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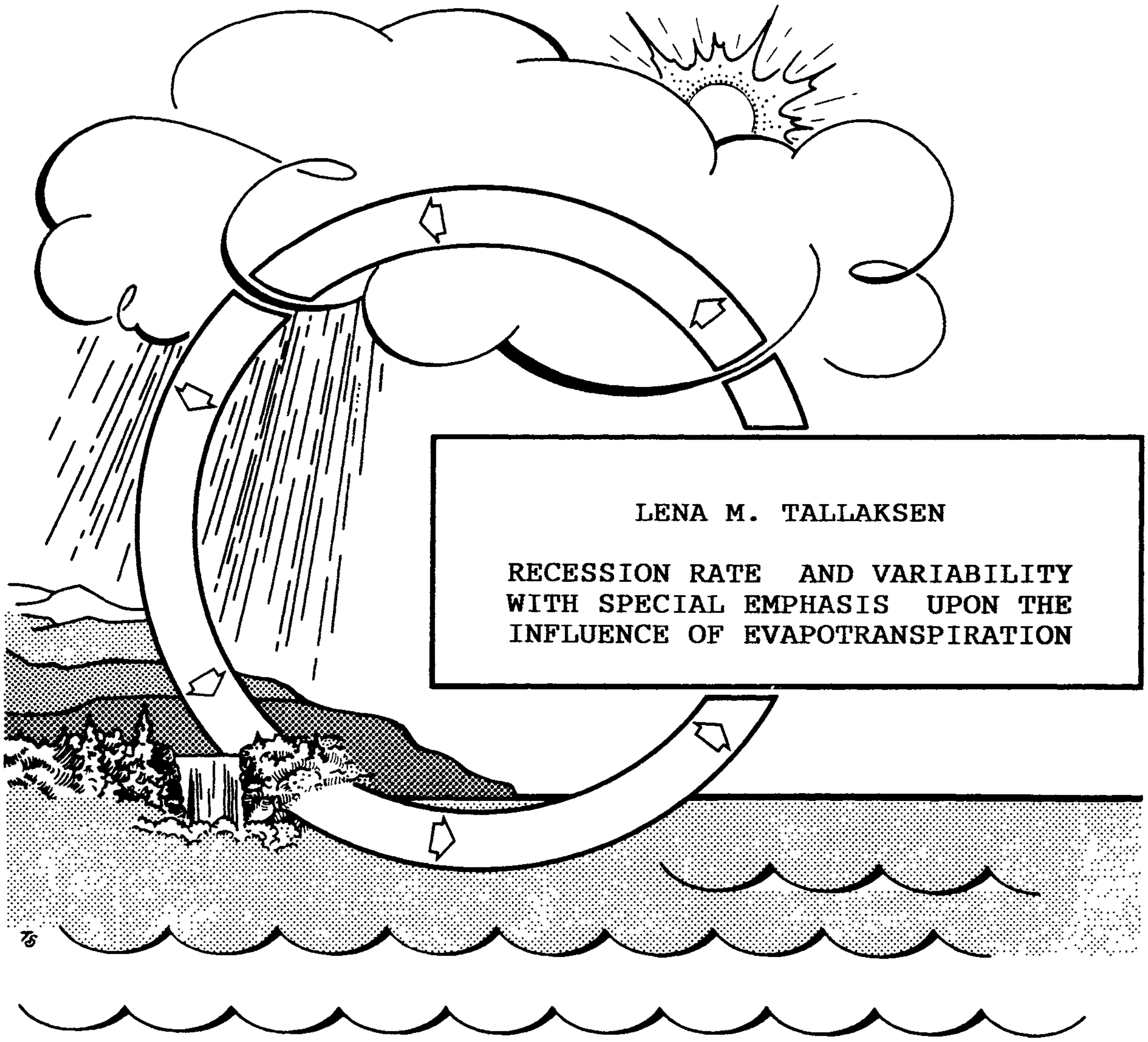

LENA M. TALLAKSEN

RECESSION RATE AND VARIABILITY WITH SPECIAL EMPHASIS UPON THE INFLUENCE OF EVAPOTRANSPIRATION

Rapport nr. **25**

Oslo **1991**

RAPPORTSERIE: HYDROLOGI
UNIVERSITETET I OSLO

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Geografisk institutt
Postboks 1042
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RECESSION RATE AND VARIABILITY

WITH SPECIAL EMPHASIS UPON THE INFLUENCE OF EVAPOTRANSPIRATION

Lena M. Tallaksen

Thesis

Submitted to the Department of Geography

in Partial Fulfillment of the Requirements

for the Degree

Doctor Scientiarum

University of Oslo

NORWAY

1991

To Maria & Ida

ABSTRACT

The recession curve provides important information about the low flow behaviour of rivers, and tells in a general way about the natural water storages feeding the stream. This work has, however, found a high time variability in recessions. In order to derive recession characteristics which are representative for the storage properties of a catchment, it is important to have quantitative knowledge about the factors influencing the recession variability. Using a new, automatic method for calculating recession characteristics developed in this study, the following issues were addressed:

1) The regional variability in the recession rate. The adoption of an average recession constant for the catchment is shown to be useful in regional analysis. The most important characteristics found to affect the recession rate, are related to geological characteristics, relief and climate.

2) The time variability in the recession rate. Variations due to limitations in the recession model and climatic influences during the recession period are studied. The results demonstrate the need for incorporating these effects in recession analysis.

3) The low flow model performance of the conceptual HBV rainfall-runoff model. The climatic factors precipitation and temperature, are to a much lesser extent than in the observed series, responsible for the time variability in the simulated series.

