}^t = physiographic and climatic characteristics of the spatial unit i during the time period t
- β = model parameters to be estimated
- ϵ = error term independent from the variables

2.2.3 SCC - What's to be done

The multiple regression regional analysis is just coming into bloom, nevertheless, some people have doubted how long the bloom would really last and if at all it would actu-

ally come into bloom. Kuczera and Mroczkowski (1998) believed that "poor parameter identifiability may result in considerable uncertainty in the prediction of fluxes including the streamflow flux used in calibration and, perhaps more importantly, virtually makes impossible attempts to regionalize model parameters for the purpose of application to ungauged catchments." Merz and Bloeschl (2004) came to the conclusion that "there is no tight relationship between the (model) parameters and any of the (catchment) attributes." McIntyre et al. (2005) admited "that regression has proven to be a useful tool for making predictions of runoff in ungauged catchments", but pointed out "that the need to neglect or greatly simplify the interdependencies between model parameters and the neglect of errors in the catchment descriptors, leads to the view that further effort at refining the application of regression techniques may not be the optimum way forward."

Despite the problems of parameter interdependencies and input errors, a regression function pre-defined between model parameters and catchment descriptors is usually subjective and arbitrary. One can also argue that a priori function is neither able to represent the highly complex hydrological processes nor consider the interdependences amongst model parameters. Nevertheless, regression-based methods will still play important rolls in the future because a regression function can help to understand and quantify the relationship between model parameters/streamflow and catchment descriptors. Even if relationships between catchment characteristics and model parameters will not lead to the best predictions in ungauged basins, studies of these relationships still are of value as a means to improve the physical basis of conceptual models (Seibert, 1999). Alternatives to regression type methods are already "on the road" and yet to become as popular as the former type.

Canonical correlation analysis

Hundecha et al. (2007) has tested a new approach based on the former work of (Ouarda et al., 2001) and (Hundecha and Bárdossy, 2004) where the relationships between catchment descriptors and model parameters are not defined with multiple regression functions but a linear canonical correlation (see Equation 2.11 and Equation 2.12).

$$V = \sum_{i=1}^{n} a_i X_i = a'X \tag{2.11}$$

$$W = \sum_{j=1}^{r} b_j Y_j = b'Y \tag{2.12}$$

where: V = canonical variable
W = canonical variable
X = catchment physiographic-climatic descriptors (*i=1,. . .,n*)
Y = model parameters (*j=1,. . .,r*)
a = linear coefficient vector
b = linear coefficient vector

Vectors *a* and *b* can be identified by performing a canonical correlation analysis to obtain maximum correlation coefficients between *V* and *W*. Catchment descriptors *X* are replaced by canonical variable *V*. Catchment locations can be identified with their canonical coordinates *a*. The spatial structure of the model parameters is considered in the canonical space. The model parameter values are optimized with a parametric and a non-parametric approach. The parametric approach assumes *a priori* spatial structure of each parameter with a predefined variogram and the model is optimized such that the objective function O_H (see Equation 2.9) is maximized and the variograms are best fitted. In contrary, the non-parametric approach does not assume any variograms functions. In addition to maximize the O_H, Lipschitz and monotonic conditions are imposed on each parameter. In other words, the objective is not only to maximize the model performance but also require that model parameters display similar values if the catchments are close to each other (Lipschitz condition) and the difference in parameter values increases as the distance between the catchments increases (monotonic condition). The distance in this context is a Euclidean distance measured in the canonical space. The theoretical variogram for each parameter is manually fitted to the experimental variogram obtained after the non-parametric optimization. Both approaches obtained improved results reported in Hundecha and Bárdossy (2004). Canonical correlation analysis has its limitation in that it only accounts for a linear transformation.

Ensemble predictions of runoff in ungauged catchments

McIntyre et al. (2005) treats the relationships between catchment descriptors and model parameters as a response surface of likelihood. Discharge at an ungauged catchment can be estimated using a weighted average expressed in Equation 2.13 and Equation 2.14. An explicit assumption in the ensemble predictions lies in a Gaussian-type noise, in other words, each individual prediction shall be independent so that the structural errors can be averaged out. This would require a large number of model simulations with different model structures and parameter values.

$$\overline{Q}(t) = \sum_{j=1}^{S} \sum_{i=1}^{N} Q_{i,j}(t) \times W_{i,j} \tag{2.13}$$

$$W_{i,j} = \frac{P_{i,j} B_j}{\sum_{j=1}^{S} \sum_{p=1}^{Pa} P_{p,j} B_j} \tag{2.14}$$

where:

$\overline{Q}(t)$	=	predicted discharge at the ungauged catchment
i	=	the index number of the candidate model, (*i=1,. . .,N*)
j	=	the index number of the donor catchment, (*j=1,. . .,S*)
p	=	the index number of the parameter set, (*p=1,. . .,Pa*)
$Q_{i,j}(t)$	=	discharge obtained from the *i*th candidate model and the *j*th gauged donor catchment
$W_{i,j}$	=	posterior likelihood given to the *i*th candidate model originating from the *j*th gauged donor catchment, $\sum W = 1$
$P_{p,j}$	=	likelihood of the *p*th parameter set using a candidate model for the *j*th gauged donor catchment
B_j	=	likelihood of the model used for the *j*th gauged donor catchment being applicable to the target catchment (a measure of similarity between the two catchments)

Catchment pooling

Catchment pooling, as its name implies, collects catchments on the basis of their hydrological similarity. Examples of this approach include the 'region of influence' (ROI) approach (Burn, 1990), hybrid-cluster analysis (Rao and Srinivas, 2006b), fuzzy-cluster analysis (Rao and Srinivas, 2006a), and site-similarity approach (Kay et al., 2006).

Local variance reduction

Bárdossy et al. (2005) proposed application of a local variance reduction method to regional streamflow prediction. The method assumes that a distance defined on the space of catchment descriptors can be used to find a most similar observed case. The subset of independent catchment response of the most similar case can be used for prediction. It was along the same line of thought, Bárdossy (2007) suggests further research be extended to model parameters to understand why some catchments show a similar behavior by sharing good parameter sets for a given rainfall-runoff model. He also suggests further investigation on the questions to what extent the similar behavior depends on (1) the model and (2) the catchment characteristics. His suggestions lead to the endeavors read in this undertaking.

Closing remark

Methods reviewed in section 2.1 are not completely independent from the methods reviewed in section 2.2, although two types of methods have considerably different bases and serve different purposes. The two might potentially compensate each other and formulate a hybrid catchment classification scheme, in other words, they are complementary and not mutually exclusive. The procedures in looking for criteria of hydrological similarity will

certainly lead to prolific understanding of the complicated hydrological processes.

Catchment classification is, to some extent, a controversial subject. In part, controversy reflects differences in the purposes for which catchment classifications are made and differences in concepts of hydrology as a scientific discipline. Hydrology is fragmented amongst a broad variety of professions ranging from civil engineers, geographers, soil scientists, ecologists, geologists, meteorologists to hillslop hydrologists and statistical hydrologists. We cannot say that one catchment classification scheme is better than another without reference to the purposes for which both were made. Comparisons of the merits of various schemes made for different purposes can be useless. When many different disciplines claim hydrology, it will become almost impossible to reach a general-purpose catchment classification scheme. In this case, a venn diagram could be drawn to show the various interests of different disciplines, only the region of a common interest, if there is any, could be the basis to design a general-purpose classification scheme. In any case, the system of classification needs to be devised with a specific purpose in mind (Grigg, 1965). A more coordinated and harmonized approach is desired to replace the generally existing "piecemeal" approach to cope with the "formidable" task of catchment classification.

James (1972) has encouraged the followers by saying "For the moment, this is a dream. The reality will be realized as the research continues". And it is worth noting Samuel Taylor Coleridge, English poet, critic and philosopher, who wrote in *The Friend* (1828): "The dwarf sees farther than the giant, when he has the giant's shoulder to mount on.", as the mere intension of the text in this Chapter.

3 The study area

This work aims at development of a non-parametric catchment classification scheme as well as its application in regional catchment hydrology. It is therefore worthwhile to select as many catchments as possible, and at the mean time, these catchments should be well documented with respect to their catchment properties. To this end, a total of 27 catchments are selected from the Rhine River basin.

3.1 Study domain

The Rhine River is one of the principal rivers of Europe. It is approximately 1,320 kilometers long. It starts in the Swiss Alps and flows generally north, passing through Switzerland, Liechtenstein, Austria, Germany, France, and the Netherlands before emptying into the North Sea. Its important tributaries are the Aare, Neckar, Main, Moselle, and Ruhr rivers.

The study area covers the entire German section of the Rhine River Basin with 12 sub-basins situated between downstream of Maxau (end of the Upper Rhine) and upstream of Lobith (start of the Lower Rhine) of the Rhine River Basin (see Figure 3.1). These 12 sub-basins are further divided into 101 meso-scale catchments. These catchments are the major hydrological input units of the rainfall runoff models in this study. Table 3.1 lists the sub-basins, their sizes and catchments. The upper, middle and lower Middle Rhine sub-basins are refered to as UMR, MMR and LMR respectively.

3.2 Catchments selected for calibration and validation

To cover a variety of catchment characteristics, 22 catchments are selected from different parts of the Rhine basin and served as calibration catchments. These 22 catchments do not have any inflow from neighboring catchments. They are chosen in such a way that the uncertainty incurred by inaccurate data and influence of neighboring catchments are minimized. It is also to avoid errors caused by channel routing. Table 3.2 lists the catchments for calibration and their characteristics which include areas of six soil classes and four land covers, annual mean temperature and precipitation for the time period between 1980 and 1988, slope and shape. The catchment characteristics are compiled from the data described

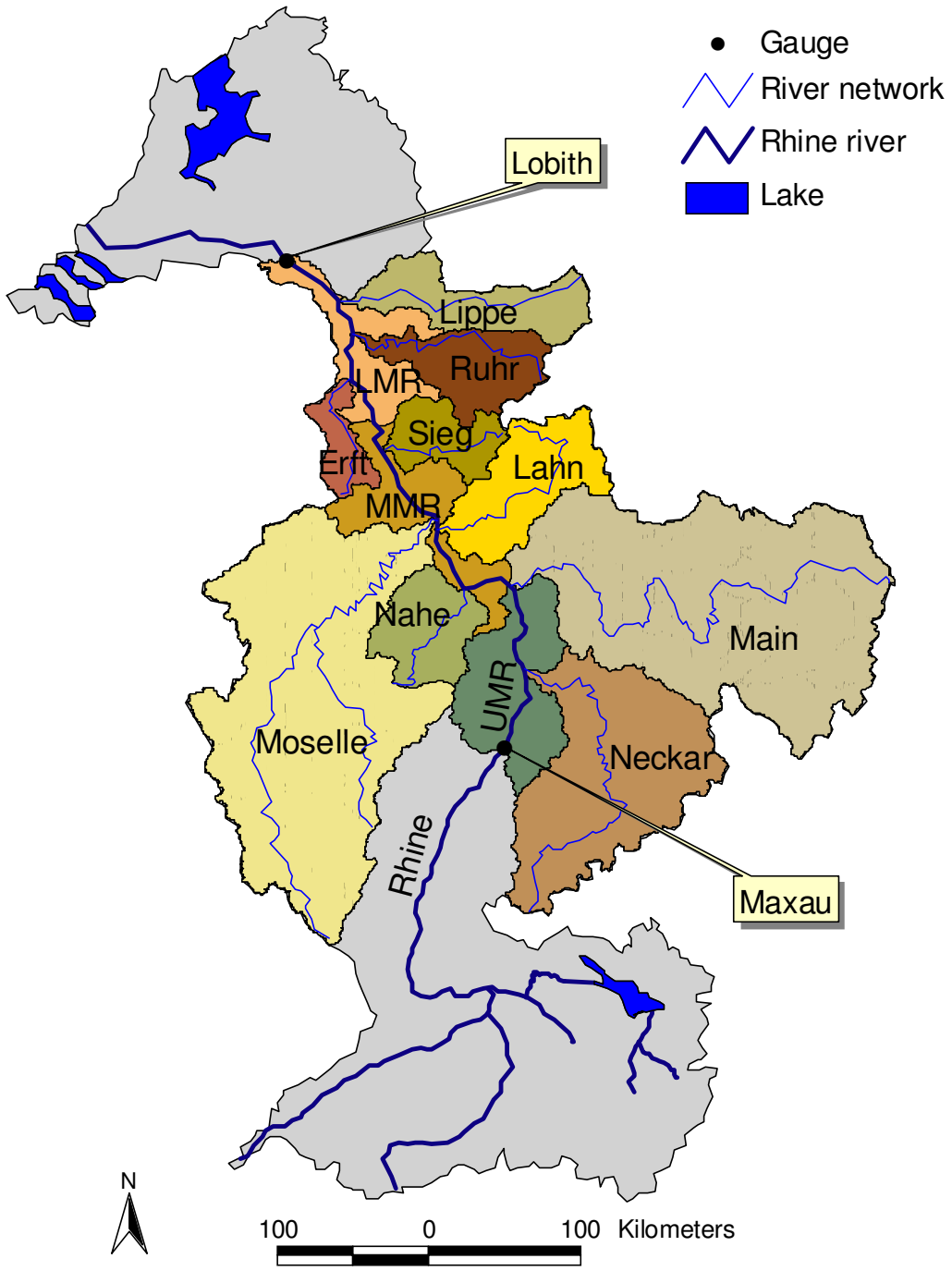

Figure 3.1: The study area covers 12 sub-basins of the Rhine River Basin located between Maxau and Lobith

Table 3.1: The major Rhine sub-basins and number of catchments within the study area

Sub-basins	Size (km^2)	Number of catchments
Neckar	13953	13
Main	27211	16
Sieg	2861	4
Lippe	4882	3
Lahn	5939	5
Ruhr	4487	4
Moselle	28152	26
Nahe	4010	3
Erft	1818	3
UMR	6688	7
MMR	5089	10
LMR	4240	7

in section 3.3

To validate the catchment classification scheme set up in this study, five other headwater catchments are chosen for validation (see Table 3.3). Figure 3.2 illustrates the location of the calibration and validation catchments.

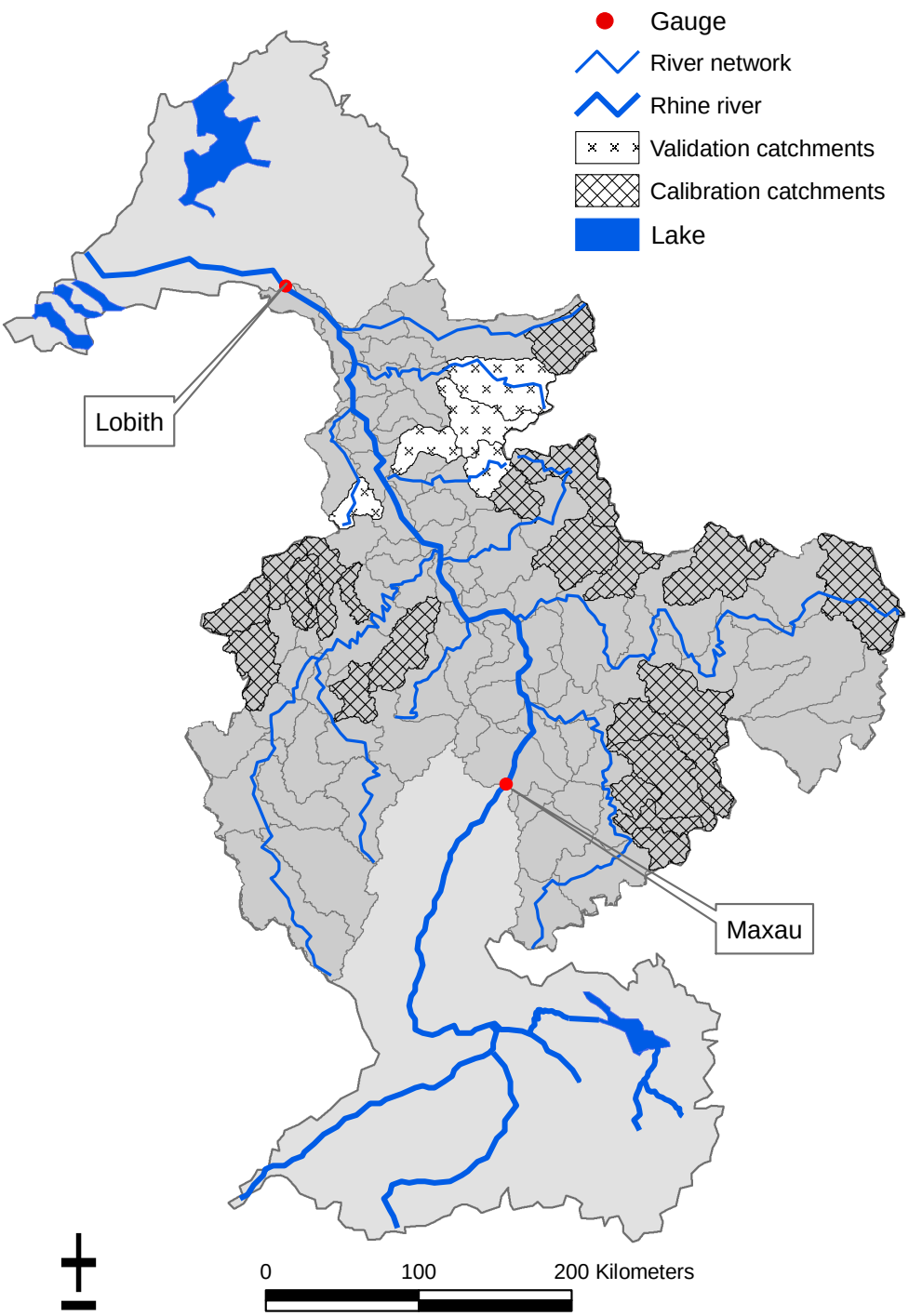

Figure 3.2: 22 headwater catchments selected for calibration and 5 other headwater catchments selected for validation

Table 3.2: List of the catchments for calibration and their basic characteristics

Index	Sub-Basin	Gauge	Drainage Area [km^2]	Lithosol [km^2]	Ranker [km^2]	Gleysol [km^2]	Cambisol [km^2]	Luvisol [km^2]	Podzol [km^2]
1	Neckar	Plochingen (Fils)	706	25.56	0.00	115.00	417.42	148.02	0.00
2		Neustadt (Rems)	581	0.00	0.00	24.66	510.96	45.38	0.00
3		Pforzheim (Enz)	1477	8.08	0.00	371.78	656.67	403.09	37.38
4		Stein (Kocher)	1957	1.48	0.00	249.62	1424.71	279.22	1.97
5		Untergrisheim (Jagst)	1836	1.02	0.00	825.61	857.86	119.77	31.73
6	Main	Schwürbitz	2426	26.11	0.00	254.05	1453.99	119.49	572.36
7		Wolfsmünster (Fränkishe Saale)	2131	0.00	0.00	371.85	1271.54	449.35	38.26
8		Waldenhausen (Tauber)	1810	0.00	0.00	910.89	377.90	473.11	48.10
9		Hanau (Kinzig)	921	37.49	23.30	56.74	528.89	274.58	0.00
10		Bad Viebel (Nidda)	1619	153.49	93.86	122.21	666.76	582.68	0.00
11	Lahn	Marburg	1666	103.24	80.97	0.00	1055.67	368.42	57.69
12		Asslar (Dill)	717	0.00	0.00	0.00	606.61	44.56	65.83
13	Mosel	Ettelbruck	1198	46.00	0.00	1.00	353.00	798.00	0.00
14		Michelau (Sauer)	933	0.00	0.00	0.00	933.00	0.00	0.00
15		Gemünd (Our)	596	0.00	1.00	0.00	550.00	0.00	45.00
16		Prümzurlay (Prüm)	600	0.00	32.00	4.00	446.00	49.00	69.00
17		Alsdorf-Oberecken (Nims)	240	0.00	0.00	39.00	171.00	2.00	28.00
18		Nalback (Prims)	734	16.00	31.00	0.00	587.00	0.00	100.00
19		Kordel (Kyll)	804	0.00	1.50	48.00	587.00	105.00	62.00
20		Platten (Lieser)	373	0.00	12.00	0.00	361.00	0.00	0.00
21	Lippe	Lippstadt	1394	70.99	41.31	458.66	398.30	327.32	97.43
22	Nahe	Martinstein	1435	0.00	108.00	0.00	1179.00	39.00	109.00

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Index	Sub-Basin	Gauge	Annual Mean Precipitation [mm]	Annual Mean Temperature [°C]	Slope [-]	Shape (l^2/Size) [-]	Forest [km^2]	Urban [km^2]	Agri-cultural [km^2]	Water bodies [km^2]
1	Neckar	Plochingen (Fils)	2.83	8.96	1.84	2.20	265.31	114.33	325.03	1.16
2		Neustadt (Rems)	2.69	9.44	1.98	6.00	225.15	95.55	260.33	0.00
3		Pforzheim (Enz)	2.98	8.48	1.53	1.08	893.99	188.99	394.15	0.00
4		Stein (Kocher)	2.76	8.99	1.25	2.84	739.23	221.30	993.50	1.37
5		Untergrisheim (Jagst)	2.51	8.95	0.87	7.89	481.49	189.39	1164.90	0.00
6	Main	Schwürbitz	2.63	8.00	1.58	0.74	976.87	198.93	1249.18	1.00
7		Wolfsmünster (Fränkishe Saale)	2.25	8.64	1.63	1.87	792.99	170.48	1167.53	0.00
8		Waldenhausen (Tauber)	2.06	9.04	1	2.62	392.50	166.87	1246.75	4.13
9		Hanau (Kinzig)	2.77	9.04	1.88	2.56	441.92	131.50	347.98	0.00
10		Bad Viebel (Nidda)	2.28	9.31	1.15	1.43	487.42	225.04	906.64	0.00
11	Lahn	Marburg	2.49	8.41	1.51	2.38	754.98	195.88	715.19	0.00
12		Asslar (Dill)	2.84	8.18	1.85	1.38	495.94	118.49	102.84	0.00
13	Mosel	Ettelbruck	2.67	9.08	1.03	0.93	388.73	121.00	687.44	1.06
14		Michelau (Sauer)	2.90	8.36	1.12	0.98	383.23	93.30	452.71	2.94
15		Gemünd (Our)	2.97	8.18	1.28	2.85	283.38	49.47	263.15	0.00
16		Prümzurlay (Prüm)	2.84	8.28	1.43	3.30	251.93	49.80	298.08	0.00
17		Alsdorf-Oberecken (Nims)	2.70	8.41	1.28	4.23	85.38	19.92	134.88	0.00
18		Nalback (Prims)	3.04	8.91	1.55	1.62	375.19	116.15	242.69	0.00
19		Kordel (Kyll)	2.74	8.35	1.36	5.66	365.24	77.94	360.26	0.00
20		Platten (Lieser)	2.53	8.69	1.58	3.98	220.06	37.67	114.31	1.04
21	Lippe	Lippstadt	2.41	8.92	1.01	1.25	472.67	177.16	738.63	5.57
22	Nahe	Martinstein	2.50	8.38	1.59	2.13	862.35	150.67	420.57	0.85

Table 3.3: List of the catchments for calibration and their basic characteristics

Index	Sub-Basin	Gauge	Drainage Area [km^2]	Lithosol [km^2]	Ranker [km^2]	Gleysol [km^2]	Cambisol [km^2]	Luvisol [km^2]	Podzol [km^2]
23	Sieg	Betzdorf	755	21.40	0.00	0.00	692.85	0.00	40.76
24		Lohmar	818	33.67	0.00	0.00	707.08	77.24	0.00
25	Ruhr	Villigst	2009	161.32	0.00	0.00	1591.17	256.51	0.00
26		Hagen-Hohenlimburg (Lenne)	1322	116.62	0.00	0.00	1205.38	0.00	0.00
27	Erft	Bliesheim	603	65.00	76.00	52.00	161.00	249.00	0.00

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Index	Sub-Basin	Gauge	Annual Mean Precipitation [mm]	Annual Mean Temperature [°C]	Slope [-]	Shape (l^2/Size) [-]	Forest [km^2]	Urban [km^2]	Agri-cultural [km^2]	Water bodies [km^2]
23	Sieg	Betzdorf	3.48	8.42	1.92	1.29	578.53	134.75	41.63	0.00
24		Lohmar	3.53	8.95	1.28	2.82	504.14	149.65	161.17	3.03
25	Ruhr	Villigst	3.13	8.35	1.77	2.21	1246.33	243.09	495.55	24.18
26		Hagen-Hohenlimburg (Lenne)	3.55	8.24	1.96	2.39	1002.57	188.98	119.95	10.12
27	Erft	Bliesheim	2.26	9.52	1.03	1.25	200.88	86.23	315.78	0.00

3.3 Data description

This study is completely based on the data that was collected and compiled in the previous work of Hundecha (2005). A detailed description of the study area and the sub-basins with respect to their drainage area, topography, elevation, land use/cover, geologic formation can be found in (Hundecha, 2005).

Hydrological processes can be associated with the underlying catchment characteristics. Numerous catchment characteristics at large or small temporal and spatial scales can be attributed to a certain hydrological process. The principal catchment characteristics at certain temporal and spatial scales are used in the rainfall runoff models as catchment descriptors. In the study of Hundecha (2005), the catchments are divided into homogeneous zones based on the principal catchment characteristics that have influence on the dominant runoff generation processes. The zones are defined based on topographic elevation, soil type and land use. Elevation is a main factor that affects spatial distribution of the basic meteorological variables including precipitation, temperature and evapotranspiration. The elevation zones were defined using a contour interval of 100 meters. Areas between successive contour intervals were considered homogeneous with respect to elevation. The elevation in the study area ranges from approximately 10 to 1000 meters and a maximum of 10 elevation zones were defined in each catchment. Soil type is another basis for distributing catchments into zones. This is because the water holding capacity, the infiltration capacity and the actual evapotranspiration are highly dependent on the specific soil type. Based on the soil map of the study area, 13 different soil types were identified. Among them, only 6 types make up the major portion of the study area. Each of the remaining types accounts for less than 1% of the area and were included in the neighbouring dominant soil type. Land use class is another catchment characteristic that has an important influence on many hydrological processes such as the rate of evapotranspiration, infiltration and snowmelt. Four land use classes were defined: urban, agricultural, forest, and water body. To model the processes in each zone, the daily precipitation and mean temperature were interpolated on a regular grid of 5×5km and the values in each zone were estimated as the mean of the values on the grids located within a given zone.