4) The influence of evapotranspiration on recession variability. This relationship is indicated by the correlation found between recession rate and temperature. In order to quantify the water lost by evapotranspiration, an appropriate model for application on a local scale is required. This study introduces AMOR, a modified MORECS (Meteorological Office (UK) Rainfall and Evaporation Calculation System) soil water budget model. It is concluded that this approach provides a promising method for estimating evapotranspiration based on routinely observed climatic data. An objective of future investigations is to prove the general applicability of the AMOR model.

ACKNOWLEDGEMENTS

I am grateful to my superviser 1. Amanuensis K. Nordseth at the Department of Geography, University in Oslo, for encouraging this project, and providing valuable comments on the manuscript.

Special thanks are also given to research scientist S. Lystad at the Norwegian Meteorological Institute, for providing me with the opportunity to work with the soil water balance model AMOR. His work with the computer program and guidance into the world of evapotranspiration is greatly appreciated.

The thesis was part of the Regional Low Flow program at the Department of Geography at the University of Oslo, supported by the Norwegian National Committee for Hydrology (NHK). Part of the study was funded by NHK during the years 1987 and 88. The Norwegian Research Council for Science and the Humanities (NAVF) provided part of the funding in 1988, and gave full financial support in 1989 and 90. I am grateful to these institutions for their support.

Thanks are due to the Norwegian Water Resources and Energy Administration (NVE) and The Norwegian Meteorological Institute (DNMI) for providing the hydrological and meteorological data, and kindly allowing access to their computer programmmes and facilities.

The thesis has also contributed to the international FREND (Flow Regimes from Experimental and Network Data) project, which was part of Project 6.1 of the Third International Hydrological Programme, IHP III, in UNESCO, and the present FRIEND (Flow Regimes from International Experimental and Network data) project, which is part of IHP IV. I appreciate the inspiring contacts and valuable discussions, made possible through the FREND and FRIEND projects.

I would also like to thank Prof. L. Gottschalk, Institute of Geophysics, University in Oslo, for giving me the idea to the analysis in Chapter 5. Hege Hisdal at NVE provided valuable advice on the model calibration in this chapter, as well as good times.

Special acknowledgements must be given to my colleagues Bredo Erichsen, Bjørn Moltzau and Eva Skarbøvik for their cheerful support during this project, encouraging discussions and valuable comments on the manuscript.

Finally, I want to express my gratitude and fondly thanks to my family for their support and encouragement during these years.

PREFACE

The thesis includes four parts. Part I is the main part, presented in Chapter 1 to 7. Part II and III are previously published articles, whereas Part IV is a separate published report, not included in this volume.

Part I: Recession rate and variability, with special emphasis upon the influence of evapotranspiration.

This main part of the thesis comprises 7 chapters. The purpose and scope of the investigation is presented in Chapter 1. A comprehensive review of recession analysis is given in Chapter 2, whereas regional aspects of recession analysis are discussed in Chapter 3. Recession rate and variability are studied in general terms in Chapter 4. Chapter 5 evaluates the low flow performance of a rainfall-runoff model using recession analysis, whereas the influence of evapotranspiration on recession variability is investigated in Chapter 6. Chapter 7 presents the main achievements of the work and gives recommendations for further research.

Part II: Analysis of summer low flows in Norway (Moltzau & Tallaksen, 1988)

A statistical model for low flow prediction in Norway is presented, and the possibility to improve the estimation accuracy by including a general index of hydrograph behaviour (BFI) is investigated. This article is linked to Chapter 3 in Part I.

Part III: Analysis of time variability in recessions (Tallaksen, 1989).

A new method for calculation recession characteristics is introduced in this article. Based on this method, both regional and catchment variation in the recession rate is investigated. The method is further discussed in Chapter 4 in Part I.

Part IV: Simulation of hourly precipitation (Lystad & Tallaksen, 1991)

A computer programme for hourly simulation of precipitation based on data from climatic stations in Norway is presented in this report. The work is linked to Chapter 6 in Part I.

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LIST OF SYMBOLS AND ABBRIVATIONS

AE	Actual evapotranspiration (mm).
AMOR	Modified version of the MORECS model.
AREA	Catchment area (km^2).
ADF	Average daily flow (l/s km^2).
ALT	Altitude range (m).
Beta (HBV)	Non-linearity root constant.
BFI	The Base Flow Index.
BOG	Bog area (%).
C	Recession constant of the simple exponential equation.
C-mean	Recession mean value.
C-var	Recession variance.
CFL (PULSE)	Capillary transport (mm/t).
CFLUX (PULSE)	Maximum capillary transport (mm/t).
CULT	Cultivated area (%).
FC (HBV)	Zone water content at saturation (mm).
FOREST	Forest area (%).
HBV	Conceptual rainfall-runoff model.
HER (MORECS)	Hydrological effective rainfall.
KLZ (HBV)	Drainage coefficicent, lower zone (1/t).
KUZ (HBV)	Drainage coefficient, upper zone, low water content (1/t).
KUZ1 (HBV)	Drainage coefficient, upper zone, rapid response (1/t).
LAI	Leaf area index.
LAKE	Lake area (%).
LENGTH	Length of recession (days).
LZ (HBV)	Lower zone water content (mm).
LZ (PULSE)	Saturated zone water content (mm).
MORECS	Meteorological Office (UK) Rainfall, Evaporation, Calculation System, model.
NUM	Minimum number of decreasing values in a recession segment.
PE	Potential evapotranspiration (mm).
PERC (HBV)	Percolation to lower zone (mm/t).
PULSE	Conceptual rainfall-runoff model for modelling hydrochemical properties.
r	Correlation coefficient.
r_a	Aerodynamic resistance (s/m).
r_s	Surface resistance (s/m).
RELIEF	Relief ratio.
REST	Catchment area not covered with BOG, CULTIV, FOREST or LAKE (%).
SAAR	Standard (1930-1960) annual average precipitation (mm).
SMC	Soil moisture capacity (mm).
SMD	Soil moisture deficit (mm).
SOIL CLASS	MORECS classification of soils of low, medium and high water capacity.
QGEN (PULSE)	Total drainage (mm/t).
QUL	Upper limit for start of recession, calculated as a percentage of ADF (l/s km^2).
UZ1 (HBV)	Threshold value for rapid response (mm).

EXECUTIVE SUMMARY

PART I:

Recession rate and variability, with special emphasis upon the influence of evapotranspiration.

Chapter 1: Introduction

Low flow characteristics of rivers have been increasingly utilized in recent years as the demand for water has increased. Information on low flow characteristics provides threshold values for different water-based activities and are required for such water resource management issues as water supply, irrigation, water quality and quantity estimates. An understanding of the outflow process from groundwater or other delayed sources is also essential in studies of water budgets and catchment response.

During dry weather, water stored in the catchment is removed by soil- and groundwater drainage and by evapotranspiration. These processes proceed at different rates in time and space, and are not readily quantified.

The gradual depletion of moisture in a catchment during periods with little or no precipitation, constitutes the drainage or recession rate, graphical presented as the recession curve. The recession curve contains valuable information concerning storage properties and aquifer characteristics. However, recession analysis suffers from the fact that no satisfactory definition of a catchment characteristic recession exists. This is mainly due to the high time variability found in recessions. The result is a lack of consistency in obtaining recession characteristics which has limited a wider use.

In order to derive recession characteristics which is representative for catchment storage capacity, it is essential to have quantitative knowledge about the main factors influencing the recession variability. In catchments without human impacts the variation is either due to natural fluctuations or model limitations. Natural fluctuations in the recession pattern are due to initial conditions of catchment wetness and influence of evapotranspiration and slight precipitation during the recession period. The effect of evapotranspiration on streamflow recessions has been reported in several studies and is considered to be a major source of variability.

The evapotranspiration rates are considered to be strongly related to the interaction between subsurface and surface water during low flow periods. It is important to improve knowledge of interface processes of water transport through the atmosphere-vegetation-soil system and to investigate how these processes can be described at various time and spatial scales. Major uncertainties in this part of the hydrological cycle include the role of vegetation.

The main purpose of the investigation has been to study recession rate and variability both in time and space, with special emphasize on the relationship between time variability in recessions and evapotranspiration. The quantification of evapotranspiration losses is a problem relating to the use of several hydrological tools, i.e. groundwater models, stream forecasting and rainfall-runoff models.

Chapter 2: A review of recession analysis

Recession analysis is in many works associated with theoretical groundwater flow. As it is difficult to distinguish between the different sources of flow, this review considers methods that are concerned with baseflow in a wide context, including groundwater, unsaturated soil and lake drainage.

It is necessary to derive a quantitative expression for the recession curve to incorporate it in comparative studies. This can be done in several ways, as also expressed in the literature. The quantification process raise the questions of:

* analytical expression
* derivation of a characteristic recession
* optimization of recession parameters
* time variability in recessions

This chapter discusses these issues separately, and review different ways of characterizing the low flow recession rate.

It is recommended that an automatic method both for obtaining a characteristic recession and to estimate its recession parameters is applied. Automatic methods are in contrast to manual techniques fast, objective and readily transferable, which ensures consistency in derivation and applicability for larger data sets. This is essential in regional studies if intercomparison is to be meaningful.

In general, the selection of the best method to apply in recession analysis should depend on the purpose of the study. The high time variability in the recession curve, argues against the use of a master recession curve except as an overall approximation which is appropriate for use at the regional scale.

Low flow forecasting is concerned with the lower end of the recession curve, and it is necessary to analyze the recession characteristics in a detailed manner where more complicated solutions might be sought. The time variability found in recessions should be incorporated in any low flow forecast, merely as a statistical variance or given as a conditional forecast with reduced variability.

One of the major natural factors thought to influence the recession variability is evapotranspiration. A presentation of works where the influence of evapotranspiration has been studied is given. If a satisfactory relationship between an index of evapotranspiration and fluctuations in the recession rate can be established, it is possible to improve our low flow forecasts. It is essential for operational purposes that an estimate of evapotranspiration can be routinely calculated.

Chapter 3: Regional analysis of recession behaviour

The influence of geology, including rock, drift and soils materials, is frequently reported as the major terrestrial influence on low flows. Many indirect methods have evolved in order to represent the geology of a catchment. The main purpose has been the need for an index of storage in multivariate analyses of both floods and low flows. Improved relationships between low flow indices and catchments characteristics have been attained by adding a storage index.

This chapter considers regional aspects of recession behaviour, with special emphasize on the use of the recession constant as an index of storage. The recession curve tells in a general way about the natural storages feeding the stream. Accordingly, it holds substantial promise as an index of storage, providing a suitable way of quantifying the recession rate exists. A brief overview of general methods used to derive an expression of geology is given, and the use of the recession constant in this context is discussed separately.

The discussion includes the recession characteristics estimated according to the method presented in this work, where the recession characteristics are calculated as the mean value (C-mean) and variance (C-var) of N estimates of the recession constant calculated from individual recession segments. The recession characteristics are in Part III, included in a regional low flow study of 68 catchments. The main results from this analysis are discussed in a general context in this chapter.