4 The HBV-IWS model

4.1 Introduction

The HBV model is a general-purpose hydrological model. Its application lies in water balance studies, flood forecasting, hydropower plant planning, irrigation scheme planning, hydraulic structure designing and study of climate change impact on hydrological processes. The model was originally developed for Scandinavian catchments. It was named after the abbreviation of Hydrologiska Byråns Vattenbalansavdelning (Hydrological Bureau Waterbalance-section, a former section at the Swedish Meteorological and Hydrological Institute (SMHI)). The model was originally developed by Sten Bergström and his colleagues. Its first application was to a 14 km^2 basin in northern Sweden (Bergström, 1972). The first operational forecasts were carried out for some basins in the northern part of Sweden in 1975 (Bergström, 1976).

The model is currently available in different forms and versions. Enormous information on its structure and applications can be obtained from literature. A few research versions of the HBV are being maintained by the Institute of Hydraulic Engineering (IWS), Universitaet Stuttgart. One of them was developed in the IRMA[1] LAHoR project for the purpose of estimating the impact of landuse changes on runoff and flood events with regression-based regionalization technique (Hundecha and Bárdossy, 2004). It has been further modified and used in this study. This model version is hereinafter referred to as the HBV-IWS model.

4.2 Model description

General Water Balance Equation

The HBV model describes hydrological processes at the catchment scale. The general water balance[2] employed in the model can be described as:

[1]INTERREG Rhine-Meuse Activities, a joint flood control programme funded by the European Commission, `http://www.irma-programme.org`

[2]Adapted from online source: `www.smhi.se/sgn0106/if/hydrologi/hbv.htm`

$$P - ET - I - Q = SP + SM + UZ + LZ + lakes \tag{4.1}$$

where:

P	=	Precipitation
ET	=	EvapoTranspiration
I	=	Interception
Q	=	Runoff
SP	=	Snow Pack
SM	=	Soil Moisture
UZ	=	Upper Groundwater Storage
LZ	=	Lower Groundwater Storage
lakes	=	Lake Volume

Model Structure

The model simplifies the hydrological processes as shown in Figure 4.1. It simulates the natural water pathway from its origin in the atmosphere through the descent to the surface. For a detailed description of hydrological processes, one can refer to Ward and Robinson (1990) and Anderson and Burt (1990). To represent the processes in a simplified way, the HBV-IWS model consists of routines for snow accumulation and melt, soil moisture, evapotranspiration and runoff generation. The model description below is mainly based on

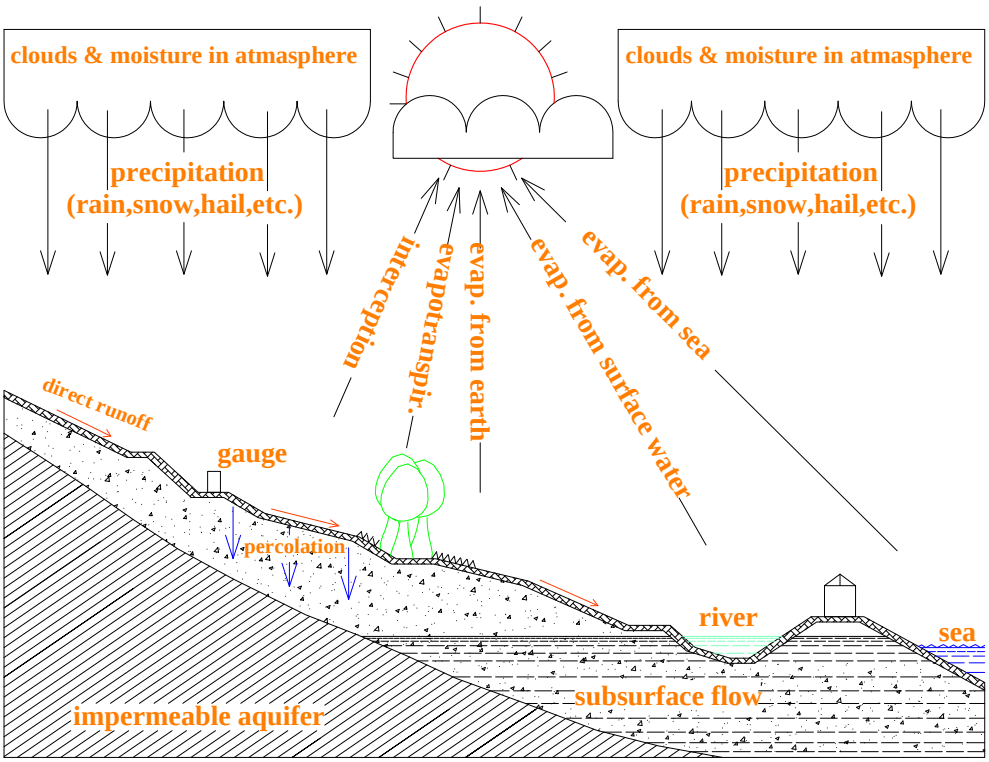


Figure 4.1: Schematic diagram of global water and moisture cycle

Bergström (1995) and Hundecha (2005).

Routine 1 - Snow Accumulation and Melt

The snowmelt routine applies a degree-day approach, based on the air temperature, with a water holding capacity of snow. At a temperature below the freezing point and at normal air pressure, water is in the form of ice. This temperature is defined as threshold temperature (TT). Below TT, precipitation is in the form of snow, as the temperature increases above TT, snow will start to melt and contribute to the runoff. The amount of snowmelt can be calculated as shown in the equation below:

$$S_{melt} = DD\,(T - TT) \tag{4.2}$$

where : S_{melt} = snow melt [mm/day]
DD = degree-day factor [mm/°C·day]
T = average daily temperature [°C]
TT = threshold temperature [°C], influenced by landuse

The amount of snow melt can also depend on the additional energy available in rain water and therefore a modification[3] needs to be applied to the degree-day factor in order to take the amount of precipitation into account (Hundecha and Bárdossy, 2004). The degree-day factor is modified as a linear function of precipitation.

$$DD = \begin{cases} DD_0 + kP & \text{if } P \leq \frac{D_{max} - DD_0}{k} \\ D_{max} & \text{else} \end{cases} \tag{4.3}$$

where : D_{max} = maximum limit to the degree-day factor [mm/°C·day]
DD_0 = degree-day factor when there is no rainfall [mm/°C·day]
k = coefficient [(°C·day)$^{-1}$]
P = daily precipitation [mm]

Routine 2 - Soil moisture

The soil moisture is the main routine that controls the runoff formation. It computes the proportion of precipitation that forms runoff at a given soil moisture. Not all precipitation can reach the ground and contribute to the soil moisture. Part of the precipitation can be intercepted and stored above the ground surface. The amount of interception is highly dependent on the vegetation type, coverage density and many other factors. To roughly estimate the amount of interception, fixed values of interception are defined for each landuse and month of a year. When $T \leq TT$, no interception storage will take place ($I = 0$). Otherwise, the amount of precipitation will be reduced by substracting the amount of interception. The

[3]This modification works fine with the study area undertaken, one should verify it before implementing it in other study areas.

relationship between runoff formation and precipitation is described by a power adjusted relationship between actual soil moisture and maximum soil moisture.

$$\frac{R}{P-I} = \left(\frac{SM}{FC}\right)^{\beta} \tag{4.4}$$

where :
R = runoff [mm]
P = precipitation (rainfall or snowmelt) [mm]
I = interception water storage [mm]
SM = actual soil moisture [mm]
FC = field capacity (maximum soil moisture storage) [mm]
β = free model parameter [-]

Routine 3 - EvapoTranspiration

Daily potential EvapoTranspiration (ET) is calculated by multiplying monthly average ET with an adjusting coefficient. It consists of the temperature gradient (difference between the actual daily air temperature and long-term monthly mean temperature) and a model parameter, which takes vegetation, elevation etc. into consideration. In addition, the soil moisture plays an important role in determining the actual ET. Another model parameter, permanent wilting point (PWP), defines the minimum soil moisture at which the full potential ET takes place from the soil water. At soil moisture values below PWP, the actual ET is reduced linearly to zero at a completely dry soil moisture condition (Bergström, 1995).

$$PE_A = (1 + C_{ET}(T - T_M))PE_M \tag{4.5}$$

where :
PE_A = daily potential evapotranspiration [mm/day]
C_{ET} = model parameter [(°C)$^{-1}$]
T = daily mean air temperature [°C]
T_M = monthly long term mean temperature [°C]
PE_M = monthly long term average evapotranspiration [mm/month]

Intercepted water storage also contributes to ET:

$$E_{int} = min(I_{act}, PE_A) \tag{4.6}$$

where :
E_{int} = evaporation from the interception storage [mm/day]
I_{act} = amount of water in the interception storage [mm/day]

The adjusted potential evapotranspiration that can take place from the soil zone is:

$$PE_A^{'} = PE_A - E_{int} \tag{4.7}$$

The actual evapotranspiration can be then obtained by:

$$ET = \begin{cases} min(SM, PE_A^{'}) & \text{if } SM > PWP \\ min(SM, \frac{SM}{LP} PE_A^{'}) & \text{else} \end{cases} \tag{4.8}$$

where : PWP = the minimum soil moisture at which a plant wilts [mm]

Routine 4 - Runoff generation and concentration

The runoff generation routine computes runoff generated from precipitation in excess of soil moisture. It consists of one upper, non-linear reservoir and one lower, linear reservoir connected by percolation from the upper reservoir to the lower reservoir. The flow generated from these hypothetical reservoirs assumes the form of the Darcy's law. It is computed with the product between a conductivity constant and the water movement potential (the water level in the reservoir). A major revision in the HBV-96 (Lindström, 1997) contains the replacement of two outflows from the upper, linear reservoir with one outflow from the upper, non-linear reservoir. This means that the lateral water movement in the upper reservoir does not differentiate interflow and surface runoff components when precipitation rates exceed infiltration and percolation rates. The research version of the HBV-IWS model used in this study adopts the HBV-96 revision. While it highly simplifies the actual hydrological processes, it is sufficient for the purpose of modeling long-term water balance with the advantage of one less model parameter.

The outflow from the upper reservoir consists of direct runoff and percolation.

$$Q_1 = k_1 h_1^{\alpha+1} \tag{4.9}$$

$$Q_{perc} = k_{perc} h_1 \tag{4.10}$$

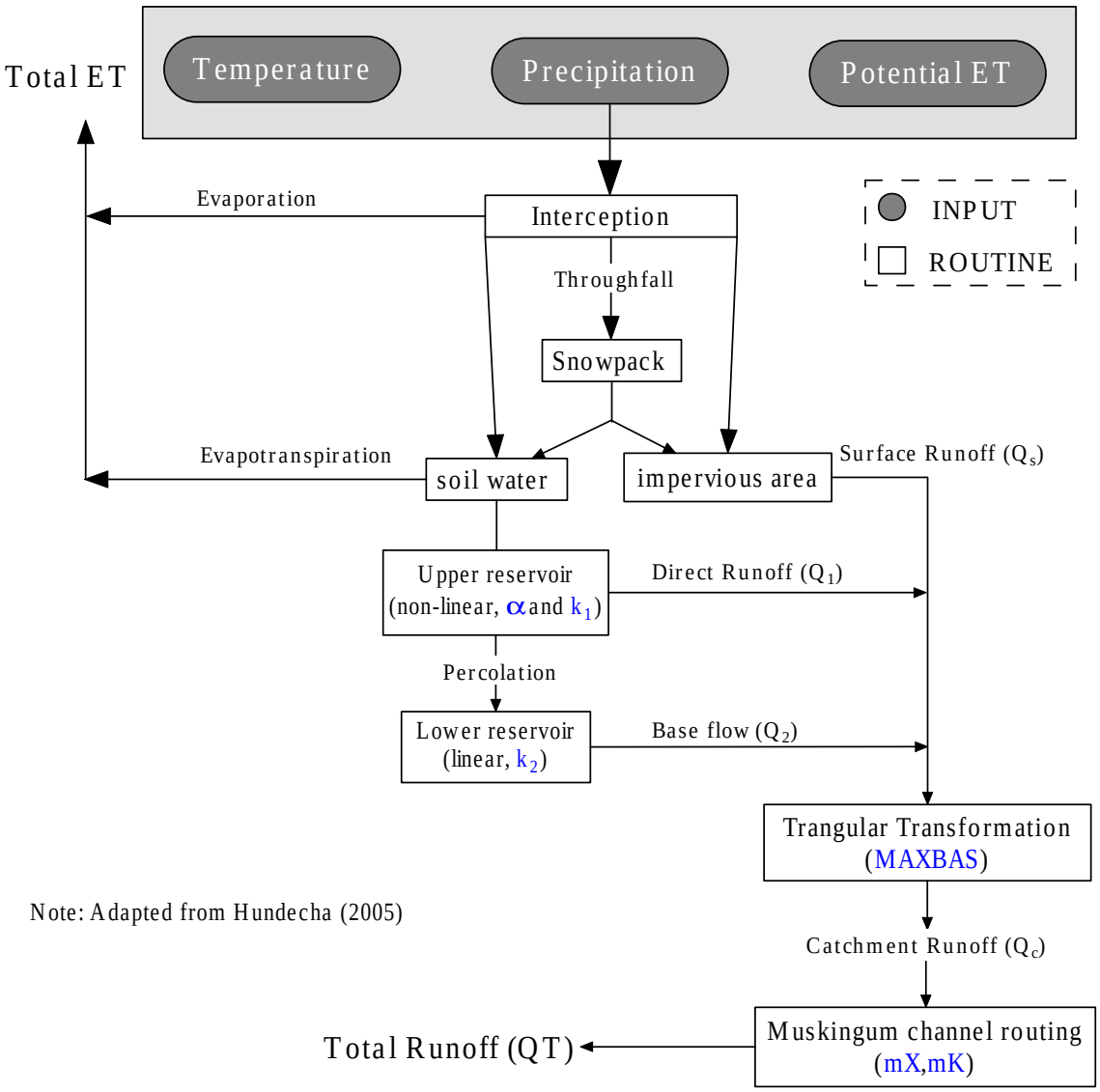
The outflow from the lower reservoir is expressed as:

$$Q_2 = k_2 h_2 \tag{4.11}$$

where :
Q_1 = direct runoff generated from the upper reservoir [mm/day]
Q_{perc} = percolation generated from the upper reservoir [mm/day]
Q_2 = slow runoff generated from the lower reservoir [mm/day]
α = model parameter for direct runoff [-]
k_1 = recession coefficient of the upper reservoir [day^{-1}]
k_{perc} = percolation rate [day^{-1}]
k_2 = recession coefficient of the lower reservoir [day^{-1}]
h_1 = the depth of water in the upper reservoir [mm]
h_2 = the depth of water in the lower reservoir [mm]

The generated total runoff is finally smoothed by a triangular transformation function whose base is defined with a parameter $MAXBAS$ [days]. $MAXBAS$ describes the approximate delayed time required for runoff concentration at the outlet of a certain drainage area. The routing between catchments applies the Muskingum method.

The HBV-IWS model is originally written in FORTRAN 77. It has been modified based on this particular study. The program has also been upgraded to a FORTRAN 90 format (see Figure 4.2).



Note: Adapted from Hundecha (2005)

Figure 4.2: Schematic structure of the HBV-IWS model

5 The XAJ-IWS model

5.1 Introduction

The Xinanjiang model was conceptualized and established in 1970's by Hohai University, formerly East China College of Water Resources. Similar to the HBV model (see section 4.1), the Xinanjiang model is also a general purpose model for rainfall runoff simulation, flood forecasting and water resources planning and management. Its name, Xinanjiang, is the name of a reservoir in Southern China where the model was first applied to forecast inflow. The model has been subsequently applied in many humid and semi-humid regions in China. Detailed information on its structure and applications can be obtained from (Zhao, 1984, 1992; Zhao and Liu, 1995).

Similar to the HBV model, the parameters of the Xinanjiang model are hard to estimate from field observation because they do not necessarily have physical meaning. Calibration by comparing the estimated and observed discharge is employed to estimate the optimum parameter values. The Xinanjiang model is currently available in different forms and versions. It has also served as the conceptual basis for several other rainfall runoff models, including the ARNO model (Todini, 1996) and the VIC (Variable Infiltration Capacity) model (Liang et al., 1994).

The model is modified and recoded for the Rhine River Basin in this study. This model version is hereinafter referred to as the XAJ-IWS model. It is selected in this study to examine if the assumption of invariant catchment similarity holds true. Invariant catchment similarity here assumes the catchments genuinely carry their similarities independent of the model used for simulation. This test is also a backstop measure to determine if the models under consideration are able to capture the underlying simplified hydrological processes in a rational manner. More details on this topic can be found in section 6.5

The XAJ-IWS model description given below is mainly adopted from (Zhao and Liu, 1995) with modifications made in this study.

5.2 Model description

The concept of 'runoff formation on repletion of storage'

Zhao and Zhuang (1963) analysed many graphs of rainfall runoff relationship in the humid regions in southern China and concluded that the key factors influencing the amount of runoff production are the amount of precipitation, initial water storage and evapotranspiration. Precipitation intensity has little to do with the amount of runoff formation in these humid regions. Zhao and Zhuang (1963) made the hypothesis based on their field observation that in humid regions the subsurface aeration zone can easily reach its water storage capacity during a rainfall event and at the point it reaches its capacity, runoff production will be equal to the increment of precipitation after satisfying the deduction rate of evapotranspiration. The hypothesis formed the basic concept of the model that is 'runoff formation on repletion of storage'. This concept suits well in humid and semi-humid regions.

The concept of 'distribution of storage capacity'

Runoff is produced on repletion of subsurface storage. If the subsurface storage is constant everywhere in the catchment, the same amount of runoff will be produced provided that the precipitation is uniformly received by the entire catchment. In reality, neither the precipitation nor the field storage capacity distributes uniformly across the catchment. The non-uniform distribution of precipitation over the catchment is taken care by dividing the catchment into 6 soil classes and 10 elevation zones. To account for the inhomogeneous nature of tension water storage, (Zhao, 1984) suggested a tension water capacity curve (see Figure 5.1 (b)).

Routine 1 - Snow Accumulation and Melt

Xinanjiang model was originally developed in parts of southern China where snow hardly occurs. In order to account for the precipitation that is contributed from the snow melt in the Rhine River basin, the same degree-day snowmelt approach is used (see Equation 4.2 and Equation 4.3).

Routine 2 - EvapoTranspiration

Original Xinanjiang model uses measured daily pan evaporation as input for subsequent calculation of EvapoTranspiration (ET). This study replaces pan evaporation with daily potential ET, which is calculated the same way as in the HBV-IWS model (see Equation 4.5). The daily potential ET is then adjusted with a model parameter K.

$$PE'_A = K \cdot PE_A \tag{5.1}$$

In the HBV-IWS model, the daily potential ET is adjusted by subtracting the ET taking place from the interception water storage. The actual daily ET is then obtained by taking

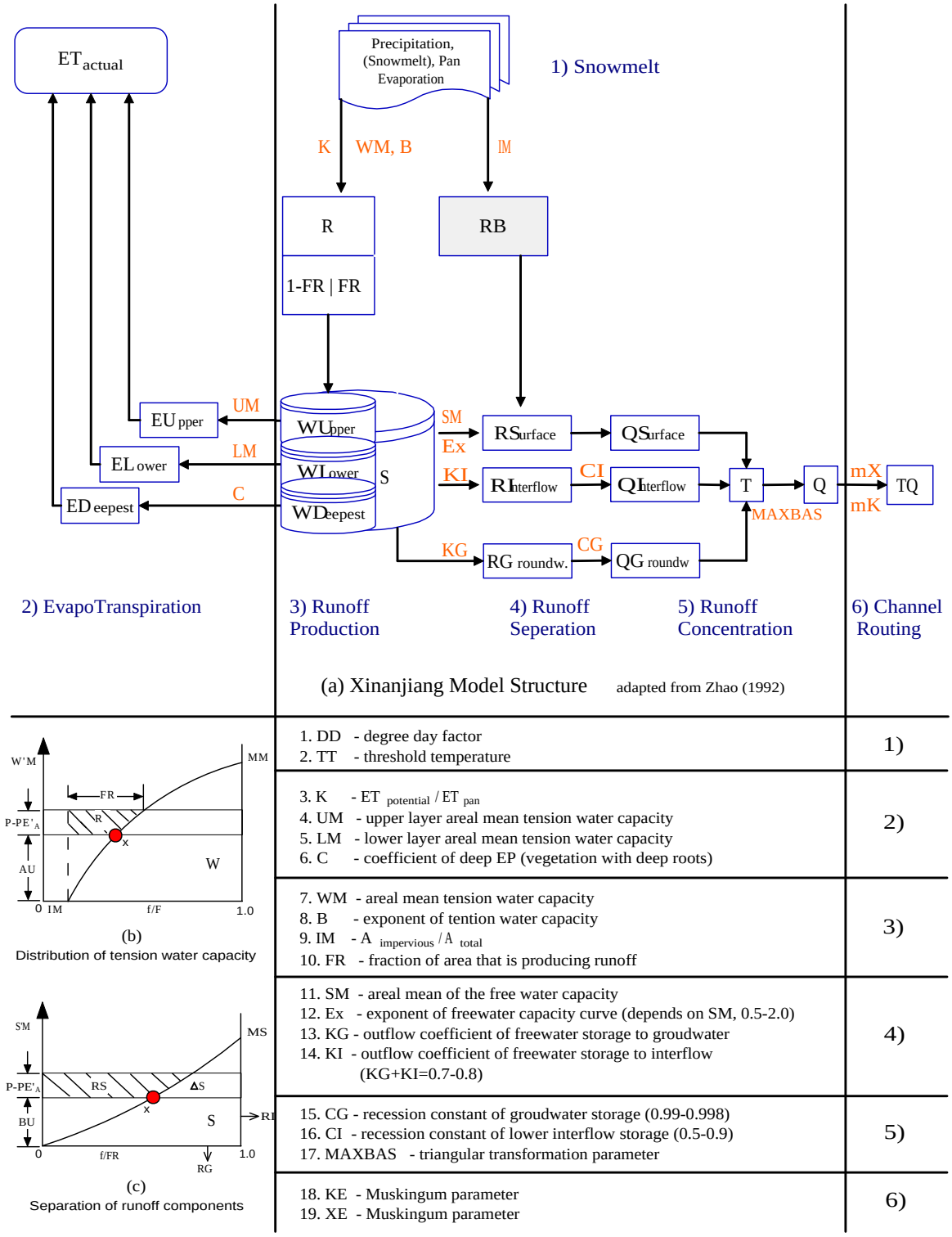


Figure 5.1: Xinanjiang rainfall runoff model structure

a proportion based on the soil moisture and permanent wilting point. This procedure considers the vertical moisture distribution of the entire soil profile as uniform. The simplification may lead to significant error of the actual daily ET because top and deep soil layers certainly play different roles in contributing to the ET.

In contrast to the ET module in the HBV-IWS model, the current standard Xinanjiang model applies a 3-layer soil moisture module which differentiates upper, lower and deeper soil layers.

The upper soil will start to lose its water storage to ET if the condition of $WU + P > PE'_A$ (soil moisture in the upper layer together with incoming precipitation is sufficient for ET to take place) fulfills as described in Equation 5.2.

$$\text{if } WU + P > PE'_A,\ EU = PE'_A \tag{5.2a}$$

$$EL = 0 \tag{5.2b}$$

$$ED = 0 \tag{5.2c}$$

Once the upper layer soil has no more water available for ET, the lower soil water will be withdrawn.

$$\text{if } WL/WML \geq C,\ EU = WU + P \tag{5.3a}$$

$$EL = \frac{WL}{WML}(PE'_A - EU) \tag{5.3b}$$

$$ED = 0 \tag{5.3c}$$

If $WL/WML < C$ but $WL \geq C(PE'_A - EU)$, ET will continue in the lower soil layer but with a reduced rate.

$$\text{if } WL \geq C(PE'_A - EU),\ EU = WU + P \tag{5.4a}$$

$$EL = C(PE'_A - EU) \tag{5.4b}$$

$$ED = 0 \tag{5.4c}$$

If $WL < C \cdot (PE'_A - EU)$, the lower soil will lose all its water storage and the deeper soil water will start to contribute to ET.

$$\text{if } WL < C(PE'_A - EU),\ EU = WU + P \tag{5.5a}$$

$$EL = WL \tag{5.5b}$$

$$ED = C(PE'_A - EU) - EL \tag{5.5c}$$

where : EU = actual evapotranspiration in the upper layer [mm/day]
EL = actual evapotranspiration in the lower layer [mm/day]
ED = actual evapotranspiration in the deeper layer [mm/day]
WU = soil moisture in the upper layer [mm/day]
WL = soil moisture in the lower layer [mm/day]
WD = soil moisture in the deeper layer [mm/day]
WMU = tension water capacity in the upper layer [mm/day]
WML = tension water capacity in the lower layer [mm/day]
WMD = tension water capacity in the deeper layer [mm/day]
K = adjustment coefficient for potential evapotranspiration [-]
C = coefficient for the deeper soil layer [-]
PE'_A = daily potential evapotranspiration [mm/day]
P = daily precipitation [mm/day]

Routine 3 - Runoff production

Runoff originated from impervious area produces direct runoff.

$$RB = IM(P - PE'_A) \tag{5.6}$$

where : IM = percentage of impervious area [%]
RB = runoff originated from impervious areas [mm]

Tension water storage is considered as non-uniformly distributed over a catchment. A distribution curve of tension water capacity over a catchment is introduced in Figure 5.1 (b). The tension water capacity at a point - *W'M* varies from zero to a maximum - *MM* according to Equation 5.7.

$$f/F = 1 - \left(1 - \frac{W'M}{MM}\right)^B \cdot (1 - IM) \tag{5.7}$$

where : f/F = proportion of the pervious area of the catchment where tension water capacity is less than or equal to the value of the ordinate $W'M$ [%]
B = exponent of the tension water capacity distribution curve [-]

The areal mean tension water capacity - *WM* constitutes an alternative parameter to the maximum value on the tension water distribution curve - *MM*. They are related through the

exponent - B (see Equation 5.8).

$$WM = \int_0^{MM} \left(1 - \frac{f}{F}\right) dW'M \tag{5.8a}$$

$$= \int_0^{MM} \left(1 - \frac{W'M}{MM}\right)^B (1 - IM) dW'M \tag{5.8b}$$

$$= \left[\frac{1 + (\frac{-1}{MM}) \cdot W'M}{(B+1) \cdot (\frac{-1}{MM})}(1 - IM)\right]_0^{MM} \tag{5.8c}$$

$$= \frac{MM}{1+B}(1 - IM) \tag{5.8d}$$

The tension water storage status of a catchment is represented by a point x (the circle point on Figure 5.1 (b) with its coordinate AU) on the curve. The area to the right and below x is proportional to the areal mean tension water storage W. The state of a point in a catchment is either at capacity tension or at a constant tension. When rainfall exceeds ET, x moves upward along the curve and runoff R is generated proportional to the shaded area shown to the left and above the point x. When ET exceeds rainfall, the three-layer tension water storage is reduced and the point x moves downward along the curve to the a level, at which the area mean tension water storage W assumes its appropriate value. The upward or downward shift of the point x is an implication of a redistribution of soil water over the catchment during wetting and drying period.