The most important factors thought to influence the recession rate, and their related parameters are presented. Earlier works, including this study, often shown that the recession characteristics are inadequately described by the indices available. This is also valid for flow related storage indexes in general. The most important indices found to affect the recession rate are related to geological characteristics, relief and climate. The best relationship is commonly found with geology. There is a general lack of relevant geological maps in many areas, and improvements in low flow estimations, depend on mapping and hydrological classification of the geology in these areas.

Estimates of the recession constant as well as other flow related indexes, are highly correlated with low flow statistics. Correlations found between low flow statistics and recession constants and an index of base flow (BFI), respectively, are compared, including data from five different studies. A high consistency in the correlations between BFI and the low flow indices is found for these data sets which vary both in size and type of region.

The results clearly confirm that the recession constant, C-mean, as defined in this study, is a powerful tool in characterizing the behaviour of low flows. The mean value represents average conditions for a catchment, and the adoption of a constant is shown to be useful in regional analysis. At the catchment scale, however, where recession analysis is useful for low flow forecasting, it is essential to understand the factors influencing the time variability in the recessions.

Chapter 4: Recession rate and variability

Recession analysis reveals great time variability of recessions. This may be a result of natural fluctuations as well as model limitations. This study suggests an automatic recession calculation procedure, where variability due to model limitations is reduced by calculating a standard recession. In a standard recession both initial discharge and recession length are constants. This chapter presents the recession calculation procedure in details.

The recession rate is quantified through the recession mean value, C-mean, calculated as the arithmetic mean of the recession constants of individual segments. To each segment the simple exponential equation is fitted and the recession constant C calculated. The recession variability, is represented by the coefficient of variation of the sample of segments, C-var.

In Part III this method is applied both in a regional study of recession characteristics and in an analysis of the time variability in recessions. A similar, but more comprehensive, analysis of the recession rate and variability is carried out in this chapter. The purpose is to study recession characteristics in more details, and to investigate the generality of the poor relationships between recession characteristics and climatic and catchment characteristics that are reported in Part III.

The recession mean value and variance are calculated for ten catchments and five different starting levels, given as percentage of average daily flow (ADF). Recession length is seven days. Due to low resolution in discharge data at low flows, the data are frequently recorded in a staircase manner. In the transformed series steps in the discharge series are modified, and both observed and transformed series are included in the recession analysis.

There is a general increase in mean values as starting levels decreases, indicating that the flow does not follow a simple exponential decay curve. A higher rate of increase is found for the transformed case due to differences in the segment selection criteria. There is a high consistency in mean and variance values for different sample selections and size. The introduction of a precipitation limit of 1.0 mm per day leads to a minor reduction in the mean values, except for the lower starting levels in the transformed series.

There is no recognizable trend in variance values with starting level. In the transformed series, the recession variance values are generally higher than in the observed series. Removing segments influenced by precipitation involves less difference between the two series.

The relationship between mean and variance values and catchment characteristics are studied through correlation analysis. Only limited conclusions can be drawn due to the low number of catchments in the analysis. Influence on mean values is only found at the 75% starting level, represented by BOG (bog percentage) and ALT (altitude range) when precipitation is included, and only ALT in precipitation free periods. A lower correlation with BOG might indicate its importance in offsetting the recession rate in response to slight precipitation, whereas ALT represents the drainage velocity in general. The correlation with ALT is not significant at the 30 % starting level, suggesting that the effect of altitude decreases as the dry period increases.

The most important factor thought to influence the recession rate is geology, including rock, drift and soil materials. Information of geology was not available in this study, due to the lack of relevant maps for the study area. In order to improve the accuracy of the estimation equations for the recession constant, it is necessary that relevant geological maps are available on a national basis.

As a first step to link the recession variability to climatic influence, a statistical analysis of the correlation between the recession constant of individual segments and precipitation and temperature is performed. Average value of temperature and total precipitation during the recession period are included.

The correlation with precipitation is generally low, and shift between positive and negative sign. The correlation is expected to be positive as precipitation offset the recession rate. The influence of precipitation on mean and variance values found at lower starting levels in the transformed series, is, however, reflected in significant correlations. By removing segments influenced by precipitation, the low level correlations disappear, and there are no major differences between observed and transformed series. Precipitation is, due to its high spatial variability a major source of error in these analysis. It is, however, difficult to evaluate the effect on these results.

High evapotranspiration losses will increase the recession rate, and thereby reduce the value of the recession constant, C. The influence of evapotranspiration on recession variability is indicated by the relationship found between recession variance and average temperature during the recession period. Temperature show significantly higher correlation coefficients with the recession constant than found in Part III. Still, there is a large scatter in the correlation figures, probably due to differences in climate and catchment characteristics.

The influence of temperature is most noticeable for the catchments which are primarily forested and situated in eastern Norway, and is evident for even the lowest starting level. This might be a result of a shallow groundwater table which favour capillary transport from the groundwater zone subsequent to the water lost by evapotranspiration. This matter is further discussed in Chapter 5 & 6.

Chapter 5: Recession analysis of HBV simulated series

The recession calculation procedure presented in Chapter 4 has revealed high time variability in recessions. In this chapter the recession distribution from observed series is compared with the distribution from a synthetic series, simulated using the conceptual HBV rainfall-runoff model.

There is a particular interest in studying the model's capability of reproducing the variability in the recession rate. The effect of evapotranspiration on the groundwater level has not been incorporated in the present HBV model. Evapotranspiration is in this analysis indexed by temperature, and its influence on the recession variability investigated for both observed and simulated series.

The recession calculation procedure is applied at four catchments for both simulated, observed and transformed series. One catchment is given two different parameter sets, where slow and fast recessions are modelled respectively.

The recession analysis is performed for recession segments both with and "without" precipitation. Threshold value for precipitation is 1.0 mm per day. The recession segments are correlated with both average temperature and total precipitation during the recession period.

Mean values of the recession constant are for high starting levels satisfactory represented by the simulated series. For lower starting levels it is common to find a marked rise in HBV mean values. This is due to the choice of lower zone model parameters, which favour a very slow recession rate and a high lower zone water content.

The simulated series will to some extent reproduce the recession variability in the observed series. However, there is a fundamental difference in the origin of these variabilities. The major course of variability in the simulated series is due to the transition effect between different drainage coefficients of the upper and lower zone in the HBV model. The difference in magnitude between these coefficients determines to a large extent the variability pattern. Precipitation and temperature are to a much lesser extent responsible for the variability, and their effect is only measurable if the transition effect is negligible.

In the observed series, however, there is an evident link to the climatic parameters. Particularly important is the correlation with temperature which link the variability to evapotranspiration losses. It is more difficult to relate precipitation to the recession rate, probably because of its high spatial variability. Contradictory to the simulated series, the true input is not known.

Generally, low flow modelling needs more attention. Improved simulations can be obtained through a better model structure or simply by an increased emphasis upon optimization of low flow related parameters. Recession analysis is a valuable tool when verifying a model's low flow performance, and can guide the choice of parameters before and during the calibration process.

Chapter 6: Modelling evapotranspiration at the catchment scale

The influence of evapotranspiration on recession variability is in Chapter 4 indicated by the relationship found between recession variance and temperature. In order to quantify the water lost by evapotranspiration, an appropriate model for application on a local scale was required. This chapter discusses principles of evapotranspiration and presents different approaches to modelling evapotranspiration, with special references to works which include the effect of vegetation.

Choice of evapotranspiration model was guided by the need to find a model structure which accounts for the effect of vegetation and soil properties in the calculations, and at the same time is applicable to areas with normal data coverage. There was no model available in Norway for this purpose. However, the MORECS model, which originates from the Meteorological Office in Great Britain, had been adjusted for use at automatic weather stations in Norway by S. Lystad at the Norwegian Meteorological Institute. This model constituted the basis for this study, which has concentrated on adjusting the model to operate on data routinely observed at climatic stations in Norway. The model work has been done in cooperation with S. Lystad.

The modified version, AMOR, permits evapotranspiration to be estimated from the routine observations of temperature, precipitation, wind, humidity and cloudiness. Evapotranspiration is estimated for each type of surface cover, and a catchment average calculated as the weighted mean. The model's estimates of evapotranspiration rates for different cover types correspond well with observations reported from similar environments.

Data from two sites are used in a preliminary testing of the AMOR model. These catchments are widely different with respect to climate, surface cover and recession variability. The purpose at this stage has been to demonstrate the applicability of the model for these widely different environments, and to study the relationship between evapotranspiration losses and recession variability.

The influence of evapotranspiration on the recession rate, is investigated through a correlation analysis of evapotranspiration estimates and recession variability. High correlations are found for catchment 1880, which is forested and located in eastern Norway. This is primarily related to a marked seasonal variation in evaporative demand. The evapotranspiration estimates as well as average temperature, reflect this variation satisfactory, and there is no significant difference between the correlation figures.

A minor increase in correlations is found for catchment 1880 if higher soil moisture capacity is selected, particularly for the lowest starting levels. This suggests that the soil moisture capacity of the original model is set too low, or that allowance of groundwater evaporation through capillary transport is not considered. Consequently, model estimates of evapotranspiration will be too low to influence the lowest discharge rates.

Evidently, water is lost through evapotranspiration that otherwise would become streamflow, at all levels of flow in catchment 1880. This suggests a shallow groundwater table, as also found in this catchment, where an upward transport from the groundwater is possible due to capillary forces.

The recession variability of catchment 955, which is located on the west coast, can not be related to evapotranspiration losses. This catchment consists mainly of grassland and is terminated by a big lake. Similar low correlations were found for temperature, and it was not possible to improve the correlations by introducing more advanced calculations of evapotranspiration. The seasonal variation in evaporative demand is low for this catchment, and it is suggested that this may explain the low recession variability and corresponding low correlation with evapotranspiration, observed in this catchment. The recession variability is dominated by other factors than evapotranspiration.

In order to evaluate the success of the evapotranspiration estimates of AMOR, the model calculations have to be verified against soil moisture measurements, or discharge measurements, providing AMOR is extended to a complete rainfall-runoff model. An important application of the model will be to evaluate the effect of land use and climatic change on the flow regime.

Chapter 7: Main conclusions and suggestions for further research

The recession calculation procedure presented in this study holds substantial promise both for use at the local and regional scale. At the regional scale the recession mean value adequately represents the average catchment conditions. Further research should concentrate on developing satisfactory relationships between catchment and recession characteristics to permit estimation at ungauged locations. The success depends on mapping and hydrological classification of the geology, including rock, drift and soil materials.

At the local (catchment) scale, the knowledge of natural factors influencing the recession variability, will permit the recession constant to be estimated with higher accuracy. This is valuable for regional analysis, as well as for low flow forecasting at the catchment scale. This study has looked at the influence of climatic factors, precipitation and evapotranspiration during the recession phase, and has demonstrated the need for incorporating these factors in recession analysis. Further research should include a larger data set and look at possible ways of quantitatively incorporating these factors in low flow forecasting.

This thesis introduces the AMOR model for calculating evapotranspiration using data from automatic weather or climatic stations. Limited data are available on evapotranspiration rates from the widely different natural environments that exist in Norway. This model could be a valuable tool in a regional study of evapotranspiration rates in Norway. However, the model needs further testing and verification. The model calculations can be verified against soil moisture or discharge measurements, the latter preferable by extending AMOR to a complete rainfall runoff model.