If $P - PE'_A + AU \geq MM$,

$$R = P - PE'_A - WM + W \tag{5.9}$$

else,

$$R = W + P - PE'_A + \int_{P-PE'_A-WM+AU}^{MM} \left(1 - \frac{f}{F}\right) dW'M \tag{5.10a}$$

$$= W + P - PE'_A - WM + \int_{P-PE'_A+AU}^{MM} \left[\left(1 - \frac{W'M}{MM}\right)^B \cdot (1 - IM)\right] dW'M \tag{5.10b}$$

$$= W + P - PE'_A - WM + \frac{MM}{1+B}(1 - IM)\left(1 - \frac{P - PE'_A + AU}{MM}\right)^{1+B} \tag{5.10c}$$

$$= W + P - PE'_A - WM + WM\left(1 - \frac{P - PE'_A + AU}{MM}\right)^{1+B} \tag{5.10d}$$

where the area mean tension water capacity WM is obtained as the sum of WMU, WML and WMD, similarly, the areal mean tension water storage W is the sum of WU, WL and WD, the maximum value MM can be derived from Equation 5.10 (d):

$$MM = \frac{WM(1+B)}{1-IM} \tag{5.11}$$

and the coordinate AU can be derived as:

$$AU = WM\left[1-\left(1-\frac{W}{WM}\right)^{\frac{1}{1+B}}\right] \tag{5.12}$$

The runoff produced from previous area can finally be computed with Equation 5.10 (d).

Routine 4 - Runoff separation

The runoff generated in Routine 3 consists of three components, namely surface runoff *RS*, interflow *RI* and groundwater runoff *RG*, which need to be separated. A distribution curve is introduced to quantify the distribution of free water storage (see Figure 5.1 (c)). The current status of free water storage in the catchment can be represented by a point x (the circle point with BU as its coordinate).

$$f/FR = 1-(1-S'M/MS)^{Ex} \tag{5.13}$$

where :	$S'M$	=	free water storage capacity [mm]
	MS	=	maximum free water storage capacity [mm]
	FR	=	the fraction of the area that is producing runoff [-]
	f/FR	=	proportion of the area where free water storage is less than or equal to S'M [%]
	Ex	=	exponent of the free water capacity distribution curve [-]

The areal mean free water storage capacity *SM* is used to replace *MS*.

$$MS = SM(1+Ex) \tag{5.14}$$

The free water storage *S* can be obtained by integration of *S'M*.

$$S = \int_0^{BU}\left(1-\frac{f}{FR}\right)dS'M \tag{5.15a}$$

$$= \int_0^{BU}\left(1-\frac{S'M}{MS}\right)dS'M \tag{5.15b}$$

$$= \frac{MS}{1+Ex}\left[1-\left(1-\frac{BU}{MS}\right)^{1+Ex}\right] \tag{5.15c}$$

If $P - PE'_A + BU \geq MS$,

$$RS = (P - PE'_A - SM + S) \cdot FR \tag{5.16}$$

else,

$$RS = \left[P - PE'_A - SM + S + SM \left(1 - \frac{P - PE'_A + BU}{MS} \right)^{1+Ex} \right] \cdot FR \tag{5.17}$$

where the coordinate BU can be derived as:

$$BU = SM \left[1 - \left(1 - \frac{S}{SM} \right)^{\frac{1}{1+Ex}} \right] \tag{5.18}$$

Interflow and groundwater runoff can be computed with Equation 5.19.

$$RI = S \cdot KI \cdot FR \tag{5.19a}$$

$$RG = S \cdot KG \cdot FR \tag{5.19b}$$

where : KI = model parameter related to interflow [-]
KG = model parameter related to groundwater [-]

Routine 5 - Runoff concentration

Runoff originated from impervious areas together with surface runoff generated from free water storage join directly in the streamflow QS without any time delay. While interflow and groundwater are routed to streamflow through linear reservoirs.

$$QS = RB + RS \tag{5.20a}$$

$$QI(t) = QI(t-1)CI + RI(1 - CI) \tag{5.20b}$$

$$QG(t) = QG(t-1)CG + RG(1 - CG) \tag{5.20c}$$

$$QT(t) = QS + QI(t) + QG(t) \tag{5.20d}$$

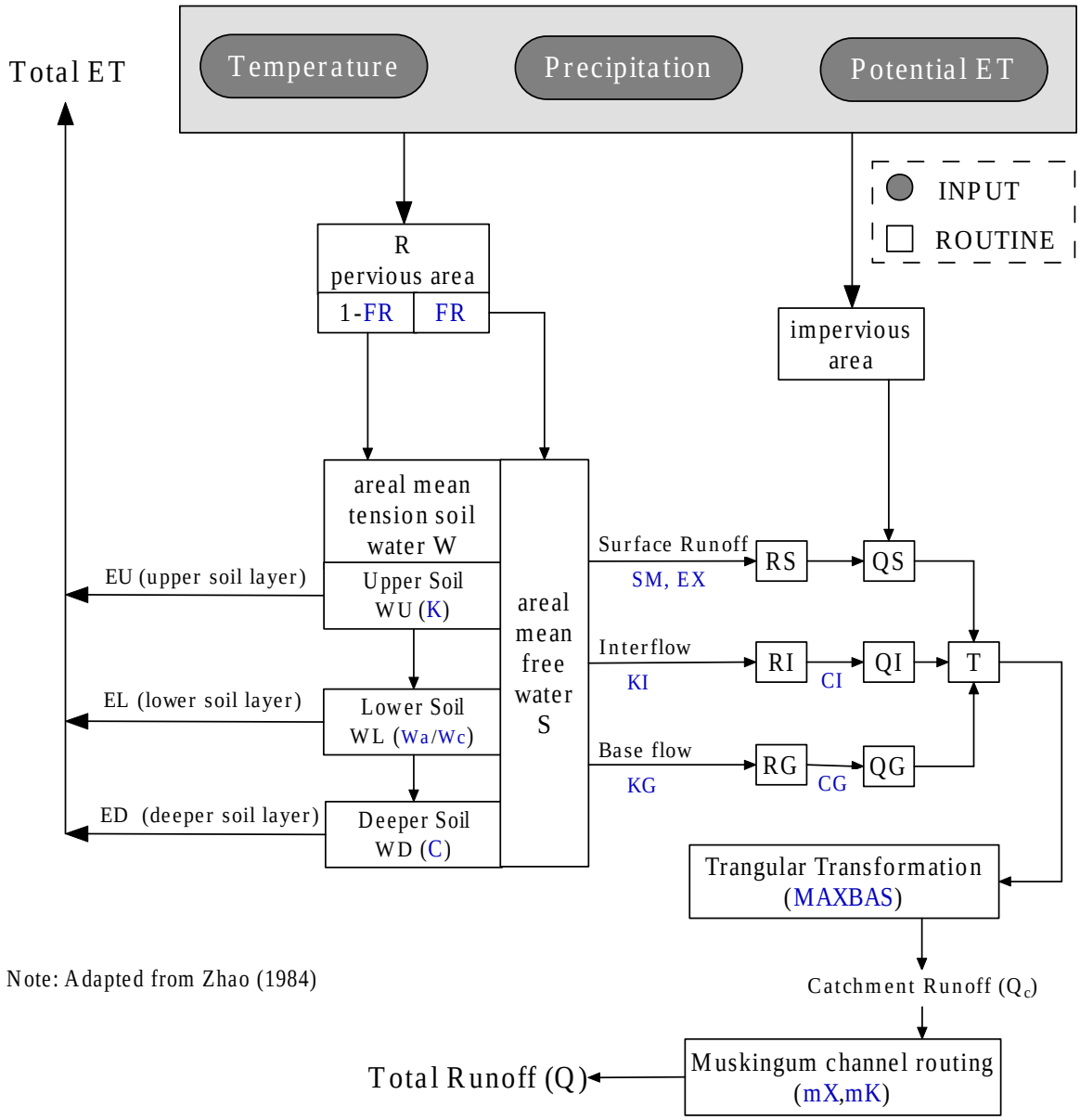
where : CI = reservoir constant related to interflow [-]
CG = reservoir constant related to groundwater [-]
QI = streamflow generated from interflow [mm]
QG = streamflow generated from groundwater [mm]
QT = total streamflow/runoff [mm]
t = time step [hour]

The generated total runoff QT is finally smoothed by a triangular transformation function whose base is defined with a parameter MAXBAS [days]. MAXBAS describes the approximate delayed time required for runoff concentration at the outlet of a certain drainage area.

Routine 6 - Channel routing

Channel routing uses the same method as the HBV-IWS model. The routing between catchments applies the Muskingum method.

Figure 5.2 illustrates the schematic structure of the XAJ-IWS model. It provides a direct comparison of the model structure with the HBV-IWS model (Figure 4.2).



Note: Adapted from Zhao (1984)

Figure 5.2: Schematic structure of the XAJ-IWS model

6 The catchment classification scheme

As mentioned earlier in section 1.2 and elaborated in chapter 2, the work is undertaken to further the study on catchment classification methods. The main objective is to establish a non-parametric catchment classification scheme and the secondary objective is to explore its applications in catchment hydrology, in particular predictions in ungauged or insufficiently gauged basins. The proposed catchment classification scheme is grounded in three basic assumptions which will be introduced in section 6.1. The main methodology is described in section 6.2 followed by three peripheral sections including the optimization algorithm (section 6.3), determination of the dimension of the catchment space (section 6.4) and a test of model dependency of the classification scheme (section 6.5).

6.1 Basic assumptions

The implementation of the catchment classification scheme is premised based upon three basic assumptions (**BA**):

I Similar catchments behave similarly;

II Similarity can be described with catchments' characteristics;

III Models are able to capture similarity.

The first assumption states the similarity of interest. It is based on functions and behaviour catchments have in common. This assumption corresponds to the point of view expressed by Grigg (1965) (see section 2.1 page 6). The second assumption links the causal effect of hydrological behaviour to catchment characteristics including physiographical and meteological features. The link between catchments' characteristics and catchment behaviour is yet to be understood, but the latter is determined by the former. The third assumption brings models into the picture. A rainfall runoff model can be set up to simulate catchment behaviour and hence capture similar behaviour.

To summarize the assumptions, if a model simulates similar hydrology (could be any hydrological components such as subsurface flow or streamflow) for two catchments, they are considered as similar catchments in the space of the catchment characteristics, provided the model reasonably reproduces dominant hydrological processes.

The three basic assumptions are essentially true and thus referred to as **BA**'s three laws hereinafter. They form the conceptual basis of this study. Hydrological units - catchments are considered as candidate objects from which neighboring objects will be selected based on a distance measurement in the given catchments.

6.2 Local variance reduction method

6.2.1 The concept

According to the basic assumption II (**BA II**), similarity is described within the space of catchment characteristics which are represented by the $\boldsymbol{X}$ vector ($dim(X) = m$) of n catchments. The coordinates in the space of catchment characteristics are denoted by $\boldsymbol{U}$. A transformation matrix $\boldsymbol{B}$ relates catchment characteristics $\boldsymbol{X}$ to the coordinates in the space **u**. Space **u** has a dimension of $\boldsymbol{k}$, which should be less than or equal to $\boldsymbol{m}$. The total number of catchments I is assumed to be larger than m. Catchments are classified in the space $\boldsymbol{u}$.

$$U = B \cdot X, k \leq m \tag{6.1}$$

Six soil properties (converted into percentage of the total drainage area), four land use covers (converted into percentage of the total drainage area), drainage slope and shape are selected from Table 3.2 and Table 3.3 to compose $\boldsymbol{X}$. For 22 catchments (see Table 3.2) selected for validation with 11 characteristics for each catchment, Equation 6.1 is actualized below:

$$[k \times 22] = [k \times 11] \cdot [11 \times 22], k \leq 11 \tag{6.2}$$

According to the **BA I**, similarity is based on catchment behaviour. And according to the **BA III**, catchment behaviour can be simulated by hydrological models. The observed or simulated discharges can be therefore considered as an indication of similarity. One can directly compare discharges between two catchments and draw conclusion on their similarity. But the aim of setting up the catchment classification scheme is not only to make predictions of streamflow but more importantly to extend its application in modeling and allow the transferability of model parameters. The Nash-Sutcliffe (**NS**) model efficiency coefficient (Nash and Sutcliffe, 1970) is used here to enable the method to function within an ungauged catchment. The starting point is to engage the **NS** as a good indicator of the overall model performance and predictive ability. The **NS** with an emphasis given to the peak flow is formulated below:

$$R_i^2 = 1 - \frac{\sum_{t=1}^{T} Q_t(\hat{Q}_t - (Q_t))^2}{\sum_{t=1}^{T} Q_t(\hat{Q}_t - (\overline{Q}_t))^2} \tag{6.3}$$

where:

i	=	index number of a catchment, *i=1,. . .,I*
R_i^2	=	the weighted (using observed discharge) Nach-Sutcliffe coefficient for catchment *i*
t	=	time step, *t=1,. . .,T*
Q_t	=	observed discharge at time step *t*
$\overline{Q}_t$	=	the mean observed discharge
$\hat{Q}_t$	=	modeled discharge at time step *t*

The distance d_{NS} is defined as a function of **NS**. If a model simulation is equally good for catchments ***r*** and ***s***, they can be considered as similar catchments. Due to the problem of "equifinality", one simulation cannot guarantee the similarity, therefore, a large number of simulations with different random parameter sets are needed to overcome this problem. N_r, N_s and N_{rs} are the numbers of simulations whose **NS** for catchment ***r***, catchment ***s*** and both catchments are larger than or equal to a threshold value - NS_t respectively. d_{NS} can be defined as follows.

$$d_{NS} = f(NS) = 1 - \frac{(N_{rs(NS>NS_t)})^2}{N_{r(NS>NS_t)}N_{s(NS>NS_t)}} \tag{6.4}$$

The obtained distance matrix not being subtracted by **1** is in fact a matrix of dissimilarity with a large value corresponding to a closeness or similarity. It needs to be substracted by 1 to derive the matrix of similarity where a low distance corresponds to closeness or similarity. It is worth noting here that d_{NS} is only a similarity measure not a strict distance function. d_{NS} has to fulfill all metric conditions to be described as a distance function, which will be discussed in section 8.1.

The distance d_B in the space ***u*** is computed as the Euclidean distance between coordinates of catchment ***r*** - U_r and coordinates of catchment ***s*** - U_s.

$$d_B = f(X) = \sqrt{(U_r - U_s)^T(U_r - U_s)} \tag{6.5}$$

If a pair of catchments is found similar with respect to the distance d_{NS}, this pair should be similar with respect to the distance d_B. A Lipschitz condition can thus be formed:

$$d_{NS} < Ld_B \tag{6.6}$$

with ***L*** being a constant. This condition does not allow any exceptional case, e.g. a pair of catchments are close in the space ***u*** (d_B is relatively small) but they do not have similar

behaviour (large d_{NS}). To loosen the strict Lipschitz condition (Equation 6.6), a number of pairs with distances not more than a threshold distance - $d_B(p)$ are considered instead of one single pair. The goal is to search for a transformation matrix B to reproduce distances amongst catchments, in the space $\boldsymbol{u}$. In other words, the accumulated distances of d_{NS} are expected to be small when their corresponding $d_B s$ are small:

$$G_B(p) = \frac{1}{N(d_B(p))} \sum_{d_B(r,s)<d_B(p)} d_{NS} \tag{6.7a}$$

$$|(r,s); d_B(r,s) < d_B(p)| = N(d_B(p)) = p\frac{n(n-1)}{2} \tag{6.7b}$$

$$G_B(p) \rightarrow min \tag{6.7c}$$

where p is a certain proportion of all possible pairs of catchments and $0 < p \leq 1$. Equation 6.7a is expressed in the form of variogram. The objective is to minimize $G_B(p)$, the local variability, which means the group of catchments have the minimum variance, a basis for the name - Local variance reduction (**LVR**).

If a pool of catchments have constantly increasing distances as the size of the pool enlarges, a p can be easily selected. In actual practice, the local variance can jump to an unexpectedly high or low level without consistence. In the former case, i.e. an unproportionally higher variance with an increasing p, a hydrological prediction can only be made with the help of "closest" catchments which are in fact far away. To take this case into consideration, $G_B(p)$ can be replaced with an integral of $G_B(p_j)$ and the objective $O(B)$ becomes:

$$O(B) = \sum_{j=1}^{J} G_B(p_j) \rightarrow min \tag{6.8}$$

with $p_1 < p_2 < \cdots < p_J < 1$. A monotonic condition is imposed as well to prevent the latter case, i.e. an unexpected low local variance with an increasing p. It is reasonable to expect lower variance with less number of catchments:

$$G_B(p_1) < G_B(p_2) < \cdots < G_B(p_J) \tag{6.9}$$

A punishing weight W is introduced here to adjust the objective function:

$$W = \prod_{j=2}^{J} max\left[1, \frac{G_B(p_{j-1})}{G_B(p_j)}\right] \tag{6.10}$$

The objective $O(B)$ finally becomes:

$$O(B) = W \sum_{j=1}^{J} G_B(p_j) \tag{6.11}$$

The similar or close catchments are identified in the space u by obtaining a minimum $\sum_{j=1}^{J} G_B(p_j)$ with a proper transformation matrix B, and at the same time satisfying the monotonic condition.

6.2.2 Identification of B

A proper transformation matrix B is to ensure a reproduction of similarity in the space u with the objective function described in Equation 6.11. The designed procedures are illustrated in Figure 6.1 and detailed in 10 steps as follows:

1 run a hydrological model MC (should be a large enough number) times, each time with a set of randomly generated model parameters;

2 select k for the dimension of space u and randomly assign values to elements of B;

3 select X and a set of portions (e.g. $p = 0.01, 0.02, ..., 0.3$);

4 compute d_{NS} with the Equation 6.4;

5 compute d_B with the Equation 6.5;

6 sort out d_B by ascending order;

7 for each portion $N(d_B(p))$, record the pair numbers s and r that correspond to d_B from the smallest to the N_{th};

8 for each portion p, sum up d_{NS} and then obtain $G_B(p)$;

9 compute W with the Equation 6.10;

10 compute $O(B)$ with the Equation 6.11

Steps 5 to 10 are iterated to obtain the minimum $O(B)$. The iterative steps follow a simulated annealing procedure which will be described in detail in section 6.3.

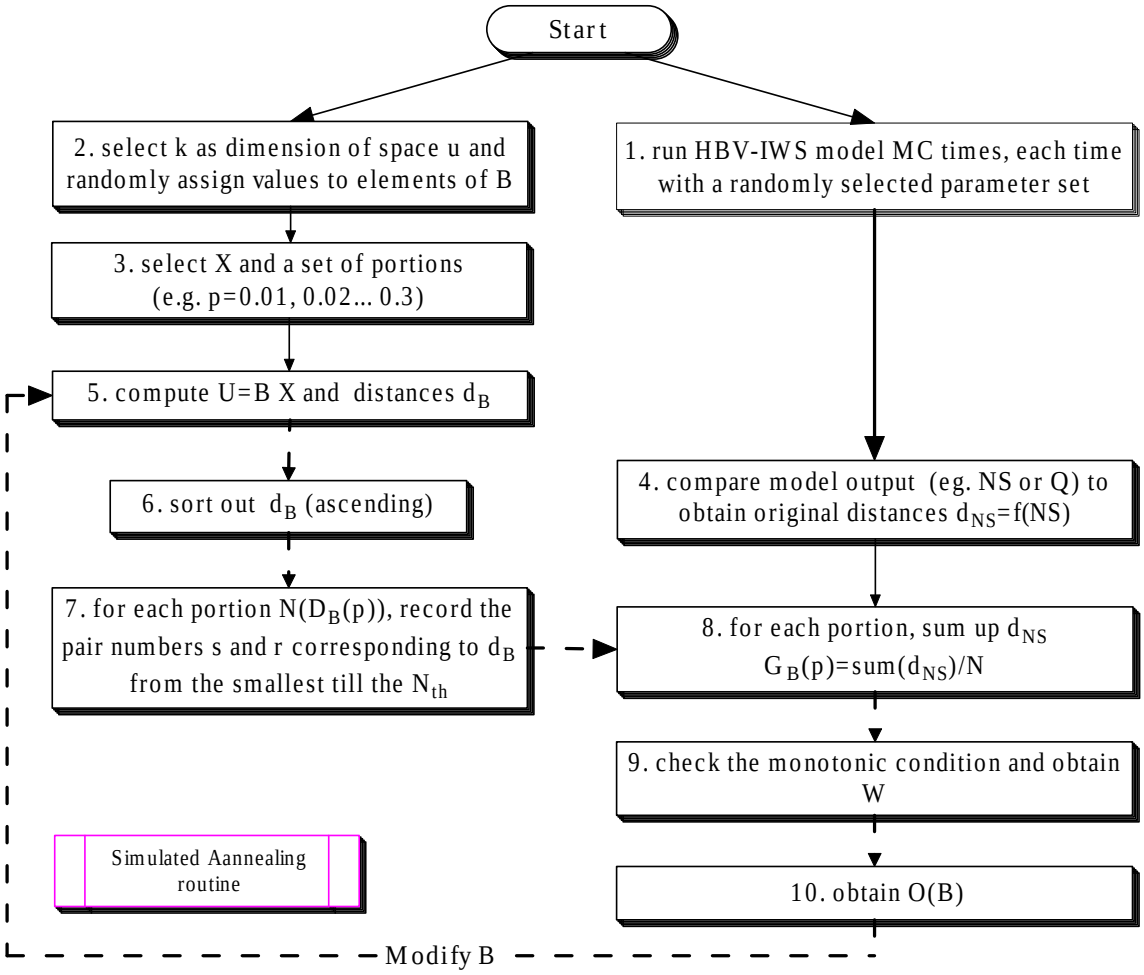


Figure 6.1: The basic procedures to identify B

6.3 Optimization algorithm

Simulated annealing (SA) is employed as the optimization algorithm for the proposed local variance reduction method described in section 6.2. The standard SA was first used by Nicholas Metropolis and his co-workers in 1953 and known as Metropolis Monte Carlo integration algorithm (Metropolis et al., 1953). It was modeled after a thermal equilibrium equation representing the metal annealing process to make the searching procedure more efficient (Kirkpatrick et al., 1983). It is based on a strong analogy between the physical annealing procedure and the problem of finding an optimal solution. In condensed matter physics, annealing is known as a thermal process for obtaining low energy states of a solid in a heat bath. The process contains the following two steps (Brünger, 1991):

- increase the temperature of the heat bath to a maximum value at which the solid melts;
- decrease slowly and carefully the temperature of the heat bath until the particles arrange themselves in the ground state of the solid.

During this procedure, the free energy of the solid is minimized and the solid crystallizes into a state with a perfect lattice (Aarts and Korst, 1989). If the temperature drops down too quickly, the atoms do not have time to orient themselves into a regular structure and the result is a more amorphous material with higher energy (Jang et al., 1997).