The soil water balance approach provides a promising method for estimating evapotranspiration based on routinely observed climatic data. An objective of future investigations is to prove the general applicability of the AMOR model.

PART II

Analysis of summer low flows in Norway

The main goal of this study is to understand the dependence of minimum runoff from climatological and physiographical factors. The low flow indices used are mean 7 and 30 day minimum discharge, standardized by both area and mean annual runoff. Data from the summer period for 75 catchments are used. The catchment selected are without glaciers, have area less than 1000 km^2 and are without severe human impacts.

It is concluded from the regression analysis that the most important characteristic in explaining the regional variation in the low flow variables is the climatic parameter, either the mean annual rainfall or the average daily flow.

Including a general index of hydrograph behaviour, the Base Flow Index (BFI) in the low flow models, improved the estimation equation of all the regression equations. The results demonstrate the need for incorporating an index of storage properties in a low flow analysis. Due to the lack of relevant geological maps in Norway, it has not been possible to include a direct expression for the influence of drift and soils materials in this study.

PART III

Analysis of time variability in recessions

It is generally accepted that it is necessary to include a numerical expression for storage properties in a regional low flow study. The recession constant has commonly been used for this purpose, and is in this study incorporated along with the Base Flow Index (BFI), for investigating the possibilities of improving the accuracy of the estimation equations. The recession constant is calculated according to the calculation procedure introduced in this study. The results show that the recession constant is preferred when the low flow indices are standardized by mean annual runoff, whereas the BFI is preferred when they are standardized by area.

The second objective of this study is to assess to what degree climatic data (precipitation and temperature) influence the time variability in the recession rate. The study concentrates on methods and difficulties arising when trying to isolate the effect of climate on the recession variability. It has not been possible to find a significant relationship between temperature or precipitation and recession variance through these statistical analyses. Neither has there been any success in relating the recession mean and variance values to catchment characteristics.

PART IV

Simulation of hourly precipitation

A program for simulating hourly values of precipitation has been developed. At climatic stations precipitation is only measured once a day, whereas the weather is recorded three times a day using weather symbols. This additional information guides the distribution of precipitation into three time intervals. Two weather symbols related to precipitation are selected: WW, which represents the weather at the time of observation, and W1, which represents the weather since last observation. Bisides reporting on precipitation-no precipitation, the symbols contain information on type of precipitation, which guides the distribution of precipitation hours within a time interval.

The precipitation model focuses on the time distribution of precipitation hours, whereas precipitation amount is given a simple representation. The precipitation model shows satisfactory results when compared with hourly recording stations.

PART I

Recession rate and variability with special emphasis upon the influence of evapotranspiration

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

Low flow characteristics of rivers have been increasingly utilized in recent years as the demand for water has increased. Information on low flow characteristics provides threshold values for different water-based activities and is required for such water resource management issues as water supply, irrigation, water quality and quantity estimates. An understanding of the outflow process from groundwater or other delayed sources, is also essential in studies of water budgets and catchment response.

Variations in low flow characteristics are caused by differences in climate and physiography of the catchments. The amount of water stored in a catchment depends on the recharge conditions and on the storage capacity. During dry weather, water stored in the catchment is removed by soil- and groundwater drainage and by evapotranspiration. These processes proceed at different rates in time and space, and are not readily quantified.

The gradual depletion of moisture in a catchment during periods with little or no precipitation, constitutes the drainage or recession rate, graphical presented as the recession curve, Figure 1.1. The recession rate reflects important physical properties of the catchment, particularly its ability to store and release water during dry weather. Both initial conditions of catchment wetness, slight precipitation and evapotranspiration losses, cause variability in the recession pattern.

The terrestrial influence on the recession rate depends on both storage characteristics and channel networks. For small catchments the routing effect of the main channel is of less importance, and the major influence on the low flow regime is catchment geology, including rock, drift and soil materials. Geological formations with low storage and infiltration capacities, encourage rapid transmission of precipitation into the stream, whereas high storage and infiltration capacity favour a slow transmission.

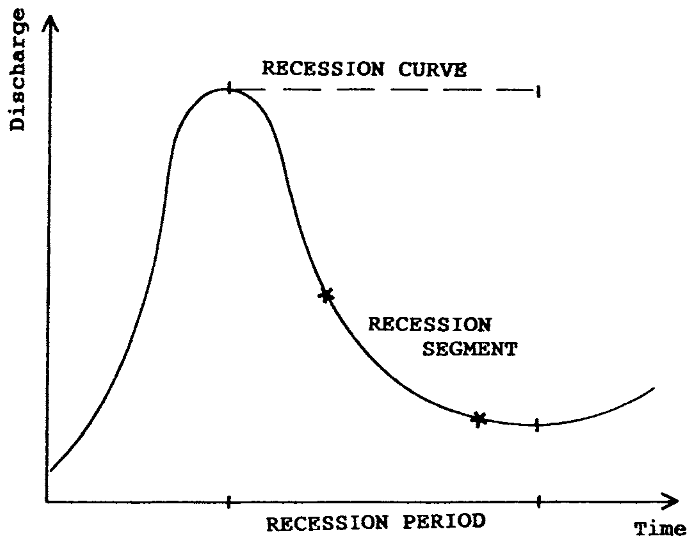


Figure 1.1 Recession curve, period and segment.

The recession curve contains valuable information concerning storage properties and aquifer characteristics. However, recession analysis suffers from the fact that no satisfactory definition of a catchment characteristic recession exists. This is mainly due to the high time variability found in recessions. The result is a lack of consistency in obtaining recession characteristics which has limited a wider use.

In order to derive recession characteristics which is representative for catchment storage capacity, it is essential to have quantitative knowledge about the main factors influencing the recession variability. In catchments without human impacts the variation is either due to natural fluctuations or model limitations. Natural fluctuations in the recession pattern are due to initial conditions of catchment wetness and influence of evapotranspiration and slight precipitation during the recession period. The effect of evapotranspiration on streamflow recession has been reported in several studies and is considered a major source of variability.

The evapotranspiration rates are considered to be strongly related to the interaction between subsurface and surface water during low flow periods. It is important to improve knowledge of interface processes of water transport through the atmosphere-vegetation-soil system and to investigate how these processes can be described at various time and spatial scales. Major uncertainties in this part of the hydrological cycle include the role of vegetation.

1.2 PURPOSE AND SCOPE OF INVESTIGATION

The main purpose of the investigation has been to study recession rate and variability, both in time and space, with special emphasis upon the relationship between time variability in recessions and evapotranspiration losses.

Recession characteristics have been analyzed both on the catchment and regional scale. On the regional scale, the relationship between recession and catchment characteristics has been studied and the use of the recession constant as an index of storage evaluated, whereas on the catchment scale the climatic influence on the time variability has been investigated.

The aim of the last part of the study was to quantify the water lost by evapotranspiration and thereby be able to evaluate its influence on the recession rate. This required an appropriate model for application on a local scale. The model had to consider the effect of vegetation and soil properties in the calculations, and at the same time be applicable for use in areas with normal data coverage. There was no model available in Norway for this purpose. This study has, therefore, adjusted the soil water balance model MORECS, which originates from the Meteorological Office in Great Britain, to fit the standard meteorological observations made at climatic stations in Norway.

Important features of the study are to investigate under which conditions and for which purposes it will be necessary to model evapotranspiration losses, and to study possible ways of incorporating the effect in low flow modelling. The quantification of evapotranspiration losses is a problem relating to the use of several hydrological tools, i.e. groundwater models, stream forecasting and rainfall-runoff models.

1.3 OUTLINE OF PART I

The thesis includes four parts. Part I is the main part, presented in Chapter 1 to 7. Part II and III are previously published articles, whereas Part IV is a separate published report, not included in this volume.

Part I of the thesis comprises 7 chapters. The purpose and scope of the investigation is presented in Chapter 1, a comprehensive review of recession analysis is given in Chapter 2, whereas regional aspects of recession analysis are discussed in Chapter 3.

In Chapter 4 the recession calculation procedure introduced in Part III is applied for ten catchments, and a detailed study of the recession rate and variability is performed. The recession characteristics are analyzed both on a catchment and a regional scale. On the regional scale the relationship between recession and catchment characteristics are studied, whereas on the catchment scale the climatic influence on the variability is investigated.

In Chapter 5 the recession model is tested on a synthetic series, simulated using the conceptual HBV rainfall-runoff model. The main interest is to investigate the model's capability to reproduce the observed variability in the recession rate, and to compare the main mechanisms behind the variability in the observed and simulated series.

The influence of evapotranspiration on recession variability is in Chapter 4 indicated by the relationship found between recession variance and temperature. Chapter 5 points to the importance of including the influence of evapotranspiration in low flow modeling. If a satisfactory relationship between an index of evapotranspiration and fluctuations in the recession rate can be established, it means that we can improve our low flow forecasts. It is essential for operational purposes that an estimate of evapotranspiration can be routinely calculated. Chapter 6 approaches this problem.

In close collaboration with research scientist S. Lystad, at the Norwegian Meteorological Institute, the water balance model MORECS (Meteorological Office (UK) Rainfall and Evaporation Calculation System) was chosen. The model is in this study adjusted to operate on data routinely observed at climatic stations in Norway.

The modified version, AMOR, permits evapotranspiration to be estimated from the routine observations of temperature, precipitation, wind, humidity and cloudiness. Evapotranspiration is estimated for each type of vegetation, and a catchment average calculated as the weighted mean.

The variability in average evapotranspiration losses during the recession periods is compared with the variability observed in the recession rate. The object is to provide general evidence on the variability of evapotranspiration, and in particular to relate its magnitude to the observed discharge variability. A further step is to expand the water balance model to a complete rainfall-runoff model and, thus, be able to verify model output against observed discharge. This has not been the task of this work.

Chapter 7 presents the main achievements of the work and gives suggestions for further research.

CHAPTER 2

A REVIEW OF RECESSION ANALYSIS

2.1 INTRODUCTION

Recession analysis can be traced back as far as Boussinesq in 1877 and Maillet, 1905. Hall (1968) gives an excellent review of different aspects of base flow recessions. Base flow as defined by Hall is the portion of flow that comes from groundwater or other delayed sources. Appleby (1970) adds further comments to the recession and base flow problem with special reference to the work by Hall.

Recession analysis is in many works associated with theoretical groundwater flow. As it is difficult to distinguish between the different sources of flow, this review considers methods that are concerned with baseflow in a wide context, including groundwater, unsaturated soil and lake drainage. In fact, as shown by a number of workers, notably Hewlett (1961), groundwater as traditionally defined, is rarely present in small upland catchments. Unsaturated drainage is extremely complex both to model and measure.

Recession analysis has also shown to be useful when estimating the storm hydrograph recession characteristics (Kelman, 1980; Fedora & Beschta, 1989). However, analysis of storm hydrograph recessions is generally handled by hydraulic techniques and not discussed here.

Recession analysis has shown useful in many areas of water resources planning and management: In low flow forecasting to benefit the management of irrigation, water supply, hydroelectric powerplants and waste dilution (Section 4.6); In mathematical modelling for calibration of, or input to, rainfall-runoff models (Chapter 5); In hydrograph analysis for graphical separation of the groundwater component of total runoff (Section 2.3.1); In regional studies for representing catchment storage capacity (Chapter 3).