SA is classified as a derivative-free (Jang et al., 1997) combinatorial optimization technique (Kirkpatrick et al., 1983). It has proven its capability to minimize complicated n-dimension cost functions very efficiently (Hu, 2004). It is essentially a stochastic approach relying on random combinations and repeated evaluations of the objective function (Jang et al., 1997). The random combinations are not entirely random in any irrelevant parameter space but based on acceptance and rejection leading to a more feasible parameter space. Hence, SA is heuristic and adaptive. It is suitable for many problems which do not yet have analytical solutions. The SA procedure that is implemented in this study is demonstrated in Figure 6.2. The steps are explained as follows:

1 select annealing schedule including initial temperature $T_{initial}$, temperature decreasing factor ΔT, stopping temperature T_{end} and number of Monte-Carlo N_{mc} runs within each temperature step;

2 compute objective function $O(B)$ with an initially assigned B (elements from each row of B should sum to unity), assign them as $O(B)_{best}$, $O(B)_{old}$ and B_{best}, B_{old} respectively;

3 zero initial control parameters, number of accepted iterations $N_{positive}$ and number of accepted iterations with a random probability $N_{negative}$:

$$N_{positive} = N_{negative} = 0 \tag{6.12}$$

An annealing loop is started and will be terminated when $T = T_{end}$:

a) a Monte-Carlo loop (i-vi) is started and will be terminated when N_{mc} times are completed:

   i. randomly modify two elements of B_{old}, two elements are randomly selected from the same row (the row number *i* is randomly selected from 1 to k). They are modified using a random number $RN1$ (0 <RN1≤ 1). As the annealing temperature T decreases, the modification to the two elements should also become smaller to fine tune the searching space. Elements of each row of B should sum up to unity.

$$B_{new}(i, j1) = B_{old}(i, j1) + \sqrt{RN1(T(1 - \Delta T)/10} \tag{6.13a}$$

$$B_{new}(i, j2) = B_{old}(i, j2) - \sqrt{RN1(T(1 - \Delta T)/10} \tag{6.13b}$$

$$\sum_{j=1}^{11} B(i, j) = 1 \tag{6.13c}$$

   ii. compute new objective function $O(B)_{new}$;

   iii. since the ideal objective is a minimum of $O(B)$, if $O(B)_{new} \leq O(B)_{old}$, the new solution will replace the old solution:

$$B_{old} = B_{new} \tag{6.14a}$$

$$O(B)_{old} = O(B)_{new} \tag{6.14b}$$

$$N_{positive} = N_{positive} + 1 \tag{6.14c}$$

   iv. if $O(B)_{new} < O(B)_{best}$, the best solution will be stored at this moment:

$$B_{best} = B_{new} \tag{6.15a}$$

$$O(B)_{best} = O(B)_{new} \tag{6.15b}$$

   v. if $O(B)_{new} > O(B)_{old}$, the solution will only be accepted with a probability (a random number $RN2$ with 0 <RN2≤ 1):

$$h = exp(\frac{O(B)_{old} - O(B)_{new}}{T}) \tag{6.16a}$$

$$\text{if } h > RN2, N_{negative} = N_{negative} + 1 \tag{6.16b}$$

$$B_{old} = B_{new} \tag{6.16c}$$

$$O(B)_{old} = O(B)_{new} \tag{6.16d}$$

   vi. if $O(B)_{new} > O(B)_{old}$ and $h \leq RN2$, this solution is rejected.

b) upon completion of each Monte-Carlo loop, the annealing temperature will be reduced with a factor of ΔT. A small ΔT is prefered as a fast temperature drop might end up in a local optima, although there is always a trade-off between the computing time and best possible optima.

$$T = T \cdot (1 - \Delta T) \tag{6.17}$$

Acceptance ratio is obtained after completion of each temperature step:

$$R_a = \frac{N_{positive} + N_{negative}}{N_{mc}}. \tag{6.18}$$

The major difficulties in the implementation of a SA algorithm include the following:

1 SA is computationally intensive. All exact methods known for determining an optimal route require a computing effort that increases exponentially with the number of variables to optimize (Kirkpatrick et al., 1983).

2 The annealing schedule such as the initial temperature and the number of Monte-Carlo simulations within each temperature step are usually determined by trial and error (Kirkpatrick et al., 1983; Jang et al., 1997). As a heuristic approach, SA is rather problem-specific or application-specific. In other words, there is no guarantee that a heuristic procedure for finding near-optimal solutions for one problem will be effective for another (Kirkpatrick et al., 1983). The reason is due to lack of obvious analogy for the temperature T with respect to a free parameter in the combinatorial problem. The Boltzmann factor has no mapping at all in its analogy of SA. This feature has unavoidably determined the weakness of SA. A solution to it is to analyze the acceptance ratio (see Equation 6.18) and optimization route along with the temperature decrease, which helps determine an efficient and competent annealing schedule. For further reading on this issue, the author will recommend Lester Ingber's Archive at CalTech at `http://www.ingber.com/#ASA`, Aarts and Korst (1989) at Philips Research Laboratories and many other works in this field.

6.4 Multidimensional scaling

So far, the number of dimensions - k has been pre-selected assuming it is fixed and known. In practice, we only know k shall not be larger than m, the number catchment descriptors. The final determination of how many coordinates to recover from the data rests ultimately with the scientific judgment of the experimenter (Kruskal, 1964a). Formally and scientifically, it can be determined with the help of multidimensional scaling (MDS).

The objective of MDS is to recover the configuration or coordinates of n points in k-dimensional space with the given information of the distances or the ranking relations between n points. A straightforward and mathematically simple way is to implement a metric MDS approach if all concerned $n(n-1)/2$ distances are given in a Euclidean space. The procedure to derive a metric MDS solution can be found in many text books, the author recommends Härdle and Simar (2004) and Mardia et al. (1979). To obtain a metric MDS solution, it is necessary to check if the distance matrix D is Euclidean. Theorem 1 below can be used to do so.

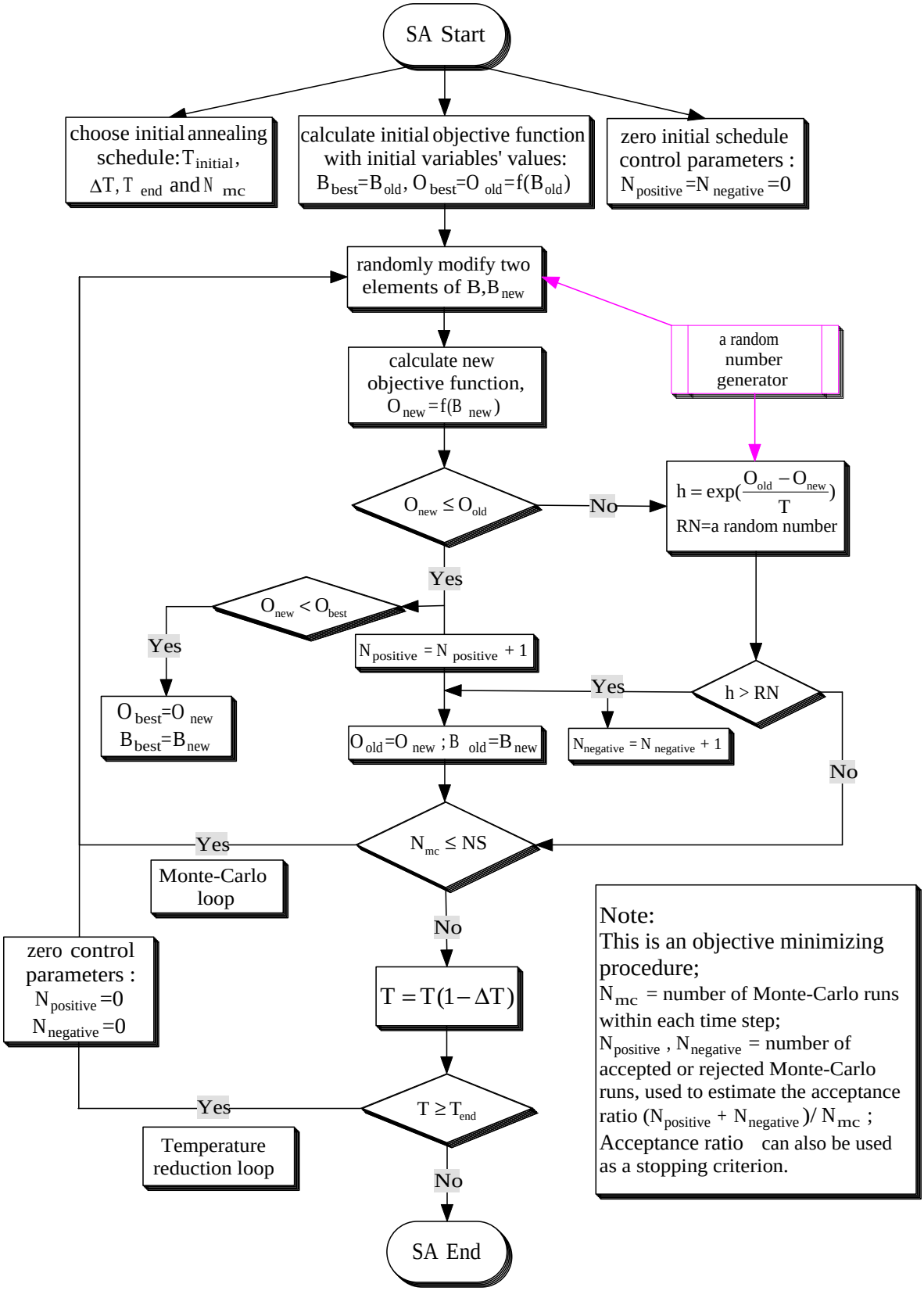


Figure 6.2: Flow chart of the simulated annealing algorithm

Theorem 1 *Define $A = (a_{rs})$, $a_{rs} = -\frac{1}{2}d_{rs}^2$ and $C = HAH$ where H is the centering matrix. D is Euclidean if and only if C is positive semidefinite (p.s.d.).*

To obtain a Euclidean configuration from a given distance matrix D, the following equations can be used:

$$C = ZZ^T \tag{6.19a}$$

$$C = \Gamma\Lambda\Gamma^T \tag{6.19b}$$

$$Z = \Gamma\Lambda^{\frac{1}{2}} \tag{6.19c}$$

$$rank(C) = rank(XX^T) = k \tag{6.19d}$$

where:

$$\begin{array}{rcll} \Lambda & = & diag(\lambda_1, \cdots, \lambda_k) & \text{is the diagonal matrix of the eigenvalues of } B, \\ \Gamma & = & diag(\gamma_1, \cdots, \gamma_k) & \text{is the matrix of corresponding eigenvectors and} \\ Z_{n,k} & = & \begin{pmatrix} z_{1,1} & z_{1,2} & \cdots & z_{1,k} \\ z_{2,1} & z_{2,2} & \cdots & z_{2,k} \\ \vdots & \vdots & \ddots & \vdots \\ z_{n,1} & z_{n,2} & \cdots & z_{n,k} \end{pmatrix} & \text{is the matrix of the coordinates.} \end{array}$$

If C is $p.s.d.$, the number of nonzero eigenvalues gives the number of eigenvalues required for representing the distances D. It is fundamentally the same as the principal component analysis.

The metric MDS can recover the configuration or coordinates of n points whose interpoint distances almost resemble the measured dissimilarities. In reality, it is not often required to strictly reproduce them. More importantly, many applications do not provide similarities in a Euclidean space, which is beyond the scope of a metric MDS. A less rigid MDS would be useful in the latter case. Roger Shepard (Shepard, 1962a,b) first made it clear that we should be concerned with a monotone relation between the experimental data and the distances in the configuration that we are looking for. The monotone relation refers to a resemblance of the ranking order between the objects. Figure 6.3(a) shows an example of a monotone relation where the ranking orders are the same between the measured dissimilarities and distances of the recovered configuration. He pointed out that it is sufficient to obtain the solution once the monotone relation is preserved. Two years after, Joseph Bernard Kruskal (Kruskal, 1964a,b) provided a theoretical foundation and defined a goodness-of-fit measurement which he named as ***Stress***.

$$RawStress = S^* = \sum_{r<s} (d_{rs} - \hat{d}_{rs})^2 \tag{6.20a}$$

$$ScalingFactor = T^* = \sum_{r<s} d_{rs}^2 \tag{6.20b}$$

$$Stress = (\frac{S^*}{T^*})^{1/2} = (\frac{\sum_{r<s} (d_{rs} - \hat{d}_{rs})^2}{\sum_{r<s} d_{rs}^2})^{1/2} \tag{6.20c}$$

$\hat{d}_{rs}$ is the so called disparities of the points which violates the ranking order of the measured dissimilarities. One possible configuration is shown in Figure 6.3(b) in which points (1,4) and (2,4) do not obey the monotone relation and thus called violators. The arrows in Figure 6.3(c) illustrate the directions of movement which can reduce $Stress$. Their disparities can be computed as:

$$\hat{d}_{14} = \hat{d}_{24} = \frac{d_{14} + d_{24}}{2} \tag{6.21}$$

As defined in Equation 6.20, $RawStress$ is nothing more than the residual sum of squares associated with many curve fitting objective functions. $ScalingFactor$ normalizes the solution so that it is not affected when a scaling factor is multiplied. Finally, the goodness-of-fit measure $Stress$ is invariant under change of scale, i.e. uniform stretching or shrinking. If the distance concerned in the study is Euclidean, the solution is also invariant of any rotation in addition to stretching or shrinking.

Kruskal (1964a) proposed an iterative procedure to minimize $Stress$ for a given dimension k. The $Stress$ evaluation can be performed from the lowest to the highest possible dimensions. A graph can be plotted to show how the $Stress$ varies with the change of k. Ideally, the minimum $Stress$ is sought after. (Kruskal, 1964a) recommended three criteria to determine the most appropriate dimension k:

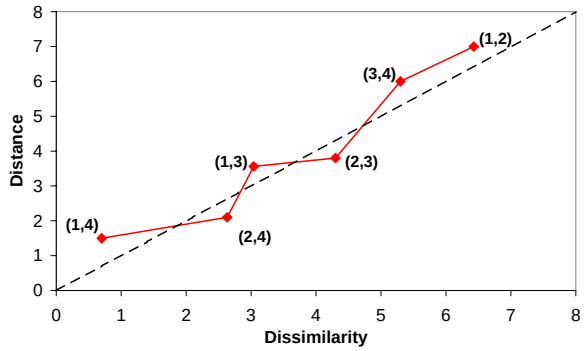
1 a noticeable "elbow" point in the curve is the most appropriate value of k;

2 if the k-dimensional solution provides a satisfying interpretation, but the (k+1)-dimensional solution reveals no further structure, it may be sufficient to use the k-dimensional solution;

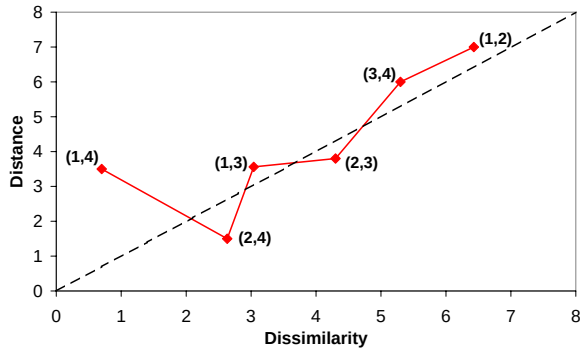
3 if an independent estimate of the statistical error of the data can be performed, the more accurate the data is the more dimensions one is entitled to extract.

He also gave the following verbal evaluation corresponding to different $Stress$ values:

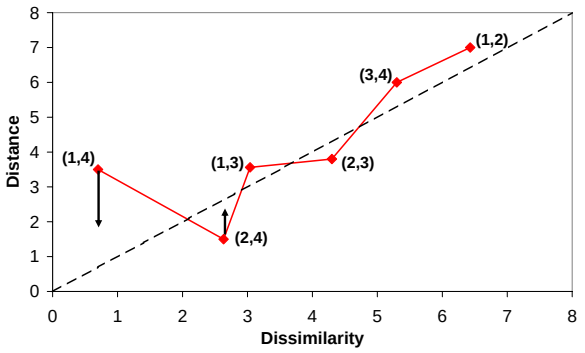
Stress	Goodness of fit
20%	poor
10%	fair
5%	good
2.5%	excellent
0%	perfect



(a) A monotone ranking relation



(b) A non-monotone ranking relation



(c) Violators of the monotone ranking relation

Figure 6.3: A ranking relation between the experimental data and the distances in the configuration

6.5 Model dependency

One interesting research question that has been raised within the scope of catchment classification is the assumption of invariant catchment similarity. The similar catchment pairs or clusters that have been found by using the HBV-IWS model are assumed to be the same if we use a different rainfall runoff model. It is to test if the catchments genuinely carry their similarities independent of the model used for simulation. It is also a backstop measure to determine if the models under consideration are able to capture the underlying simplified hydrological processes in a rational manner. The Xinanjiang model has been selected due to its different model concepts and structures from the HBV model.

The same large number of Monte-Carlo simulations are performed with both the HBV-IWS and the XAJ-IWS model. And the corresponding two groups of most similar catchments are then compared.

7 Application of catchment classification in rainfall-runoff modeling

7.1 Similar catchments

7.1.1 Identification of similar catchments

Following the procedures described in subsection 6.2.2, 20,000 Monte-Carlo simulations are carried out with the HBV-IWS model for the 22 calibration catchments within the time period between 1980 and 1988. For each simulation, both the runoff generation and runoff response parameters are assigned random values for all 22 catchments. Table 7.1 lists these parameters and their average, maximum, minimum and standard deviation values of the 20,000 sets of randomly generated values. The possible parameter space is defined based on the constraints imposed on the parameters defined in the previous study conducted by Hundecha (2005), however the parameter space selected in this study is slightly narrower. The latter is mainly due to the large number of parameters that has to be randomly assigned and limitations as a result of computational constraints. With a limited number of simulations, a smaller parameter space is prefered to a larger one to ensure a thorough search. If one parameter were to be assigned with 3 different random values, 11 parameters will require a $3^{11} = 177,147$ times of combination. 20,000 simulations are far from sufficient to explore the many possible combinations of different parameter values. The number of simulations that obtained NS value greater than or equal to 0.80 for each pair of catchment is shown in Table 7.2. Catchment 13 does not have any simulation with a NS value greater than or equal to 0.80. This might be caused by errors in the observed data. In the resulting catchment classification, catchment 13 is not considered any longer. Only 21 catchments form the pool of catchments and 210 pairs. Their distances d_{NS} is calculated according to Equation 6.4 and provided in Table 7.3.

Table 7.1: Statistics of the 11 model (HBV-IWS) parameters used for 20,000 Monte-Carlo simulations

Parameter	Unit	mean	max	min	σ	comments
Runoff generation parameters						
C_{ET}	[(°C)$^{-1}$]	0.15	0.23	0.08	0.04	for all elevation zones
TT	[°C]	0.00	0.09	-0.09	0.03	
DD	[mm/°C·hour]	0.09	0.14	0.05	0.03	
PWP	[mm]					
Lithosol		65.30	97.49	32.51	18.73	
Ranker		65.29	97.48	32.51	18.70	
Gleysol		64.82	97.49	32.51	18.73	
Cambisol		65.08	97.49	32.51	18.78	
Luvisol		65.18	97.49	32.51	18.71	
Podzol		65.04	97.49	32.51	18.69	
FC	[mm]					
Lithosol		170.58	254.99	85.01	49.13	
Ranker		185.13	277.49	92.51	53.32	
Gleysol		250.07	374.99	125.01	72.37	
Cambisol		149.97	224.99	75.01	43.36	
Luvisol		199.73	299.98	100.01	57.80	
Podzol		185.30	277.49	92.51	53.42	
β	[–]					
Lithosol		1.45	2.17	0.73	0.41	
Ranker		2.00	2.99	1.01	0.58	
Gleysol		2.00	2.99	1.01	0.57	
Cambisol		1.70	2.54	0.86	0.49	
Luvisol		1.85	2.77	0.93	0.53	
Podzol		2.00	2.99	1.01	0.57	
Runoff response parameters						
α	[–]	0.30052	0.45000	0.15000	0.08648	
k_1	[$hour^{-1}$]	0.00404	0.00610	0.00200	0.00117	
k_2	[$hour^{-1}$]	0.00083	0.00120	0.00040	0.00024	
k_{perc}	[$hour^{-1}$]	0.00021	0.00030	0.00010	0.00007	
$MAXBAS$	[–]	23.98	35.00	13.00	6.45	

Table 7.2: Number of simulations obtaining NS value greater than or equal to 0.80 for each pair of catchment out of the 20,000 Monte-Carlo simulations (HBV-IWS model)

Catchment	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1	19647	9701	2073	15986	12958	19299	7873	4435	1082	462	13626	19128	0	15803	17154	18549	17342	18797	17459	17128	1258	18247
2	9701	9701	1312	9701	9386	9699	6695	3612	560	228	9636	9682	0	9669	8215	9620	8789	9700	9701	8826	704	9316
3	2073	1312	2384	2317	2382	2092	2382	2132	1376	690	2343	1879	0	2185	259	1449	501	2058	1994	613	1506	1037
4	15986	9701	2317	16230	13195	16004	8117	4665	1318	633	13842	15729	0	15544	13634	15357	14210	15968	15901	14256	1468	14881
5	12958	9386	2382	13195	13267	12977	8170	4715	1383	693	12457	12711	0	12998	10606	12329	11182	12942	12875	11228	1519	11853
6	19299	9699	2092	16004	12977	19398	7892	4453	1096	481	13645	18947	0	15831	16978	18482	17283	18767	17431	17079	1274	18139
7	7873	6695	2382	8117	8170	7892	8182	4520	1383	693	8143	7629	0	7985	5529	7245	6107	7857	7794	6148	1519	6769
8	4435	3612	2132	4665	4715	4453	4520	4715	1271	666	4686	4261	0	4544	2638	3897	2985	4426	4367	3050	1384	3520
9	1082	560	1376	1318	1383	1096	1383	1271	1385	690	1344	975	0	1186	31	566	113	1067	1007	120	1025	293
10	462	228	690	633	693	481	693	666	690	695	659	457	0	539	17	208	41	473	414	41	492	99
11	13626	9636	2343	13842	12457	13645	8143	4686	1344	659	13896	13379	0	13660	11274	12997	11850	13610	13547	11896	1493	12521
12	19128	9682	1879	15729	12711	18947	7629	4261	975	457	13379	19206	0	15527	17069	18422	17328	18572	17173	17124	1170	18180
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	15803	9669	2185	15544	12998	15831	7985	4544	1186	539	13660	15527	0	15939	13475	15198	14051	15788	15718	14097	1355	14722
15	17154	8215	259	13634	10606	16978	5529	2638	31	17	11274	17069	0	13475	17175	16825	16706	16531	15195	16442	88	16989
16	18549	9620	1449	15357	12329	18482	7245	3897	566	208	12997	18422	0	15198	16825	18550	17223	18233	16919	17054	723	18063
17	17342	8789	501	14210	11182	17283	6107	2985	113	41	11850	17328	0	14051	16706	17223	17342	17028	15772	16761	116	17287
18	18797	9700	2058	15968	12942	18767	7857	4426	1067	473	13610	18572	0	15788	16531	18233	17028	18870	17421	16972	1265	17781
19	17459	9701	1994	15901	12875	17431	7794	4367	1007	414	13547	17173	0	15718	15195	16919	15772	17421	17469	15816	1190	16443
20	17128	8826	613	14256	11228	17079	6148	3050	120	41	11896	17124	0	14097	16442	17054	16761	16972	15816	17128	246	17121
21	1258	704	1506	1468	1519	1274	1519	1384	1025	492	1493	1170	0	1355	88	723	116	1265	1190	246	1519	477
22	18247	9316	1037	14881	11853	18139	6769	3520	293	99	12521	18180	0	14722	16989	18063	17287	17781	16443	17121	477	18249

Table 7.3: The similarity matrix obtained with d_{NS}, catchment 13 is removed because no simulations produce NS values greater than or equal to 0.80 (HBV-IWS model)

Catchment	1	2	3	4	5	6	7	8	9	10	11	12	14	15	16	17	18	19	20	21	22
1	0	0.5062	0.9083	0.1986	0.3558	0.0227	0.6144	0.7877	0.9570	0.9844	0.3199	0.0304	0.2025	0.1280	0.0559	0.1173	0.0470	0.1119	0.1282	0.9470	0.0714
2	0.5062	0	0.9256	0.4023	0.3155	0.5001	0.4353	0.7148	0.9767	0.9923	0.3112	0.4969	0.3954	0.5950	0.4857	0.5408	0.4860	0.4447	0.5312	0.9664	0.5098
3	0.9083	0.9256	0	0.8613	0.8206	0.9054	0.7091	0.5956	0.4266	0.7127	0.8343	0.9229	0.8744	0.9984	0.9525	0.9939	0.9059	0.9045	0.9908	0.3737	0.9753
4	0.1986	0.4023	0.8613	0	0.1914	0.1865	0.5039	0.7156	0.9227	0.9645	0.1505	0.2063	0.0660	0.3332	0.2167	0.2826	0.1675	0.1082	0.2689	0.9126	0.2523
5	0.3558	0.3155	0.8206	0.1914	0	0.3456	0.3851	0.6446	0.8959	0.9479	0.1583	0.3659	0.2011	0.5063	0.3824	0.4565	0.3310	0.2848	0.4452	0.8855	0.4197
6	0.0227	0.5001	0.9054	0.1865	0.3456	0	0.6076	0.7832	0.9553	0.9828	0.3093	0.0364	0.1894	0.1348	0.0507	0.1121	0.0378	0.1034	0.1221	0.9449	0.0705
7	0.6144	0.4353	0.7091	0.5039	0.3851	0.6076	0	0.4704	0.8312	0.9156	0.4168	0.6296	0.5111	0.7825	0.6542	0.7372	0.6002	0.5750	0.7303	0.8144	0.6931
8	0.7877	0.7148	0.5956	0.7156	0.6446	0.7832	0.4704	0	0.7526	0.8646	0.6649	0.7995	0.7253	0.9141	0.8264	0.8910	0.7798	0.7685	0.8848	0.7326	0.8560
9	0.9570	0.9767	0.4266	0.9227	0.8959	0.9553	0.8312	0.7526	0	0.5054	0.9061	0.9643	0.9363	1.0000	0.9875	0.9995	0.9564	0.9581	0.9994	0.5006	0.9966
10	0.9844	0.9923	0.7127	0.9645	0.9479	0.9828	0.9156	0.8646	0.5054	0	0.9550	0.9844	0.9738	1.0000	0.9966	0.9999	0.9829	0.9859	0.9999	0.7707	0.9992
11	0.3199	0.3112	0.8343	0.1505	0.1583	0.3093	0.4168	0.6649	0.9061	0.9550	0	0.3293	0.1575	0.4674	0.3447	0.4173	0.2936	0.2440	0.4054	0.8944	0.3818
12	0.0304	0.4969	0.9229	0.2063	0.3659	0.0364	0.6296	0.7995	0.9643	0.9844	0.3293	0	0.2125	0.1168	0.0474	0.0985	0.0483	0.1210	0.1086	0.9531	0.0570
14	0.2025	0.3954	0.8744	0.0660	0.2011	0.1894	0.5111	0.7253	0.9363	0.9738	0.1575	0.2125	0	0.3367	0.2188	0.2857	0.1713	0.1127	0.2721	0.9242	0.2549
15	0.1280	0.5950	0.9984	0.3332	0.5063	0.1348	0.7825	0.9141	1.0000	1.0000	0.4674	0.1168	0.3367	0	0.1115	0.0630	0.1568	0.2305	0.0810	0.9997	0.0791
16	0.0559	0.4857	0.9525	0.2167	0.3824	0.0507	0.6542	0.8264	0.9875	0.9966	0.3447	0.0474	0.2188	0.1115	0	0.0779	0.0503	0.1166	0.0846	0.9815	0.0362
17	0.1173	0.5408	0.9939	0.2826	0.4565	0.1121	0.7372	0.8910	0.9995	0.9999	0.4173	0.0985	0.2857	0.0630	0.0779	0	0.1140	0.1789	0.0542	0.9995	0.0557
18	0.0470	0.4860	0.9059	0.1675	0.3310	0.0378	0.6002	0.7798	0.9564	0.9829	0.2936	0.0483	0.1713	0.1568	0.0503	0.1140	0	0.0793	0.1088	0.9442	0.0819
19	0.1119	0.4447	0.9045	0.1082	0.2848	0.1034	0.5750	0.7685	0.9581	0.9859	0.2440	0.1210	0.1127	0.2305	0.1166	0.1789	0.0793	0	0.1640	0.9466	0.1519
20	0.1282	0.5312	0.9908	0.2689	0.4452	0.1221	0.7303	0.8848	0.9994	0.9999	0.4054	0.1086	0.2721	0.0810	0.0846	0.0542	0.1088	0.1640	0	0.9977	0.0622
21	0.9470	0.9664	0.3737	0.9126	0.8855	0.9449	0.8144	0.7326	0.5006	0.7707	0.8944	0.9531	0.9242	0.9997	0.9815	0.9995	0.9442	0.9466	0.9977	0	0.9918
22	0.0714	0.5098	0.9753	0.2523	0.4197	0.0705	0.6931	0.8560	0.9966	0.9992	0.3818	0.0570	0.2549	0.0791	0.0362	0.0557	0.0819	0.1519	0.0622	0.9918	0

Catchment descriptors that are selected from calibration catchments (refer to Table 3.2) for classification are listed in Table 7.4. The areas of 6 soil classes and 3 landuse are normalized by the total area of each catchment. The initial transformation matrix B is shown in Table 7.5(a). The initial dimension k is set at 4. A proper dimension is determined with the help of multi-dimensional scaling later on. The coordinates in space u can be obtained with Equation 6.2. The initial coordinates U is shown in Table 7.5(b).

Simulated annealing is applied to optimize the transformation matrix B which leads to a minimum local variance. The actual annealing parameters that are used in this study read as follows:

initial temperature $T_{initial} = 70.0$,

temperature reduction factor $\Delta T = 0.9$,

number of iterations within each temperature step $N_{mc} = 30,000$,

and the annealing procedure is reheated once the acceptance ratio $R_a \leq 0.2$ or the current temperature $T \leq 0.0001$. The iteration is terminated once $O_{best} \leq O_{threshold}$ ($O_{threshold}$ is a value pre-defined based on the expectation of the modeler). It is a slight modification made to the steps described in section 6.3 in order to get out of a lengthier iteration.

Table 7.6 shows the results of an optimum configuration of B and U. As mentioned earlier in section 6.3, the elements of each row of the matrix B should sum up to unity (Equation 6.13c). Each column of B corresponds to each catchment characteristic (recall Table 7.4). The values corresponding to slope and shape are comparatively insignificant, which is due the reason that their original values were not normalized to a scale between 0 and 1. Soil class and land use areas were normalized. Their corresponding values in each column may suggest to how much extent they contribute to the transformed space u to resemble similarities amongst catchments. Almost all the 22 catchments have little or no portion of Lithosol and Ranker. The highest sum of weights (1.022) associated with Lithosol in comparison with the much lower (0.3696) weighted Ranker may suggest the importance of Lithosol in composing catchment similarity defined in this study. Lithosol seems to dominate the hydrological responses once it exits in the catchment, even though it is hard to be found in most of the catchments under study. The dominant soil type in the study area is Cambisol which has a relatively higher sum of weights than the rest three soil types. By vector wise, Lithosol plays no role in the third and fourth dimension of space, which seems to be compensated by the other five types of soil, Cambisol and Gleysol in particular, as well as the slope. Among the three land uses, urban area is the least important factor. Agriculture and forest areas account for the most of the catchment areas and they also demonstrate larger influence on the hydrological behaviour of the catchments. One might argue that the initial conditions of simulated annealing could have random influence on these values. Three different initial conditions were then tested and compared. The relative weights of each column of the B remained similar.

The local variance that is obtained with the optimized configuration has been highly reduced from the initial configuration (see Figure 7.1). A proportion $p \leq 30\%$ is used for calculating $G_B(p)$ since only the close/similar catchments are of interest for parameter transfer for a rainfall runoff model. In Figure 7.1, the line with diamand marks shows the local variance $G_B(p)$ calculated from ascendingly ordered d_{NS} using Equation 6.7. It is to assume the we found the ideal solution that the transformation matrix B could reproduce similarity in the space u. In other words, d_{NS} would have the same ascending order as d_B for all pairs of catchments. Table 7.7 lists the top 30% similar catchment pairs, their distances d_{NS} and the corresponding $G_B(p)$ and O_B (note: they are calculated based on the ascendingly ordered d_{NS}). The squre marked line located on the top of Figure 7.1 is obtained from the initial configuration. The third line marked with trangular is the optimum $G_B(p)$. A very close match between the lines marked with diamand and trangular can be observed, which indicates the minimum O_B found by the optimization is satisfatory.

With the optimized transformation matrix B (see Table 7.6(a)), the catchments that are similar with respect to their modeled output, the Nash-Sutcliffe efficiency in this study, are expected to be reproduced in the space u. Table 7.8 lists 63 catchment pairs ($p \leq 30\%$) that behave similarly with respect to their modeled performance NS as well as 63 classified similar catchment pairs in the transformed space u. Ideally, if the minimum O_B obtained by optimization was exactly the same as or close to the one obtained with the ascendingly ordered d_{NS}, two sets of ranked catchment pairs would be exactly or almost the same. In reality, the two sets that are listed differ in both the distances and rank orders although Figure 7.1 shows a comparatively low variance has been found. Nevertheless, similar catchment pairs have been reproduced in many cases. Many of the similar pairs appear in both sets. Figure 7.2 provides a comparison between the rank order before optimization and after optimization. The cicle marks are those close/similar pairs within the top 30%. The stars represent the rest 70% pairs. Before optimization, the rank orders (based on d_B) of any pair is random. After optimization, the cicles demonstate a dinstinct cluster around the diagonal line with the exception of the pairs ranking above the 50th. Since the objective function is formulated based on only the 30% closest pairs, we do not expect any change made to the rest of the pairs even though their rank orders are unavoidably affected by the change caused by the relocations of the first 30% pairs in the space u.

Table 7.4: List of the 11 selected catchments descriptors $[X]_{cali}$

$[X]$		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
Lithosol	**(%)**	0.0362	0.0000	0.0055	0.0008	0.0006	0.0108	0.0000	0.0000	0.0407	0.0948	0.0620
Ranker	**(%)**	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0253	0.0580	0.0486
Gleysol	**(%)**	0.1629	0.0424	0.2517	0.1276	0.4497	0.1047	0.1745	0.5033	0.0616	0.0755	0.0000
Cambisol	**(%)**	0.5912	0.8794	0.4446	0.7280	0.4672	0.5993	0.5967	0.2088	0.5743	0.4118	0.6337
Luvisol	**(%)**	0.2097	0.0781	0.2729	0.1427	0.0652	0.0493	0.2109	0.2614	0.2981	0.3599	0.2211
Podzol	**(%)**	0.0000	0.0000	0.0253	0.0010	0.0173	0.2359	0.0180	0.0266	0.0000	0.0000	0.0346
Slope	**(-)**	1.8358	1.9769	1.5265	1.2475	0.8710	1.5804	1.6342	0.9983	1.8787	1.1501	1.5067
Shape	**(-)**	2.2000	6.0000	1.0800	2.8400	7.8900	0.7400	1.8700	2.6200	2.5600	1.4300	2.3800
Forest	**(%)**	0.3758	0.3875	0.6053	0.3777	0.2622	0.4027	0.3721	0.2169	0.4798	0.3011	0.4532
Urban	**(%)**	0.1619	0.1645	0.1280	0.1131	0.1032	0.0820	0.0800	0.0922	0.1428	0.1390	0.1176
Agriculture	**(%)**	0.4604	0.4481	0.2669	0.5077	0.6345	0.5149	0.5479	0.6888	0.3778	0.5600	0.4293

		12	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**
Lithosol	**(%)**	0.0000	0.0000	0.0000	0.0000	0.0000	0.0218	0.0000	0.0000	0.0509	0.0000
Ranker	**(%)**	0.0000	0.0000	0.0017	0.0533	0.0000	0.0422	0.0019	0.0322	0.0296	0.0753
Gleysol	**(%)**	0.0000	0.0000	0.0000	0.0067	0.1625	0.0000	0.0597	0.0000	0.3290	0.0000
Cambisol	**(%)**	0.8460	1.0000	0.9228	0.7433	0.7125	0.7997	0.7306	0.9678	0.2857	0.8216
Luvisol	**(%)**	0.0621	0.0000	0.0000	0.0817	0.0083	0.0000	0.1307	0.0000	0.2348	0.0272
Podzol	**(%)**	0.0918	0.0000	0.0755	0.1150	0.1167	0.1362	0.0772	0.0000	0.0699	0.0760
Slope	**(-)**	1.8457	1.1229	1.2756	1.4297	1.2757	1.5498	1.3602	1.5791	1.0127	1.5938
Shape	**(-)**	1.3800	0.9800	2.8500	3.3000	4.2300	1.6200	5.6600	3.9800	1.2500	2.1300
Forest	**(%)**	0.6917	0.4107	0.4755	0.4199	0.3557	0.5112	0.4546	0.5900	0.3391	0.6009
Urban	**(%)**	0.1653	0.1000	0.0830	0.0830	0.0830	0.1582	0.0970	0.1010	0.1271	0.1050
Agriculture	**(%)**	0.1434	0.4852	0.4415	0.4968	0.5620	0.3306	0.4484	0.3065	0.5299	0.2931

Table 7.5: Initial configuration of transformation matrix B (a) and coordinates U (b)

(a) Initial transformation matrix B

B	0.0909	0.0909	0.0909	0.0909	0.0909	0.0909	0.0909	0.0909	0.0909	0.0909	0.0909
	0.0909	0.0909	0.0909	0.0909	0.0909	0.0909	0.0909	0.0909	0.0909	0.0909	0.0909
	0.0909	0.0909	0.0909	0.0909	0.0909	0.0909	0.0909	0.0909	0.0909	0.0909	0.0909
	0.0909	0.0909	0.0909	0.0909	0.0909	0.0909	0.0909	0.0909	0.0909	0.0909	0.0909

(b) Initial Coordinates U

$U = B[X]$	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
	0.5485	0.907	0.4188	0.5533	0.9783	0.3927	0.5004	0.5106	0.5854	0.4164	0.5352
	0.5485	0.907	0.4188	0.5533	0.9783	0.3927	0.5004	0.5106	0.5854	0.4164	0.5352
	0.5485	0.907	0.4188	0.5533	0.9783	0.3927	0.5004	0.5106	0.5854	0.4164	0.5352
	0.5485	0.907	0.4188	0.5533	0.9783	0.3927	0.5004	0.5106	0.5854	0.4164	0.5352
	12	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	
	0.4751	0.3726	0.5569	0.6118	0.6824	0.4700	0.8200	0.6870	0.3872	0.5203	
	0.4751	0.3726	0.5569	0.6118	0.6824	0.4700	0.8200	0.6870	0.3872	0.5203	
	0.4751	0.3726	0.5569	0.6118	0.6824	0.4700	0.8200	0.6870	0.3872	0.5203	
	0.4751	0.3726	0.5569	0.6118	0.6824	0.4700	0.8200	0.6870	0.3872	0.5203	

Table 7.6: Configuration of transformation matrix B (a) and coordinates U (b) after optimization

(a) Transformation matrix B after optimization

												$\sum$
B	0.6295	0.0148	0.0376	0.0804	0.0536	0.1470	0.0000	0.0060	0.0309	0.0000	0.0001	1.00
	0.3927	0.0802	0.0000	0.0000	0.0416	0.0286	0.0000	0.0000	0.2149	0.0708	0.1712	1.00
	0.0000	0.1469	0.2061	0.2372	0.1033	0.1507	0.0448	0.0000	0.0124	0.0011	0.0975	1.00
	0.0000	0.1277	0.1306	0.1158	0.1230	0.1260	0.0285	0.0000	0.1198	0.0968	0.1318	1.00
$\sum$	1.0222	0.3696	0.3743	0.4334	0.3215	0.4523	0.0733	0.0060	0.3780	0.1687	0.4006	
	Lith.	Rank.	Gley.	Camb.	Luvi.	Podz.	Slop.	Shap.	Fore.	Urba.	Agri.	

(b) Coordinates U after optimization

U=B[X]	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
	0.1125	0.1242	0.0922	0.1003	0.116	0.1132	0.0912	0.076	0.1206	0.1337	0.1359
	0.1941	0.175	0.1992	0.1824	0.1758	0.1936	0.1888	0.1827	0.2084	0.2273	0.2177
	0.3275	0.3627	0.2914	0.3241	0.3171	0.3305	0.3334	0.2989	0.3106	0.269	0.3007
	0.2893	0.2948	0.2847	0.2773	0.2729	0.288	0.2912	0.2796	0.2891	0.2654	0.2764
	12	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	
	0.1145	0.099	0.117	0.1148	0.1172	0.1242	0.1272	0.1203	0.1087	0.1111	
	0.1902	0.1784	0.186	0.1922	0.1823	0.1936	0.1892	0.1891	0.2068	0.1962	
	0.3264	0.3401	0.3368	0.3291	0.3374	0.3247	0.3215	0.3424	0.2761	0.3278	
	0.2876	0.2707	0.2762	0.2829	0.2806	0.2795	0.2802	0.2821	0.2692	0.2839	

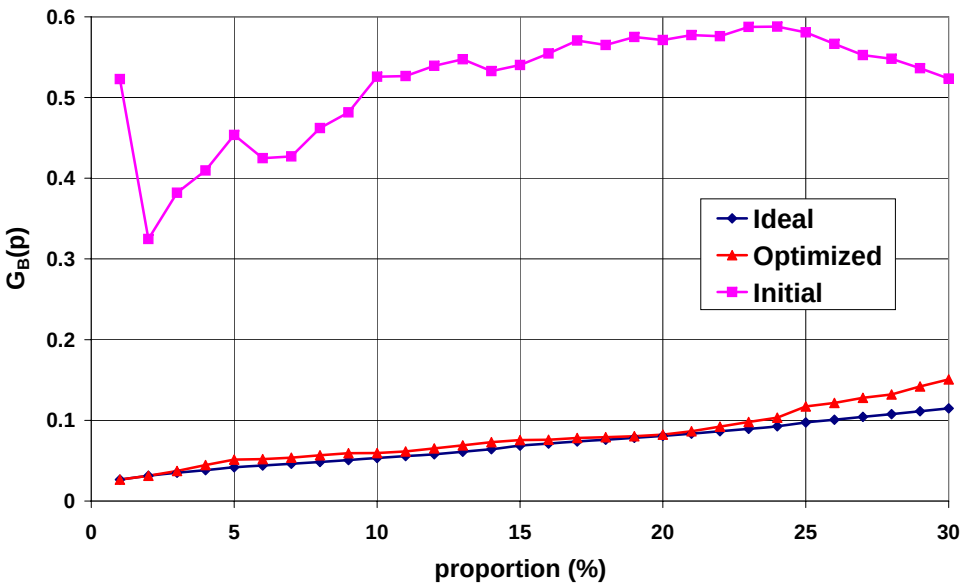


Figure 7.1: Local variance $G_B(p)$ obtained from the initial configuration of U (Initial), d_{NS} in an ascending order (Ideal) and the optimized configuration U in the transformed space u (Optimized)

Table 7.7: The catchment pairs (Catchment r - Cat. r and Catchment s - Cat. s) that are ranked by similarity d_B and the corresponding $G_B(p)$ and $O_B(p)$ used as the optimization goal, d_{NS} in an ascending order is used here to obtain $G_B(p)$ and $O_B(p)$

$nr.$	**Index**	d_{NS}	accumulated d_{NS}	**Cat.** r	**Cat.** s	p	$G_B(p)$	$O_B(p)$
1	5	0.0227	0.0227	1	6			0
2	11	0.0304	0.0531	1	12	1	0.0266	0.0266
3	195	0.0362	0.0893	16	22			0.0266
4	96	0.0364	0.1257	6	12	2	0.0314	0.0580
5	101	0.0378	0.1635	6	18			0.0580
6	16	0.0470	0.2105	1	18	3	0.0351	0.0931
7	168	0.0474	0.2579	12	16			0.0931
8	170	0.0483	0.3062	12	18	4	0.0383	0.1313
9	191	0.0503	0.3565	16	18			0.1313
10	99	0.0507	0.4072	6	16			0.1313
11	198	0.0542	0.4614	17	20	5	0.0419	0.1733
12	200	0.0557	0.5171	17	22			0.1733
13	14	0.0559	0.5730	1	16	6	0.0441	0.2174
14	174	0.0570	0.6300	12	22			0.2174
15	209	0.0622	0.6922	20	22	7	0.0461	0.2635
16	184	0.0630	0.7552	15	17			0.2635
17	66	0.0660	0.8212	4	14	8	0.0483	0.3118
18	105	0.0705	0.8917	6	22			0.3118
19	20	0.0714	0.9631	1	22	9	0.0507	0.3625
20	190	0.0779	1.0410	16	17			0.3625
21	189	0.0791	1.1201	15	22	10	0.0533	0.4158
22	201	0.0793	1.1994	18	19			0.4158
23	187	0.0810	1.2804	15	20	11	0.0557	0.4715
24	204	0.0819	1.3623	18	22			0.4715
25	193	0.0846	1.4469	16	20	12	0.0579	0.5294
26	169	0.0985	1.5454	12	17			0.5294
27	102	0.1034	1.6488	6	19	13	0.0611	0.5904
28	71	0.1082	1.7570	4	19			0.5904
29	172	0.1086	1.8656	12	20	14	0.0643	0.6548
30	202	0.1088	1.9744	18	20			0.6548
31	183	0.1115	2.0859	15	16			0.6548
32	17	0.1119	2.1978	1	19	15	0.0687	0.7235
33	100	0.1121	2.3099	6	17			0.7235

continued on next page

$nr.$	**Index**	d_{NS}	accumulated d_{NS}	**Cat. r**	**Cat. s**	p	$G_B(p)$	$O_B(p)$
34	179	0.1127	2.4226	14	19	16	0.0713	0.7947
35	196	0.1140	2.5366	17	18			0.7947
36	192	0.1166	2.6532	16	19	17	0.0737	0.8684
37	167	0.1168	2.7700	12	15			0.8684
38	15	0.1173	2.8873	1	17	18	0.0760	0.9444
39	171	0.1210	3.0083	12	19			0.9444
40	103	0.1221	3.1304	6	20	19	0.0783	1.0227
41	13	0.1280	3.2584	1	15			1.0227
42	18	0.1282	3.3866	1	20	20	0.0806	1.1033
43	98	0.1348	3.5214	6	15			1.1033
44	64	0.1504	3.6718	4	11	21	0.0835	1.1867
45	207	0.1519	3.8237	19	22			1.1867
46	185	0.1568	3.9805	15	18	22	0.0865	1.2733
47	157	0.1575	4.1380	11	14			1.2733
48	80	0.1583	4.2963	5	11	23	0.0895	1.3628
49	205	0.1640	4.4603	19	20			1.3628
50	70	0.1674	4.6277	4	18	24	0.0926	1.4553
51	178	0.1713	4.7990	14	18			1.4553
52	197	0.1789	4.9779	17	19			1.4553
53	59	0.1865	5.1644	4	6	25	0.0974	1.5528
54	97	0.1894	5.3538	6	14			1.5528
55	58	0.1914	5.5452	4	5	26	0.1008	1.6536
56	3	0.1986	5.7438	1	4			1.6536
57	82	0.2011	5.9449	5	14	27	0.1043	1.7579
58	12	0.2025	6.1474	1	14			1.7579
59	65	0.2063	6.3537	4	12	28	0.1077	1.8656
60	166	0.2125	6.5662	12	14			1.8656
61	68	0.2167	6.7829	4	16	29	0.1112	1.9768
62	176	0.2188	7.0017	14	16			1.9768
63	186	0.2305	7.2322	15	19	30	0.1148	2.0916

Table 7.8: Similar catchments with respect to their modeled performance NS and the classified similar catchments in the transformed space u

Catchement pairs with similar model performance					Similar catchment pairs in space *u*				
Rank	Index	d_{NS}	Catchment *r*	Catchment *s*	Index	d_B	Catchment *r*	Catchment *s*	Rank
1	5	0.0227	1	6	5	0.0304	1	6	1
2	11	0.0304	1	12	11	0.0428	1	12	2
3	195	0.0362	16	22	96	0.0491	6	12	4
4	96	0.0364	6	12	195	0.0507	16	22	3
5	101	0.0378	6	18	99	0.0509	6	16	21
6	16	0.047	1	18	168	0.0517	12	16	23
7	168	0.0474	12	16	184	0.052	15	17	6
8	170	0.0483	12	18	105	0.0526	6	22	17
9	191	0.0503	16	18	20	0.0528	1	22	15
10	99	0.0507	6	16	201	0.0557	18	19	5
11	198	0.0542	17	20	14	0.0647	1	16	13
12	200	0.0557	17	22	174	0.0706	12	22	34
13	14	0.0559	1	16	198	0.0814	17	20	11
14	174	0.057	12	22	187	0.0835	15	20	12
15	209	0.0622	20	22	191	0.0987	16	18	38
16	184	0.063	15	17	183	0.1084	15	16	7
17	66	0.066	4	14	170	0.1181	12	18	32
18	105	0.0705	6	22	190	0.1197	16	17	8
19	20	0.0714	1	22	204	0.1288	18	22	9
20	190	0.0779	16	17	193	0.1318	16	20	18
21	189	0.0791	15	22	101	0.135	6	18	31
22	201	0.0793	18	19	192	0.1353	16	19	10
23	187	0.081	15	20	16	0.1389	1	18	14
24	204	0.0819	18	22	169	0.1389	12	17	19
25	193	0.0846	16	20	171	0.1391	12	19	20
26	169	0.0985	12	17	103	0.1407	6	20	24
27	102	0.1034	6	19	100	0.1409	6	17	40
28	71	0.1082	4	19	98	0.1418	6	15	85
29	172	0.1086	12	20	167	0.1447	12	15	33
30	202	0.1088	18	20	185	0.1458	15	18	39
31	183	0.1115	15	16	189	0.1494	15	22	16
32	17	0.1119	1	19	66	0.1593	4	14	41
33	100	0.1121	6	17	172	0.1603	12	20	27
34	179	0.1127	14	19	200	0.1637	17	22	108
35	196	0.114	17	18	15	0.1642	1	17	36
36	192	0.1166	16	19	196	0.165	17	18	22
37	167	0.1168	12	15	13	0.1659	1	15	29
38	15	0.1173	1	17	209	0.1676	20	22	35
39	171	0.121	12	19	202	0.1693	18	20	25
40	103	0.1221	6	20	102	0.1694	6	19	26
41	13	0.128	1	15	17	0.1695	1	19	37
42	18	0.1282	1	20	18	0.1699	1	19	42
43	98	0.1348	6	15	207	0.1701	19	22	28
44	64	0.1504	4	11	58	0.1701	4	5	170
45	207	0.1519	19	22	68	0.1703	4	16	43
46	185	0.1568	15	18	186	0.1705	15	19	30
47	157	0.1575	11	14	74	0.1706	4	22	187
48	80	0.1583	5	11	65	0.1728	4	12	152
49	205	0.164	19	20	87	0.1738	5	19	59
50	70	0.1674	4	18	197	0.1794	17	19	80
51	178	0.1713	14	18	60	0.1795	4	7	100
52	197	0.1789	17	19	175	0.1843	14	15	50
53	59	0.1865	4	6	3	0.1873	1	4	54
54	97	0.1894	6	14	59	0.1889	4	6	90
55	58	0.1914	4	5	177	0.1904	14	17	44
56	3	0.1986	1	4	67	0.191	4	15	53
57	82	0.2011	5	14	69	0.1953	4	17	91
58	12	0.2025	1	14	86	0.1968	5	18	96
59	65	0.2063	4	12	205	0.1982	19	20	48
60	166	0.2125	12	14	83	0.2006	5	15	92
61	68	0.2167	4	16	81	0.2028	5	12	45
62	176	0.2188	14	16	85	0.2032	5	17	82
63	186	0.2305	15	19	84	0.2033	5	16	46

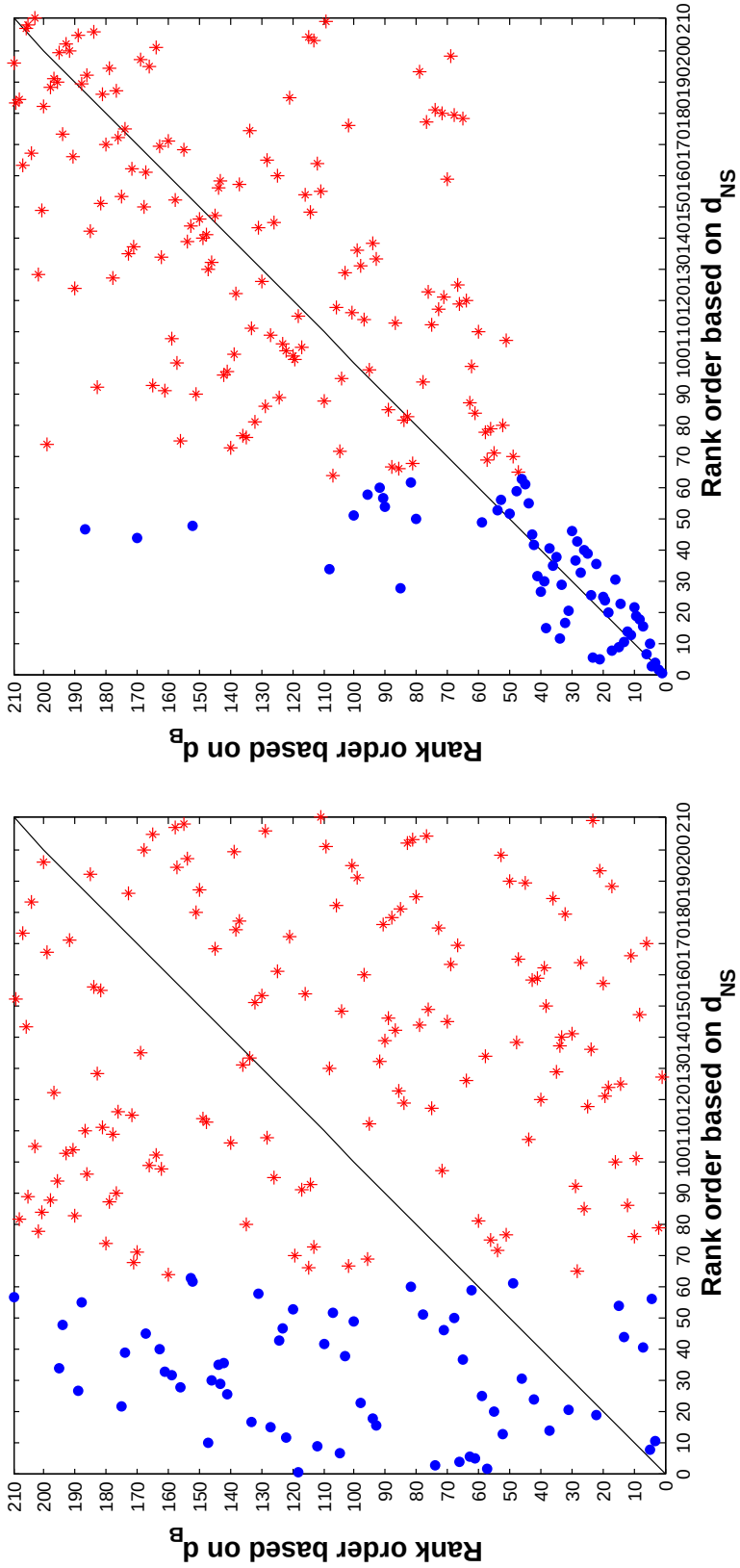


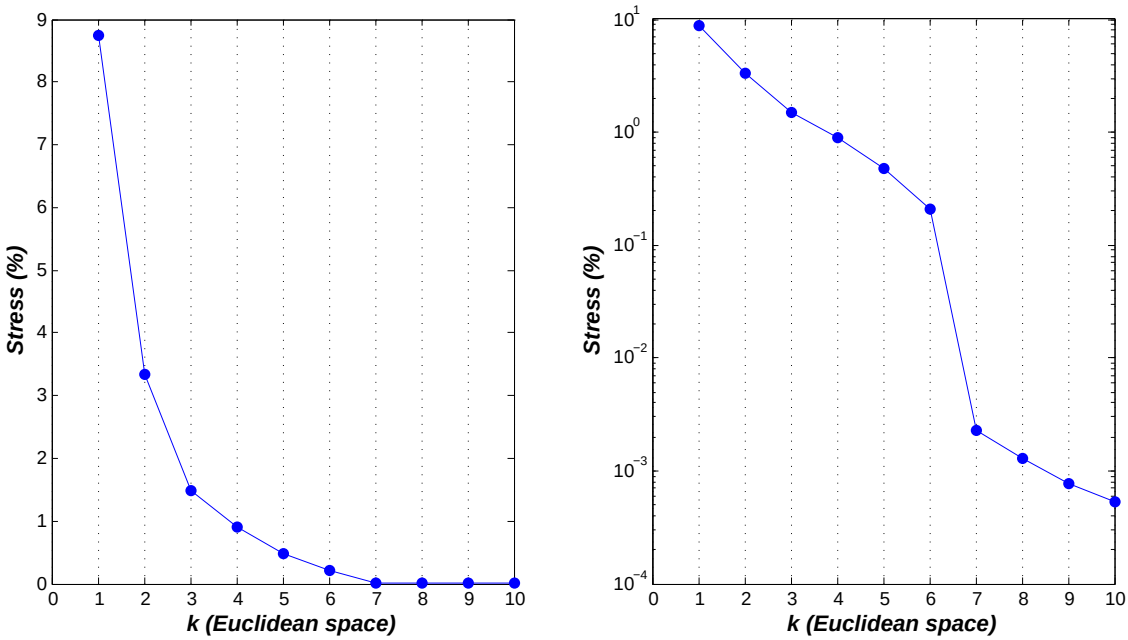
Figure 7.2: Comparison of rank orders of similar catchment pairs with respect to their modeled performance NS and the classified similar catchments in the transformed space u (left: before optimization, right: after optimization, circles: close/similar pairs within the top 30%, stars: rest 70% pairs)

7.1.2 Determination of a proper dimension

The number of dimensions k of the space u is pre-selected as 4 in the previous section. The first guess "4" is based on the number of selected catchment descriptors. The proposed catchment classification scheme aims not only at classification of similar catchments but also predictions in ungauged basins. It would be most practical to use those readily available catchment characteristics to achieve our goals. This is the reason why only a small number ($m = 11$) of physiographic catchment descriptors are selected. A low dimension of space might not be sufficient to represent the very complex and non-linear hydrological system. We could in principle use as many dimensions as possible to represent the hydrological system, but a large dimension does not necessarily lead to sensible meaning. To make a first reasonable guess, $m = 11$ is used as a yardstick and $k = 4$ is selected as a number being not too small nor too big for the purposes of this study. A proper dimension k will have to be determined scientifically, if possible.

We are concerned with the monotone relationship between the original similarities d_{NS} and the reproduced distances d_B in a transformed space. To this end, the non-metric multidimensional scaling (MDS) is most suitable. As introduced in section 6.4, $Stress$ is used as the objective function for the distance matrix of d_{NS} to find a proper k. Dimensions are tested from 1 up to 10 and their $Stress$ values are listed in Table 7.9 and plotted in Figure 7.3. It can be seen that $Stress$ generally decreases with the increase of k. According to Kruskal (refer to section 6.4), a "perfect" match is obtained in 10 dimensions ($Stress = 0.0005267\%$), a "good" match can be obtained from 2 to 3 dimensions and a close to perfect match starts from 4 dimensions. The decrease of $Stress$ is trivial from 7 up to 10 dimensions, which can be seen clearly from the log scaled $Stress$ (see Figure 7.3(b)). Figure 7.4 to Figure 7.6 illustrates the change from a "fair" to "perfect" match as k increases. One can indeed observe a perfect match of the rank orders as well as distances between the recovered and the original spaces. It shows that the non-metric MDS has found a configuration of points in 10 dimensions whose interpoint distances approximate the similarities, which is in fact a transformation of the original catchment distances d_{NS}.

The results suggest 4 dimensions are the minimum and 10 the maximum for the reconstructed configuration to closely resemble the original one. While the non-metric MDS reconstructs the entire space with all possible pairs of objects, the local variance reduction only looks at the closest 30% of pairs. It is reasonalbe to take a smaller dimension as an approriate number for reconstruction because the space of interest is less than halved (from 100% to 30%). The results of the non-metric MDS and the fact of a smaller space suggest the number 4 to be appropriate. In fact, an exact reconstruction might not exist even if 10 dimensions lead to a "perfect" match. This issue will be discussed later on in section 8.1.



(a) $Stress$ in percentage

(b) $Stress$ in percentage with log scale

Figure 7.3: $Stress$ varies with dimension k

Table 7.9: $Stress$ varies with dimension k ($k = 1, 2, \cdots, 10$)

k	$Stress$ **(%)**
1	8.747908
2	3.330472
3	1.493136
4	0.894362
5	0.472817
6	0.209292
7	0.002278
8	0.001290
9	0.000779
10	0.000527

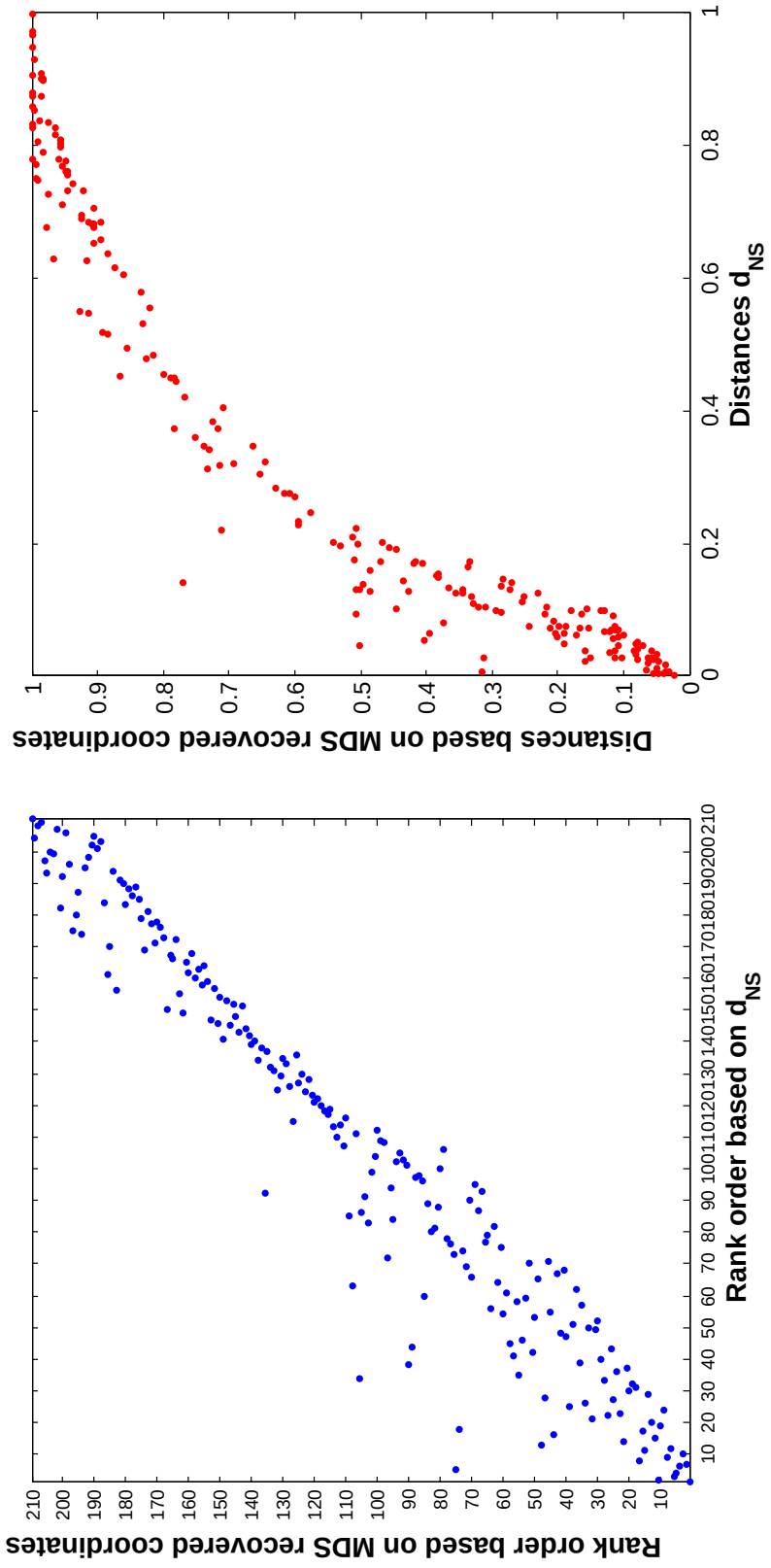


Figure 7.4: Non-metric MDS recovered coordinates in **1** dimension, left: rank order based on recovered coordinates vs. rank order based on d_{NS}, right: distances based on recovered coordinates vs. d_{NS}

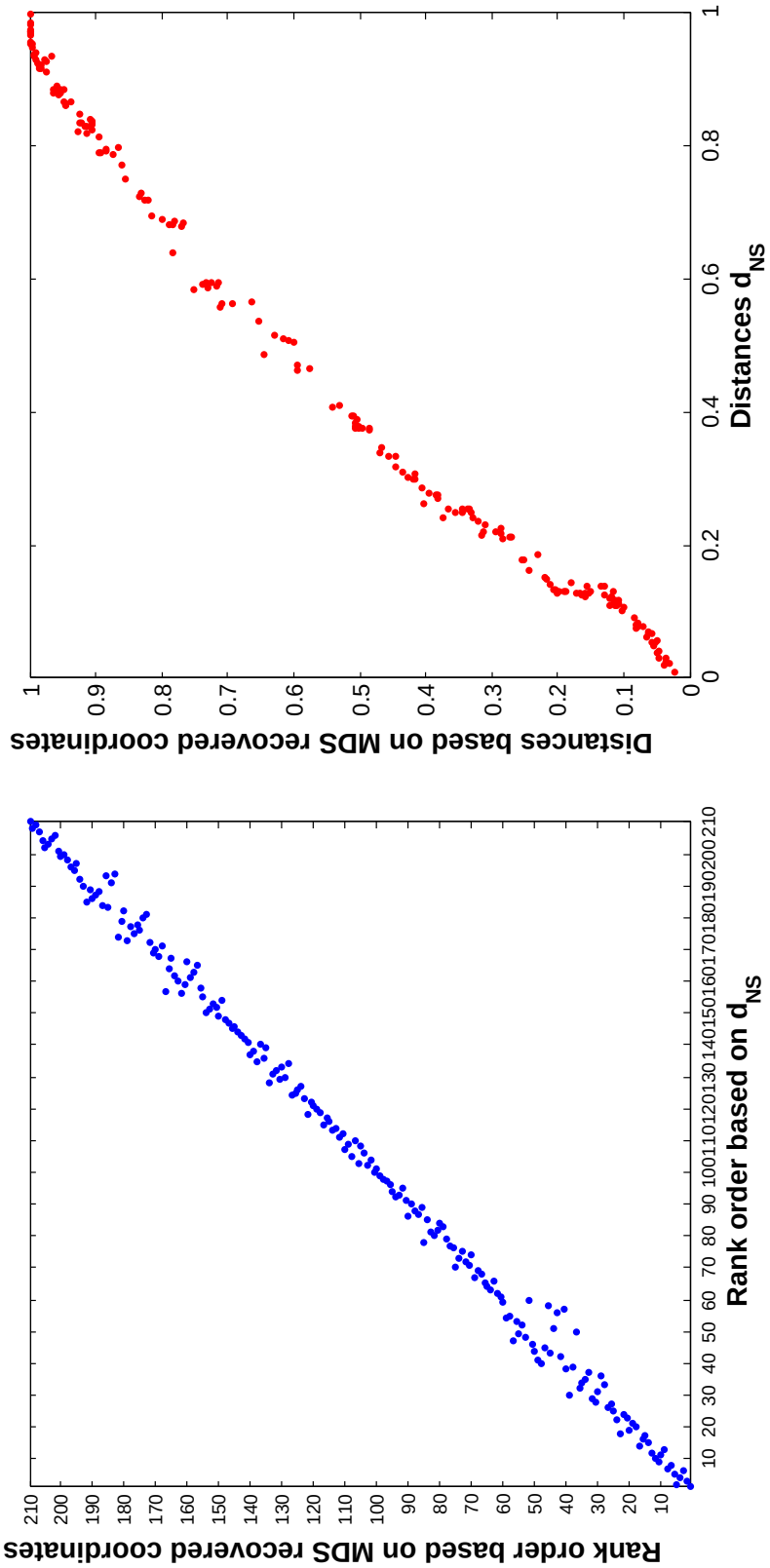


Figure 7.5: Non-metric MDS recovered coordinates in **4** dimensions, left: rank order based on recovered coordinates vs. rank order based on d_{NS}, right: distances based on recovered coordinates vs. d_{NS}

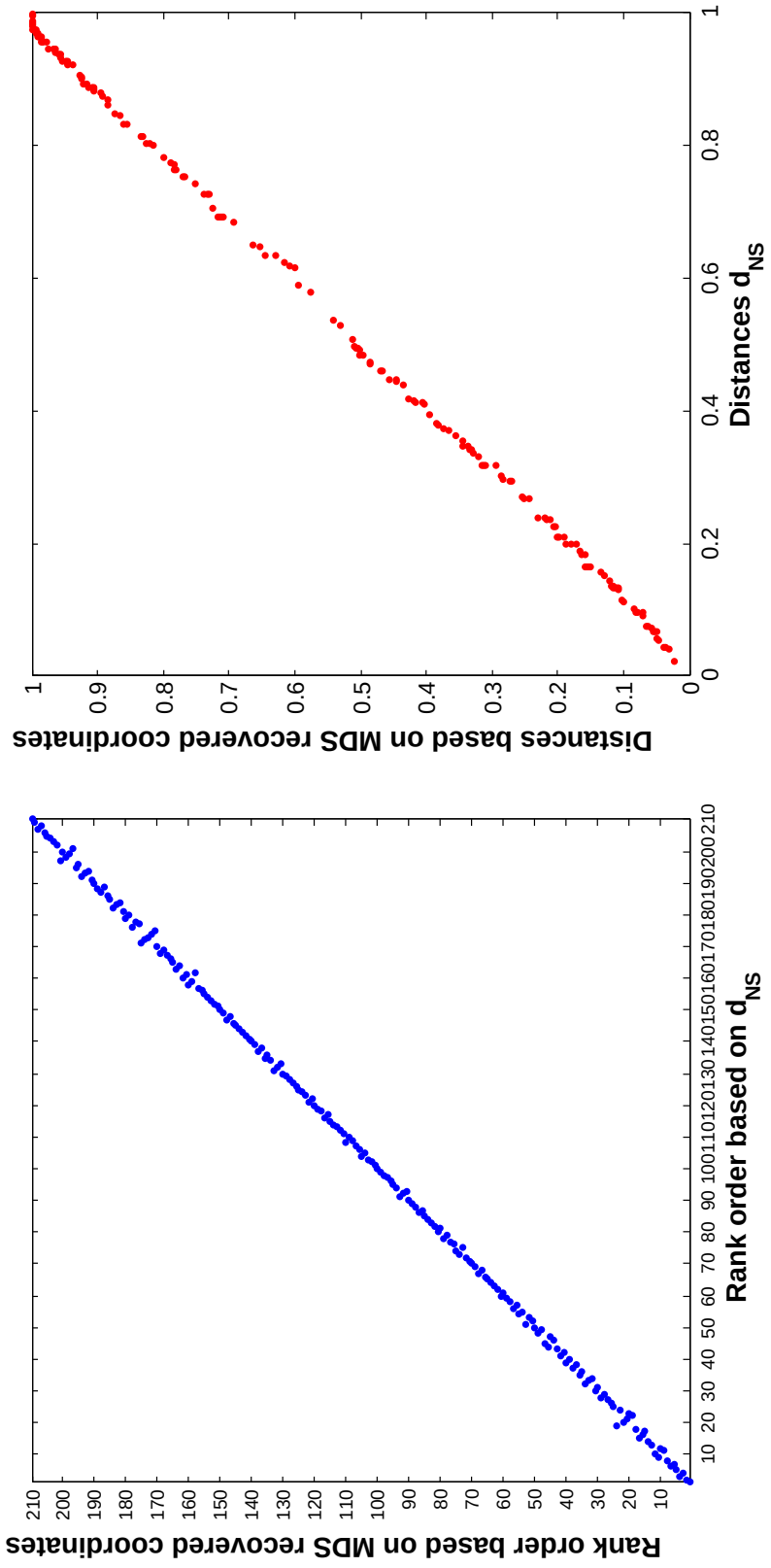


Figure 7.6: Non-metric MDS recovered coordinates in **10** dimensions, left: rank order based on recovered coordinates vs. rank order based on d_{NS}, right: distances based on recovered coordinates vs. d_{NS}

7.2 Regional transfer of model parameter sets

An attempt has been made to establish a catchment classification scheme using a number of selected catchments in the Rhine River Basin. The classification scheme assumes that a distance defined on the space of catchment descriptors can be used to reproduce similarity with respect to catchment responses (represented by the model performance - NS). In other words, their similarity can be reconstructed in the space of catchment descriptors when similar catchments are found with respect to their responses.

The subset of independent catchment response of the most similar cases is expected to be used for prediction. An example has been provided by Bárdossy et al. (2005) where the subset of similar catchments was used for streamflow prediction. Another basic application would be to transfer the model parameters within similar catchments. One can simply borrow the set of model parameters that produces good model performance for catchment r and apply it to catchment s that is similar to r (similarity is measured in the space of catchment descriptors). Five validation catchments (catchment 23-27, see section 3.2) are used to verify this application.

The HBV-IWS model is run for the 5 validation catchments with the same 20,000 sets of randomly generated parameters used for calibration catchments for the same time period from 1980 to 1988. The simulation results are combined with the ones obtained from the calibration catchments. Same as catchment 13, catchment 27 does not have any simulation with a NS value greater than or equal to 0.80 and is therefore excluded from further processing. The distances d_{NS} for all possible pairs $\frac{25(25-1)}{2} = 300$ are then computed and ranked with an ascending order. The transformation matrix B found from the calibration catchments are multiplied with the 11 catchment descriptors of 5 validation catchments $[X]_{vali}$ (see Table 7.10) to obtain the coordinates of the validation catchment U_{vali} in the space u. The ascending rank orders of the distances based on d_B for both calibration and validation catchments can then be established and plotted against the rank orders based on d_{NS} (see Figure 7.7). The dots represent the calibration catchment pairs after including the validation catchment pairs. The stars represent 90 pairs related to validation catchments. Compared to Figure 7.2(right), a similar scatter pattern along the diagonal line can be observed. The ideal situation would be a cluster of points along the diagonal line, which indicates a perfect reproduction of the similarity in the transformed space.

The most similar catchment pairs found in the transformed space are taken to test if any set of model parameters leading to good model performance can be directly applied within similar catchments. The * point that is the closest to the origin (0,0) on Figure 7.7 has rank orders 21 (in the original space) versus 12 (in the space u) as its coordinate of the corresponding catchment pair **1** and **23**. Table 7.11 lists the number of simulations obtaining NS value greater than or equal to 0.80 for the pair of catchment **1** and **23** out of the 20,000 Monte-Carlo simulations. This result suggests that the two catchments tend to have similar model performance and responses because they share a significant number (18,887 out

Table 7.10: List of the 11 selected catchments descriptors $[X]_{vali}$

[X]		23	24	25	26	27
Lithosol	**(%)**	0.0283	0.0412	0.0803	0.0882	0.1078
Ranker	**(%)**	0.0000	0.0000	0.0000	0.0000	0.1260
Gleysol	**(%)**	0.0000	0.0000	0.0000	0.0000	0.0862
Cambisol	**(%)**	0.9177	0.8644	0.7920	0.9118	0.2670
Luvisol	**(%)**	0.0000	0.0944	0.1277	0.0000	0.4129
Podzol	**(%)**	0.0540	0.0000	0.0000	0.0000	0.0000
Slope	**(-)**	1.9191	1.2800	1.7733	1.9611	1.0294
Shape	**(-)**	1.2900	2.8200	2.2100	2.3900	1.2500
Forest	**(%)**	0.7663	0.6163	0.6204	0.7584	0.3331
Urban	**(%)**	0.1785	0.1829	0.1210	0.1430	0.1430
Agriculture	**(%)**	0.0551	0.1970	0.2467	0.0907	0.5237

of 20,000 sets) of parameters leading to good model performance for the given HBV-IWS model. If one does not have the luxury to optimize a rainfall runoff model on a certain catchment for prediction, a fairly reliable prediction can be obtained by using its "similar counterpart catchment" as such. An example is provided in Figure 7.8, where the same set of model parameters (randomly selected out of the 20,000 sets) that obtained good model performance (NS=0.9118) for the calibration catchment Nr. 1 could result in good model performance (NS=0.9248) for the validation catchment Nr. 23 during the time period from 1980 to 1988 (refer to Figure 7.8(c) for their locations).

The efficacy of parameter transfer or regionalization is closely related to the definition of hydrologic similarity, which will be discussed in section 8.2.

Table 7.11: Number of simulations with NS values greater than or equal to 0.80 for the pair of catchment **1** and **23** out of the 20,000 Monte-Carlo simulations

	Catchment 1	Catchment 23
Catchment 1	19647	18887
Catchment 23	18887	18946

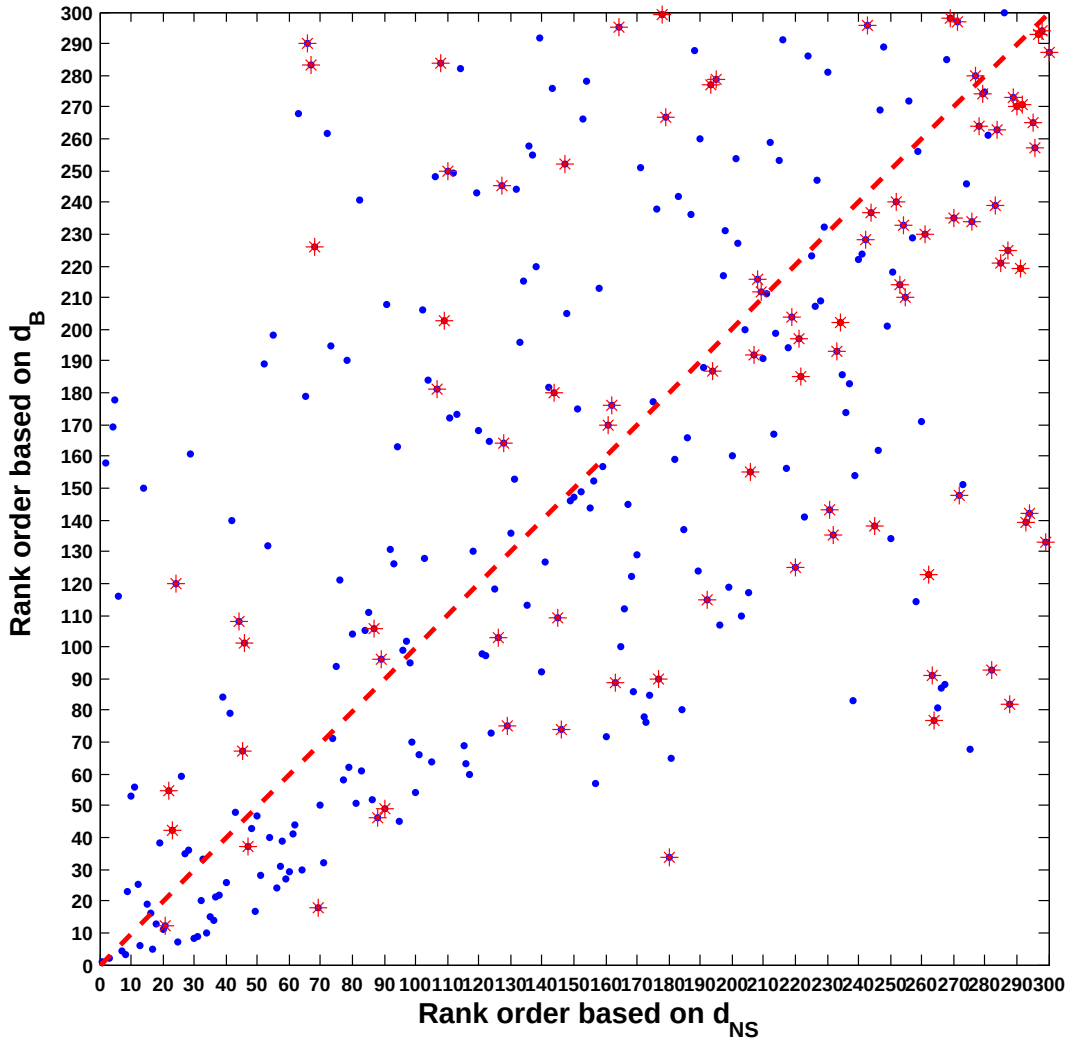
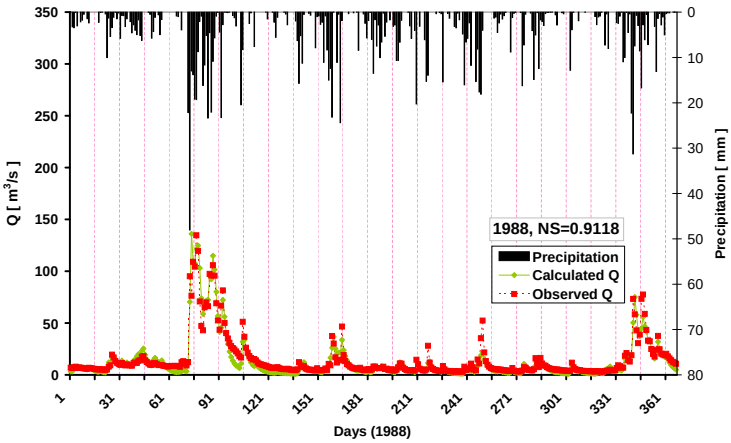
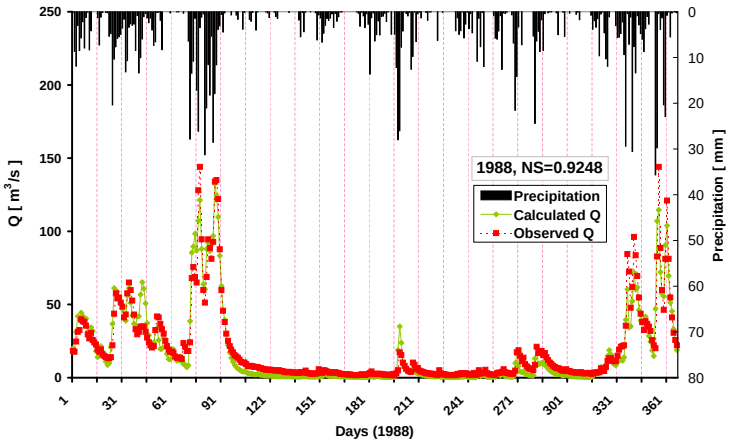


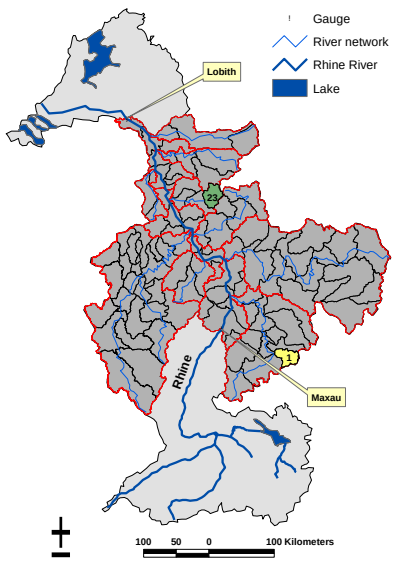
Figure 7.7: The ascending rank orders of the distances based on d_B for both calibration and validation catchments versus the rank orders based on d_{NS}, dots: the calibration catchment pairs after including the validation catchment pairs; stars: 90 pairs related to validation catchments



(a) Catchment Nr. 1



(b) Catchment Nr. 23



(c) Location map

Figure 7.8: A same set of model parameters applied to a pair of similar catchments (Nr. **1** and **23**) during the time period 1980-1988: (a) and (b) show the observed precipitation, observed discharge and simulated discharge during the year 1988 ; (c) shows where the two catchments are located in the basin

7.3 Model dependency

To investigate on the questions to what extent the similar behavior depends on (1) the model and (2) on the catchment characteristic posed by Bárdossy (2007), the XAJ-IWS model is selected. Same as the procedures applied to the HBV-IWS model, 20,000 Monte-Carlo simulations are carried out with the XAJ-IWS model for the 22 calibration catchments within the same time period between 1980 and 1988.

7.3.1 Calibration of the XAJ-IWS model

The Xinanjiang model has never been tested in the Rhine River Basin before this study. In order to run the XAJ-IWS model, the revised version of Xinanjiang model, a careful calibration is required to make the model fit in the new environment. Zhao and Liu (1995) provides reasonable parameter spaces suitable for humid and semi-humid catchments in southern China. They are used as references and adapted for this study area. A manual calibration is then carried out. The original Xinanjiang model uses daily pan evaporation as input data which is not available in this study area. The daily pan evaporation is replaced with monthly mean ET. Due to the replacement of input data, as well as change of the study area, several parameters values do not fall in the ranges recommended by (Zhao and Liu, 1995).

K is the first parameter that is manually calibrated to adjust the water balance in a long-term prediction. Its values are between 0.006 and 0.1 depending on the landuse class and catchment. C, coefficient of ET for the deeper soil layer, varies from 0.01 to 0.04. WM, as a measure of aridity, is defined with local experience. In this specific study area, the values of WMU, WML and WMD are taken as 16-46 mm, 63-103 mm and 13-33 mm respectively, varying with the catchment. WM needs to be adjusted if W becomes negative during the simulation. The sum of KG and KI falls between 0.7 and 0.9. Ex lies in the range between 0.5 and 2.0. CG and CI are both in the range of 0.96-0.99. B is another sensitive parameter to be calibrated. Depending on the size of the catchment, its value starts from 0.2 on and a large value indicates a high degree of non-uniformity tension water capacity over the catchment.

7.3.2 Model dependency

If the rainfall runoff model describes the hydrological processes reasonably well, the group of similar catchments with respect to their catchment's behavior or response shall be independent from the model. A numerical model is nothing more than a "Mathematical Formula Translating System", as FORTRAN originated its name from. Regardless of using either the HBV-IWS or XAJ-IWS model, similar catchments should be invariant because

their behavior is assumed to be only associated with their characteristics. This section is to investigate if the models under study are doing a good "mathematical translating job".

Let us assume that both models lead to the same or similar group of similar catchments, there could be two conclusions:

1 both models are bad;

2 both models are good.

We tend to believe in (2) that both models are good, as the HBV-IWS model has performed many successful applications in the Rhine River Basin. The result could be opposite, i.e. similar catchments are dependent on the model used. Again, two conclusions can be made:

1 both models are bad;

2 one of them is bad.

If both of them are not able to capture the dominant hydrological processes, they might lead to the difference in similar catchments. If it is only one model that is bad, we cannot say which one it is since we do not have at least one additional reference.

Before exploring the results, it is worth comparing the HBV-IWS with the XAJ-IWS model. Both models can be categorized as ESMA-type model (Beven, 2000). ESMA stands for **e**xplicit **s**oil **m**oisture **a**ccounting, a generic concept implemented in many conceptual models on a lumped or semi-distributed scale. As ESMA-type models, they use a number of conceptual reservoirs to describe subsurface water storage and transformation into discharge. Both have taken $snowmelt$ into consideration with the simple degree-day approach (see section 4.2 page 41). Muskingum method is applied to the outflow routing between catchments for both models. Despite the features they share in common, they contain many differences in both runoff production and runoff response. The XAJ-IWS differentiates ET from three soil layers whereas the HBV-IWS does not, but the latter considers ET from intercepted water storage. To account for a non-uniform distribution of free/tension water storage over a catchment that can contribute to runoff, the parameter β in HBV-IWS functions in a similar way as the parameter B in XAJ-IWS. Field capacity FC in HBV-IWS is in fact a different name for the areal mean tension water capacity WM in XAJ-IWS to denote the maximum water holding capacity of soil. But the difference is that the non-uniform distribution refers to free water storage for the HBV-IWS model whereas tension water storage for the XAJ-IWS. Their mathematical expressions are also different. After obtaining the effective volume producing runoff, the HBV-IWS model computes runoff directly with one upper, non-linear reservoir and one lower, linear reservoir connected by percolation from the upper reservoir to the lower reservoir. In contrast, before proceeding to obtain runoff, the XAJ-IWS model introduces another non-uniform distribution to the distribution of free water storage over a catchment. Runoff is then separated into surface runoff, interflow and groundwater.

The model performance measured by NS defined in Equation 6.3 is compared between the HBV-IWS and XAJ-IWS model for the 22 catchments (see Figure 7.9) for the time period between 1980 and 1988. The comparison shows that both models can simulate streamflow in the given study area fairly well in terms of the peak flow weighted NS. Overall, the HBV-IWS model performs better than the XAJ-IWS model with respect to the peak flow weighted NS in the study area. In some cases, however, the XAJ-IWS model performs slightly better in capturing the peak flow as well as the recession parts of the hydrograph (see Figure 7.10). All catchments demonstrate NS above 0.80 with the exception of catchment 13.

One may argue that the NS value does not reflect the quality of simulation of many hydrological processes in a local scale such as groundwater recharge or ET. Indeed, the NS is a holistic and integrated indicator of model performance, a high NS value does not necessarily suggest a good simulation of hydrology of any intermediate processes. For the purpose of water resources management with regards to a long term water balance and daily streamflow prediction, NS is a good indicator. The similarity can also be well defined based on the specific objective one has in mind (refer to subsection 2.1.3, page 13).

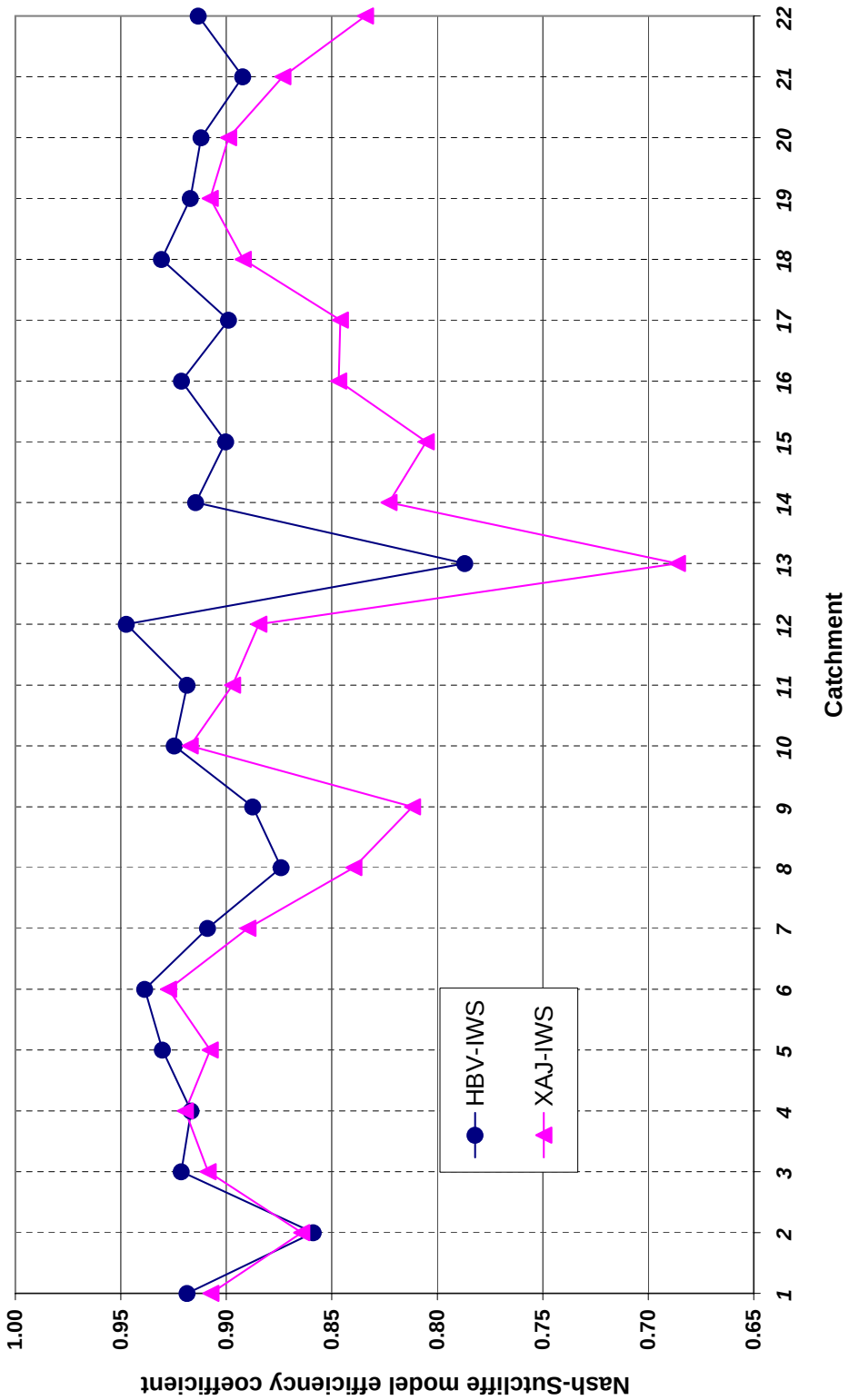


Figure 7.9: Overall comparison of model performance between the HBV-IWS and XAJ-IWS model

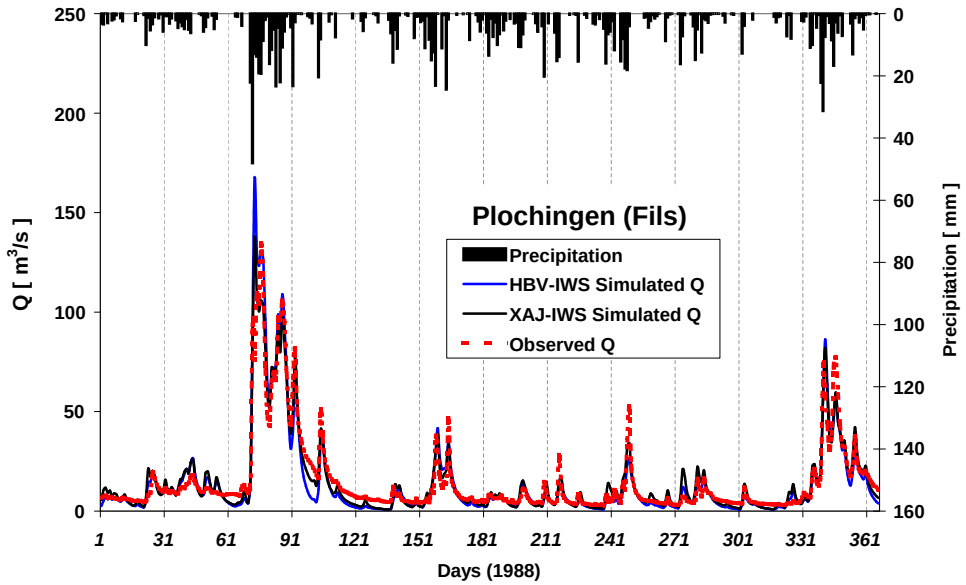
Once the XAJ-IWS model is calibrated and ready for this task, it is put in a set of 20,000 Monte-Carlo simulations. For each simulation, both the runoff generation and runoff response parameters are assigned random values for all 22 catchments. Table 7.12 lists these parameters and their average, maximum, minimum and standard deviation values of the 20,000 sets of randomly generated values.

Table 7.12: Statistics of the 11 model (XAJ-IWS) parameters used for 20,000 Monte-Carlo simulations

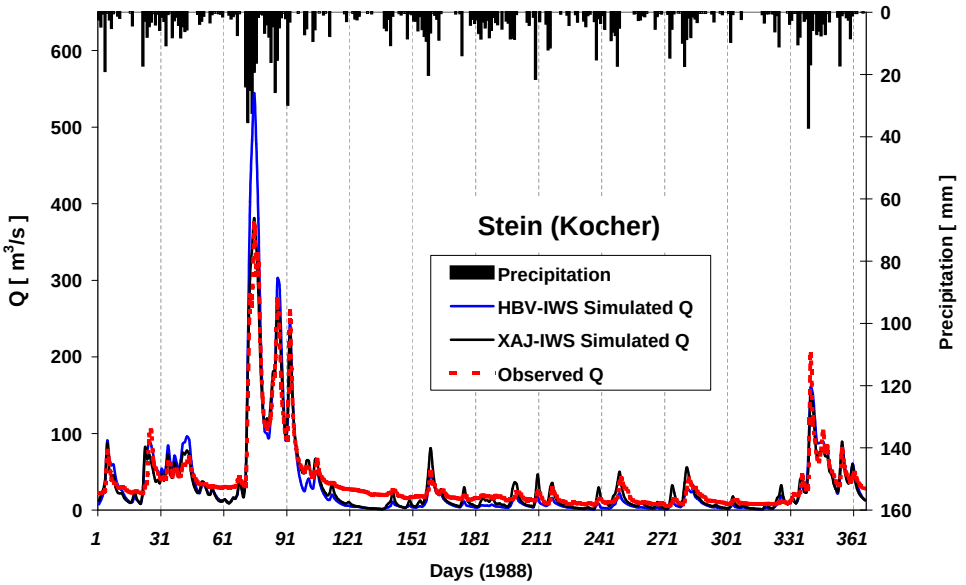
Parameter	Unit	mean	max	min	σ	comments
Runoff generation parameters						
C_{ET}	[(°C)$^{-1}$]	0.15	0.22	0.08	0.04	for all elevation zones
TT	[°C]	0.00	0.09	-0.09	0.03	
DD	[mm/°C·hour]	0.09	0.14	0.05	0.03	
B	[–]	1.2063	1.7817	0.5947	0.3444	
SM	[mm]	26.0856	51.1963	0.0210	15.0186	
Ex	[–]	1.4251	1.9228	0.9284	0.2907	
Runoff response parameters						
KG	[–]	0.3668	0.4403	0.2936	0.0423	
KI	[–]	0.4158	0.4975	0.3317	0.0483	
CG	[–]	0.9854	0.9904	0.9657	0.0029	
CI	[–]	0.9976	0.9996	0.9951	0.0011	
$MAXBAS$	[–]	24.08	45.00	3.00	12.08	

The number of simulations that have obtained NS value greater than or equal to 0.80 for each pair of catchment is shown in Table 7.13. Catchment 13 does not have any simulation with a NS value greater than or equal to 0.80. The distances d_{NS} of the rest 210 pairs can be calculated according to Equation 6.4 and provided in Table 7.14. All pairs of catchments are sorted out with an ascending order and compared with the ranked pairs obtained with the HBV-IWS model. Figure 7.11 plots the rank orders from the more similar to less similar catchment pairs obtained with the HBV-IWS model versus XAJ-IWS model. One can see that the two models lead to completely different rank orders of similar catchment pairs. Figure 7.12 plots the d_{NS} obtained with the XAJ-IWS model against the d_B obtained with the optimized coordinates U based on the HBV-IWS model. Except $d_{NS}(XAJ - IWS)$ are in most cases larger than d_B, no other patterns can be observed. This figure has no practical use since the goal is to reproduce the similar catchments in the same ranking order in the space u (not the same distance value), nevertheless, it shows the transfered distance d_B between a pair of catchments is most likely smaller than their original distance $d_{NS}(XAJ - IWS)$.

Catchments genuinely carry their characteristics and thus similarities shall be independent of the model, but the interpretation of the hydrological processes taking place in the



(a) Catchment Nr. 1



(b) Catchment Nr. 4

Figure 7.10: Comparison of model performances between the HBV-IWS and the XAJ-IWS model

catchment is different from model to model. One model could have captured one or more process components correctly while mistakened other process components. Different process interpretation and conceptualization between the two models under study might have led to the different similar catchment pairs. The implications of the result are two fold:

1 both models require thorough reexamination vis-a-vis their process conceptualization and structure

2 it is necessary to seek for a better similarity measure (further discussed in section 8.2)

Catchment	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
1	6768	3566	6332	6763	6737	6522	4986	3989	4040	1279	6723	2726	0	3434	129	2359	5008	6763	6762	2243	0	4391
2	3566	7127	7108	6931	7037	4577	5775	1693	4377	3495	7092	1374	0	905	0	837	3501	6271	6831	1162	0	2548
3	6332	7108	19135	13096	15072	8506	14792	4675	12375	12029	16957	2394	0	3197	5	1974	5157	11011	12873	1920	1132	4233
4	6763	6931	13096	13542	13476	8917	11234	5007	9557	7073	13474	2797	0	3589	129	2358	5522	11438	13033	2279	13	4643
5	6737	7037	15072	13476	15495	8905	13039	5002	11125	8949	15444	2771	0	3582	129	2355	5489	11399	13239	2258	280	4623
6	6522	4577	8506	8917	8905	8921	7198	4808	6187	3370	8901	2715	0	3591	129	2358	5266	8815	8911	2231	0	4570
7	4986	5775	14792	11234	13039	7198	14800	4108	12322	10566	14444	1553	0	2444	0	1291	3906	9388	11095	1234	1001	3205
8	3989	1693	4675	5007	5002	4808	4108	5009	3663	1702	5007	2182	0	3059	127	2083	3199	4960	5001	1819	0	3274
9	4040	4377	12375	9557	11125	6187	12322	3663	12381	9394	12130	1001	0	2040	0	859	2912	7913	9398	746	950	2449
10	1279	3495	12029	7073	8949	3370	10566	1702	9394	12060	10641	121	0	332	0	10	985	5242	6920	53	1133	682
11	6723	7092	16957	13474	15444	8901	14444	5007	12130	10641	17360	2758	0	3588	129	2352	5478	11395	13253	2242	776	4606
12	2726	1374	2394	2797	2771	2715	1553	2182	1001	121	2758	2808	0	2044	129	2102	2731	2797	2798	2190	0	2754
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	3434	905	3197	3589	3582	3591	2444	3059	2040	332	3588	2044	0	3591	129	2099	2673	3583	3587	1649	0	2778
15	129	0	5	129	129	129	0	127	0	0	129	129	0	129	129	129	122	129	129	127	0	129
16	2359	837	1974	2358	2355	2358	1291	2083	859	10	2352	2102	0	2099	129	2359	2236	2359	2358	1803	0	2332
17	5008	3501	5157	5522	5489	5266	3906	3199	2912	985	5478	2731	0	2673	122	2236	5539	5524	5523	2263	0	4330
18	6763	6271	11011	11438	11399	8815	9388	4960	7913	5242	11395	2797	0	3583	129	2359	5524	11449	11418	2279	0	4645
19	6762	6831	12873	13033	13239	8911	11095	5001	9398	6920	13253	2798	0	3587	129	2358	5523	11418	13311	2280	15	4645
20	2243	1162	1920	2279	2258	2231	1234	1819	746	53	2242	2190	0	1649	127	1803	2263	2279	2280	2288	0	2278
21	0	0	1132	13	280	0	1001	0	950	1133	776	0	0	0	0	0	0	0	15	0	1133	0
22	4391	2548	4233	4643	4623	4570	3205	3274	2449	682	4606	2754	0	2778	129	2332	4330	4645	4645	2278	0	4648

Table 7.13: Number of simulations obtaining NS value greater than or equal to 0.80 for each pair of catchment out of the 20,000 Monte-Carlo simulations (XAJ-IWS model)

Catchment	1	2	3	4	5	6	7	8	9	10	11	12	14	15	16	17	18	19	20	21	22
1	0	0.7364	0.6904	0.5010	0.5672	0.2955	0.7518	0.5306	0.8052	0.9800	0.6153	0.6090	0.5148	0.9809	0.6515	0.3310	0.4097	0.4925	0.6751	1.0000	0.3871
2	0.7364	0	0.6295	0.5023	0.5516	0.6705	0.6838	0.9197	0.7829	0.8579	0.5935	0.9057	0.9680	1.0000	0.9583	0.6895	0.5181	0.5081	0.9172	1.0000	0.8040
3	0.6904	0.6295	0	0.3381	0.2338	0.5762	0.2274	0.7720	0.3536	0.3730	0.1344	0.8933	0.8513	1.0000	0.9137	0.7491	0.4466	0.3494	0.9158	0.9409	0.7985
4	0.5010	0.5023	0.3381	0	0.1345	0.3418	0.3703	0.6304	0.4552	0.6937	0.2278	0.7943	0.7351	0.9905	0.8260	0.5935	0.1562	0.0577	0.8324	1.0000	0.6575
5	0.5672	0.5516	0.2338	0.1345	0	0.4263	0.2586	0.6776	0.3549	0.5714	0.1133	0.8235	0.7694	0.9917	0.8483	0.6490	0.2676	0.1502	0.8562	0.9955	0.7033
6	0.2955	0.6705	0.5762	0.3418	0.4263	0	0.6076	0.4827	0.6534	0.8944	0.4884	0.7057	0.5975	0.9855	0.7358	0.4388	0.2392	0.3313	0.7562	1.0000	0.4963
7	0.7518	0.6838	0.2274	0.3703	0.2586	0.6076	0	0.7724	0.1714	0.3745	0.1880	0.9420	0.8876	1.0000	0.9523	0.8139	0.4799	0.3751	0.9550	0.9402	0.8507
8	0.5306	0.9197	0.7720	0.6304	0.6776	0.4827	0.7724	0	0.7836	0.9521	0.7117	0.6615	0.4798	0.9750	0.6328	0.6312	0.5710	0.6249	0.7113	1.0000	0.5396
9	0.8052	0.7829	0.3536	0.4552	0.3549	0.6534	0.1714	0.7836	0	0.4090	0.3154	0.9712	0.9064	1.0000	0.9747	0.8764	0.5583	0.4641	0.9804	0.9357	0.8958
10	0.9800	0.8579	0.3730	0.6937	0.5714	0.8944	0.3745	0.9521	0.4090	0	0.4592	0.9996	0.9975	1.0000	1.0000	0.9855	0.8010	0.7017	0.9999	0.9061	0.9917
11	0.6153	0.5935	0.1344	0.2278	0.1133	0.4884	0.1880	0.7117	0.3154	0.4592	0	0.8440	0.7935	0.9926	0.8649	0.6879	0.3467	0.2399	0.8735	0.9694	0.7371
12	0.6090	0.9057	0.8933	0.7943	0.8235	0.7057	0.9420	0.6615	0.9712	0.9996	0.8440	0	0.5857	0.9541	0.3330	0.5205	0.7567	0.7906	0.2535	1.0000	0.4189
14	0.5148	0.9680	0.8513	0.7351	0.7694	0.5975	0.8876	0.4798	0.9064	0.9975	0.7935	0.5857	0	0.9641	0.4799	0.6408	0.6877	0.7308	0.6690	1.0000	0.5376
15	0.9809	1.0000	1.0000	0.9905	0.9917	0.9855	1.0000	0.9750	1.0000	1.0000	0.9926	0.9541	0.9641	0	0.9453	0.9792	0.9887	0.9903	0.9454	1.0000	0.9723
16	0.6515	0.9583	0.9137	0.8260	0.8483	0.7358	0.9523	0.6328	0.9747	1.0000	0.8649	0.3330	0.4799	0.9453	0	0.6174	0.7940	0.8229	0.3977	1.0000	0.5040
17	0.3310	0.6895	0.7491	0.5935	0.6490	0.4388	0.8139	0.6312	0.8764	0.9855	0.6879	0.5205	0.6408	0.9792	0.6174	0	0.5188	0.5863	0.5959	1.0000	0.2718
18	0.4097	0.5181	0.4466	0.1562	0.2676	0.2392	0.4799	0.5710	0.5583	0.8010	0.3467	0.7567	0.6877	0.9887	0.7940	0.5188	0	0.1445	0.8017	1.0000	0.5946
19	0.4925	0.5081	0.3494	0.0577	0.1502	0.3313	0.3751	0.6249	0.4641	0.7017	0.2399	0.7906	0.7308	0.9903	0.8229	0.5863	0.1445	0	0.8293	1.0000	0.6513
20	0.6751	0.9172	0.9158	0.8324	0.8562	0.7562	0.9550	0.7113	0.9804	0.9999	0.8735	0.2535	0.6690	0.9454	0.3977	0.5959	0.8017	0.8293	0	1.0000	0.5120
21	1.0000	1.0000	0.9409	1.0000	0.9955	1.0000	0.9402	1.0000	0.9357	0.9061	0.9694	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	1.0000	0	1.0000
22	0.3871	0.8040	0.7985	0.6575	0.7033	0.4963	0.8507	0.5396	0.8958	0.9917	0.7371	0.4189	0.5376	0.9723	0.5040	0.2718	0.5946	0.6513	0.5120	1.0000	0

Table 7.14: The similarity matrix obtained with d_{NS}, catchment 13 is removed because no simulations produce NS values greater than or equal to 0.80 (XAJ-IWS model)

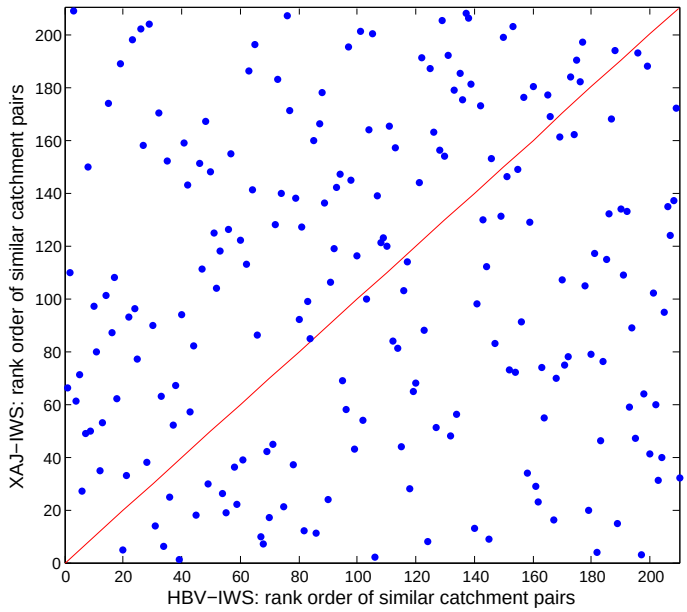


Figure 7.11: Comparison of ranked catchment pairs with the NS as distance measure between the HBV-IWS and XAJ-IWS model

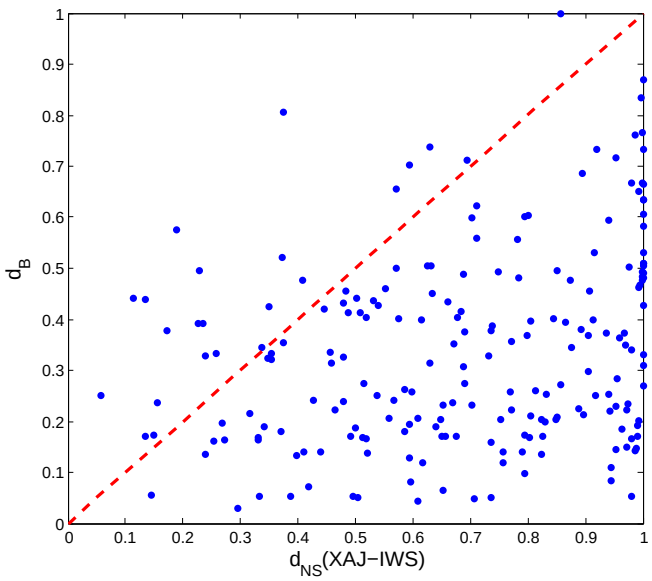


Figure 7.12: Comparison between the d_{NS} obtained with the XAJ-IWS model and the d_B obtained with the HBV-IWS model

8 The step forward in catchment classification

Whoever wants to reach a distant goal must take many small steps. - Helmut, Schmidt

The study has established a catchment classification scheme. According to the categories described in chapter 2, it is a statistical approach with model performance as similarity measure and similar catchments are classified in the transformed space of catchment descriptors to represent their hydrologic similarity. The latter enables its capability of prediction in ungauged basins if past streamflow observation is not available for model calibration but a few catchment characteristics are readily available. The transformation is achieved by using the local variance reduction method and the dimension of the transformed space is determined with the help of multi-dimensional scaling. The scheme is ready for further implementation in a field test of prediction in ungauged basins.

The scheme provides an alternative to the conventional regression-based regional approach. It does not constrain itself with *a priori* linear or non-linear function between model parameters and catchment characteristics. It avoids subjectively selecting functions, instead, it uses a transformation matrix which is very flexible to incorporate system complexity.

Having demonstrated and summarized the results, the intention of the write-up is not just to show where we are, but in what direction we think we can move forward and achieve the most out of them. The following sections will discuss issues that could potentially improve the scheme.

8.1 Feasibility of using the Euclidean space

So far, the classification scheme is set up in the Euclidean space. Similarity between catchments d_{NS} is reproduced by d_B with the Euclidean metric. It is not known if d_{NS} is Euclidean distance although reconstruction of the space configuration has taken place as Euclidean.

According to Theorem 1 (page 65), the matrix d_{NS} is Euclidean if and only if C (see definition on page 65) is positive semidefinite. The matrix is positive semidefinite if all of

its eigenvalues are greater than or equal to zero. The relative magnitude of the eigenvalues indicate the relative contribution of the corresponding columns of X (see definition on page 65) in reproducing the original distance matrix d_{NS} with the reconstructed points. The zero eigenvalues do not contribute to the system reconfiguration. The columns of Z corresponding to the positive eigenvalues provide an exact reconstruction of d_{NS}. Table 8.1 lists the sorted eigenvalues and their normalized values. d_{NS} is a 21 by 21 matrix. Out of the 21 eigenvalues, 5 are negative which suggests the matrix is not positive semidefinite and the distance is not Euclidean. It means an exact reconstruction of the original distances in an Euclidean space is impossible, although the negative eigenvalues are comparatively close zero. One can see from Figure 8.1 that the eigenvalues decrease sharply till the 10th. one. They are then approaching zero slowly from the 11th. eigenvalue. The result confirms the dimension determined by multi-dimensional scaling (see subsection 7.1.2). To reproduce the original distances, 10 dimensions will be needed. The fact that 15 eigenvalues are above zero indicates the high complexity of the hydrological system.

At this point, we are yet to examine if d_{NS} (Equation 6.4 on page 57) is a qualified metric function that needs to satisfy the following four conditions (r, s and t represent three different catchments) (Reid, 2005):

1 $d_{NS}(r,s) \geq 0$
2 $d_{NS}(r,s) = 0$ if and only if $r = s$
3 $d_{NS}(r,s) = d_{NS}(s,r)$
4 $d_{NS}(r,s) \leq d_{NS}(s,t) + d_{NS}(t,r)$

The conditions **1**, **2** and **3** certainly hold true for the definition of d_{NS}. All possible combinations of triangulars were checked against the condition 4 and no case was found that violates this condition. d_{NS} is thus proved to be a distance metic, in other words, the space within which the catchment pairs are stuided can be described by a metric function such as d_{NS}.

d_{NS} can be used as a metric function, however, it does not describe a Euclidean space. Other metric functions need to explored to provide an improved solution. One alternative maybe to use the sum of relative differences obtained from all the monte-carlo simulations (N):

$$d_{NS} = 1 - \sum_{1}^{N} \frac{max(d_{NS}(r)) - d_{NS}(r)}{max(d_{NS}(s)) - d_{NS}(s)} \tag{8.1}$$

If the relative differences between the best and each individual performance of catchments r and s vary in the same manner and magnitude, they can be considered as similar catchments.

No matter what distance metric is mostly suitable, the issue of definition of hydrological similarity is in fact a prelude to the selection of a proper distance metric, which will be

discussed in section 8.2.

Table 8.1: Eigenvalues of ZZ^T

	Eigenvalues of ZZ^T	**Normalized Eigenvalues of ZZ^T**
1	2.594800	1.000000
2	0.694520	0.267660
3	0.332890	0.128290
4	0.164250	0.063299
5	0.093144	0.035897
6	0.058080	0.022384
7	0.043672	0.016831
8	0.035691	0.013755
9	0.011827	0.004558
10	0.006397	0.002465
11	0.002411	0.000929
12	0.001152	0.000444
13	0.000983	0.000379
14	0.000400	0.000154
15	0.000181	0.000070
16	0.000000	0.000000
17	**-0.000029**	**-0.000011**
18	**-0.000210**	**-0.000080**
19	**-0.001270**	**-0.000490**
20	**-0.003660**	**-0.001410**
21	**-0.027720**	**-0.010680**

8.2 Definition of hydrologic similarity

The Nash-Sutcliffe model efficiency coefficient has been used as the measure to compare hydrologic similarity. NS is certainly not the only measure of hydrologic similarity. It is a holistic response indicator of all hydrological processes. It would be useful to examine each individual component of the entire hydrological system. The second concern of using NS as a similarity measure is its defined time frame. It is based on a certain period of time. It cannot exclude the influence from climate change and landuse change. Similar catchment pairs might turn out to be dissimilar if their physical properties are altered. If climate and landuse change are taking place slowly over a relatively long period of time, their influence can be neglected. Otherwise, the hydrological processes such as evapotranspiration, infiltration and interception within a catchment can be highly modified and hence the catchments used to be similar might be no longer similar in a new condition and status. Therefore, no catchment classification is static and the factor of change needs to be taken

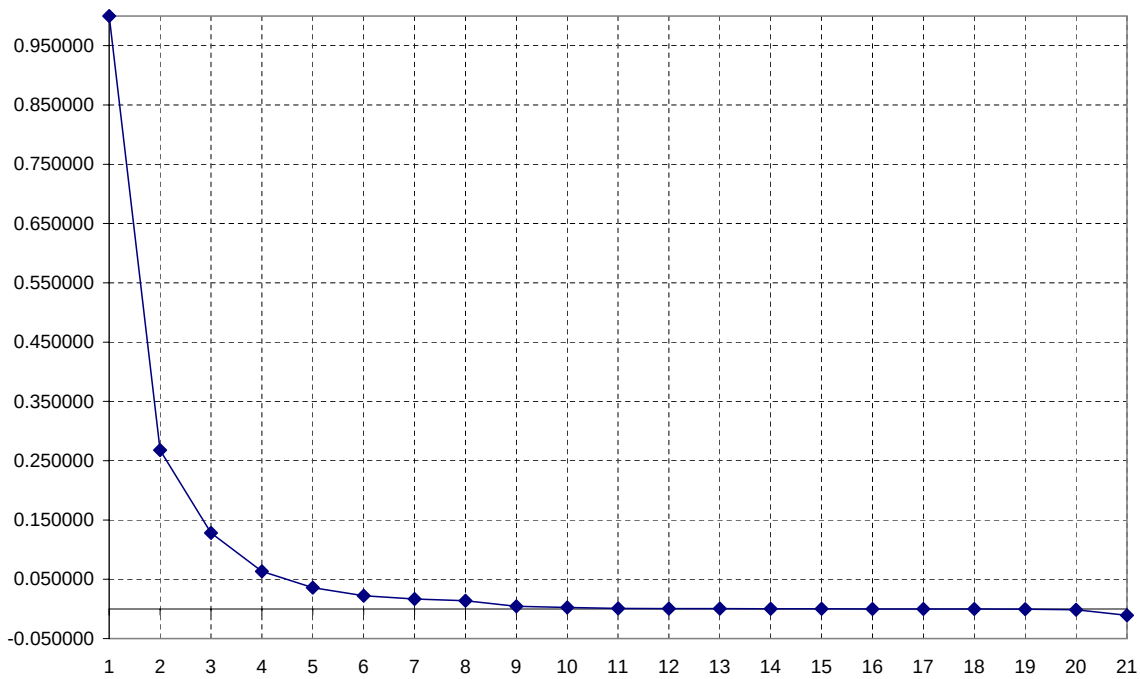


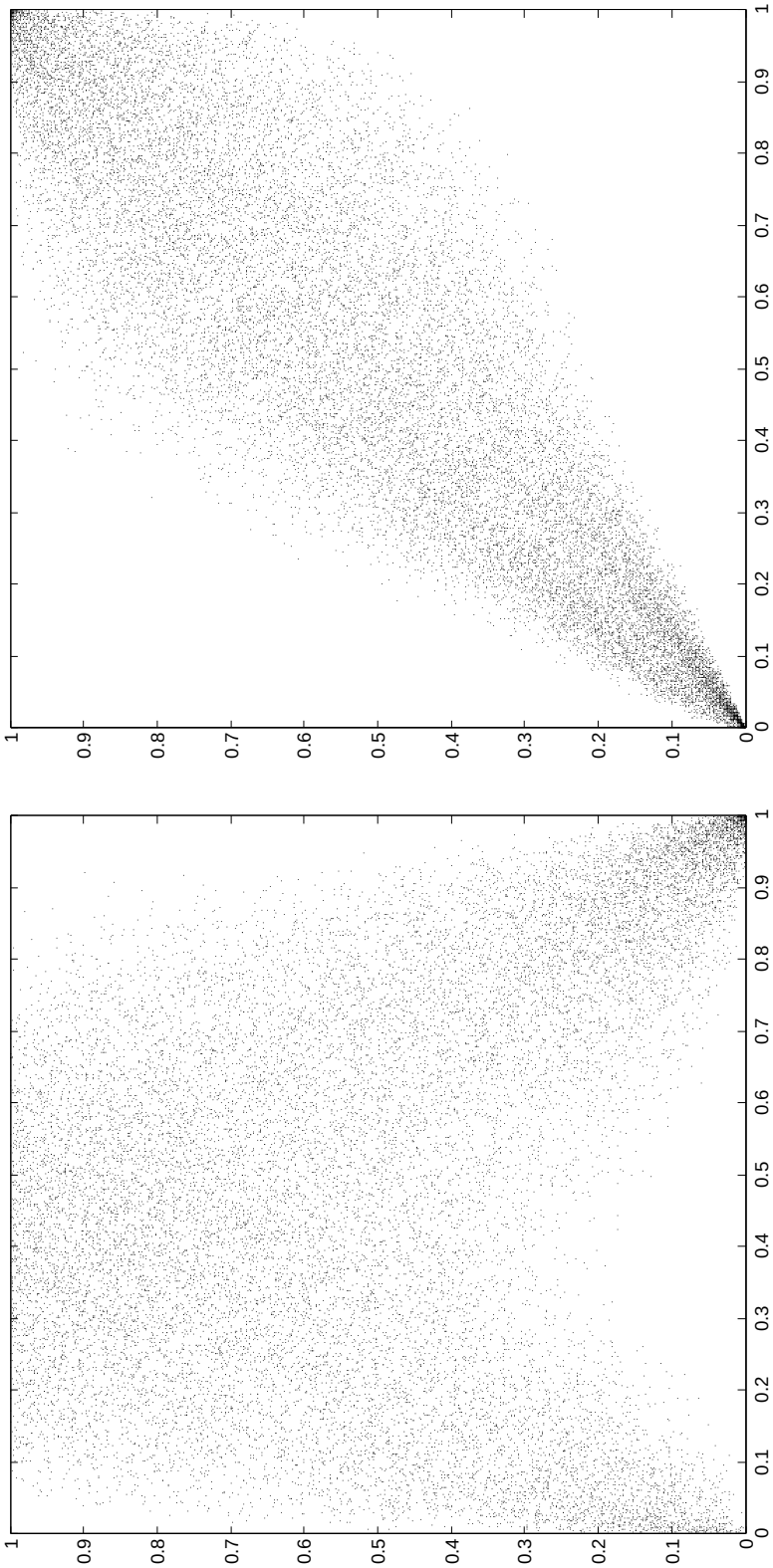
Figure 8.1: Normalized eigenvalues of ZZ^T

care of.

The formulation of d_{NS} is the third concern with regards to the definition of similarity. d_{NS} describes a type of dependency or bivariate relationship between the model performance of two catchments. The relationship will change as the marginal distribution of the model performance of one catchment changes. To study the relationship or dependency without being influenced by marginal distribution of each variable, the concept of copula can be introduced here. Copula is one type of multivariate distribution with uniform marginal distributions, a measure describing dependency disregarding the marginals (Bárdossy, 2006).

To study the bivariate relationship between a pair of catchments, the 20,000 NS values of each catchment obtained with the HBV-IWS model are ranked from the lowest to the highest and their corresponding accumulative probabilities are computed and plotted for each pair of catchments. Figure 8.2 shows accumulative probabilities of two pairs of catchments. The plot is used to obtain the bivariate copula density. A grid mash is imposed on the plot first. The number of points is counted within each grid. The number of points in a square grid is divided by the total number of points to obtain the percentage of points. It is then further divided by the size of each grid to obtain the bivariate copula density. Figure 8.3 shows the bivariate copula densities of two pairs of catchments. One can observe two distinct patterns of copulas from both figures. The non-symmetrical one is from the pair of dissimilar catchments while the quasi-symmetrical plot is from the

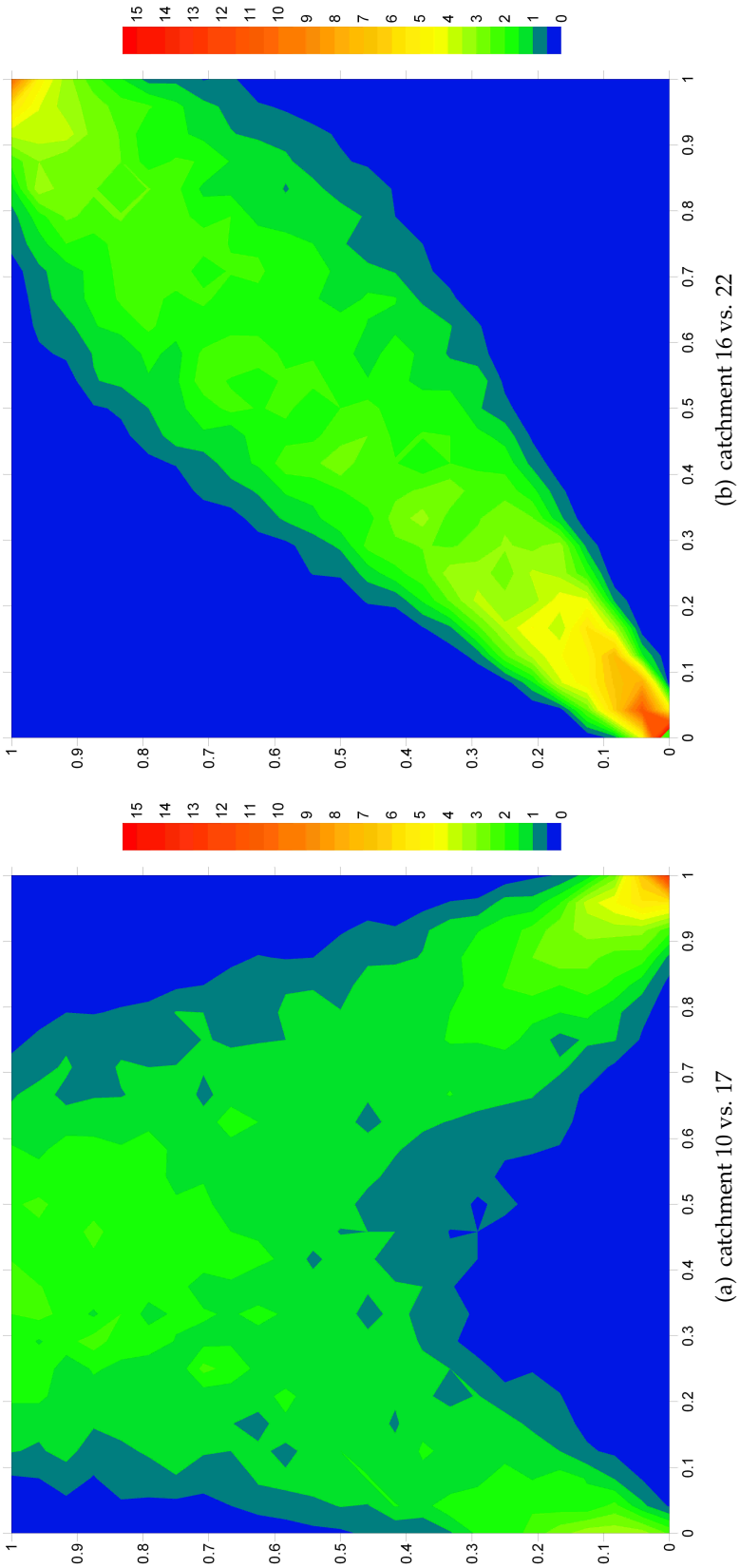
pair of similar catchments. Similar catchments demonstrate similar pattern of NS values in the low, middle and high ranges (Figure 8.2(b) and Figure 8.3(b)). It means if a set of model parameters lead to good model performance for one catchment, it will perform well with its similar catchment, and vice versa. It is not the case with the dissimilar pairs such as catchment pair 10-17. As can be seen from Figure 8.2(a) and Figure 8.3(a), even if they were to share a considerable number of parameter sets leading to good model performance, many sets of parameters do not lead to good or bad model performance simultaneously. In the copula density, the upper right corner is of the most interest because good model performance appear there. By analysing the degree of symmetry and concentration of the Copula density in the right upper corner, one can determine the relationship or dependency between two catchments. And this relationship is invariant from each individual distribution. It could be used to formulate the distance between catchments.



(a) catchment 10 vs. 17

(b) catchment 16 vs. 22

Figure 8.2: Accumulative probabilities of NS values between catchments (x-y axis: catchment 10-17, catchment 16-22)



(a) catchment 10 vs. 17

(b) catchment 16 vs. 22

Figure 8.3: Bivariate copula densities showing the relationship of NS values between catchments (x-y axis: catchment 10-17, catchment 16-22)

8.3 Uncertainty issue

A failure to disclose and estimate the limits of accuracy of a model projection will lead to fruitless outcome regardless of any research effort invested in setting up the model, collecting data and all other activities involved. The application of the local variance reduction method shall be subjected to uncertainty study in the future.

In addition to the specific issues discussed in the earlier sections, the proposed catchment classification scheme certainly needs verification with catchments in other parts of the world.

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Verzeichnis der Mitteilungshefte

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