It is necessary to derive a quantitative expression for the recession curve to incorporate it in comparative studies. This can be done in several ways, as also expressed in the literature. The quantification process raise the questions of:

* analytical expression (Section 2.2)
* derivation of a characteristic recession (Section 2.3)
* optimization of recession parameters (Section 2.4)
* time variability in recessions (Section 2.5)

This chapter discusses these issues separately, and reviews different ways of characterizing the low flow recession rate.

2.2 ANALYTICAL EXPRESSIONS

Recession analysis studies the outflow function:

$$Q = Q(t) \tag{2.1}$$

where Q is the rate of flow and t the time. There is no standard technique presently available for determining this relationship. Some authors have studied the recession flow from a theoretical point of view, starting with the basic flow equations, whereas others have studied empirical relationships. There are nearly as many methods as there are works on recession analysis, which makes it difficult to compare and evaluate the results.

2.2.1 Modelling recession from basic flow equations

The basic nonlinear differential equation governing the unsteady flow from a large unconfined aquifer to a stream channel was presented by Boussinesq in 1877 (Hall, 1968). The equation is valid under idealized conditions, that is no evapotranspiration, leakage or recharge. Singh (1968 & 1969) presents theoretical equations for groundwater flow derived from the Boussinesq equation. Brutsaert & Nieber (1977) give a wide presentation of theoretical equations for aquifer drainage used during the past century, many of which can be derived directly from Boussinesq's work.

Based on theoretical equations for groundwater flow, the decay of the aquifer outflow rate can be modelled as a function of aquifer characteristics. For application, simplifying assumptions concerning physical properties of the aquifer have to be made, and these physical based equations are in general restricted to aquifers that are homogeneous, uniform, isotropic and confirmed by specific boundary restrictions.

Relationships of this type have been presented and discussed among others by: Birtles (1978), Brutsaert & Nieber (1977), Daniel (1976), Petras (1986), Rorabaugh (1964), Singh & Stall (1971) and Zecharias & Brutsaert (1988).

These works suggest that physical expressions of the recession rate might be successful at the catchment scale for relatively homogeneous conditions. However, application in a heterogeneous catchment and at a regional scale is limited.

Boussinesq linearized the flow equation by assuming a system which can be referred to as a Depuit-Boussinesq aquifer. This is a system where the Depuit assumptions of negligible vertical flow components are valid, and where the effect of capillarity above the water table can be neglected. A linearized Depuit-Boussinesq equation results in a simple exponential equation, given as (2.2) or in the alternative forms (2.2a) or (2.2b):

$$Q_t = Q_0 \exp(-t/C) \tag{2.2}$$

$$Q_t = Q_0 \exp(-at) \tag{2.2a}$$

$$Q_t = Q_0 k^t \tag{2.2b}$$

where Q_t is the flow at time t, Q_0 is the flow when t=0 and C, a and k are constants. The k-values in (2.2b) range from 0 to unity, but have a very distinct bouncing effect as k approaches unity (Martin, 1973). A larger sensitivity in the equation constant is achieved using Equation (2.2) or (2.2a).

Horton (1933) suggested the nonlinear relationship:

$$Q_t = Q_0 \exp(-at^n) \tag{2.3}$$

where a and n are constants. This expression is often referred to as the Horton double exponential. The equation can be derived from equation (2.2) by a simple time transformation (Hall, 1968).

Boussinesq presented in 1904 an exact solution for the nonlinear differential flow equation by assuming a Depuit-Boussinesq aquifer model with zero water level in the stream and initially curvelinear water table (Hall, 1968). The nonlinear solution yields:

$$Q_t = Q_0 (1+at)^{-2} \tag{2.4}$$

Equation (2.4) with an additive constant was apparently, according to Boussinesq in 1904, first used by Maillet in his low flow analysis of the Vanne River (Brutsaert & Nieber, 1977). Maillet published a book in 1905, in which he demonstrates the applicability of equation (2.2) and (2.4) (Hall, 1968).

The same equation was shown by Werner and Sundquist (1951) and Ishihara & Takagi (1965), to yield the outflow from an unconfined aquifer. The curve is a hyperbola and plots as a straight line on a log-log paper for the variables Q_t and (1+at).

Werner and Sundquist (1951) obtained for the outflow from a confined aquifer, Q_t as a sum of exponential terms:

$$Q_t = Q_0 \sum_{i=1}^{n} a_i \exp(-b_i t) \qquad (2.5)$$

where a_i and b_i are constants. They stated that mostly only one term is needed, leading to the simple exponential function (Equation 2.2).

Ishihara & Takagi (1965) expressed the recession flow as a sum of two components, the outflow from a confined aquifer subject to a simple exponential decay (Equation 2.2), and the outflow from an unconfined aquifer expressed as Equation (2.4). The unconfined component will dominate the lower part of the recession, as the rate of recession of the confined component is faster than the unconfined one.

Singh & Stall (1971) analyzed the outflow from an unconfined aquifer under two conditions; a partially penetrating stream, and a fully penetrating stream where the horizontal impervious layer is assumed at the stream bed. The Boussinesq equation was used to show that the flow follows a single exponential decay only for the first condition.

Nutbrowne (1975) applied normal-mode analysis to groundwater flow of a partial penetrating stream. Based on the two dimensional flow equations and the validity of the Depuit assumption, Q_t was expressed as a superposition of many exponential terms:

$$Q_t = \sum_{i=1}^{\infty} A_i K_i^{\,t} \qquad (2.6)$$

where the constants A_i are dependent on the initial value of baseflow Q_0, and on the original distribution of piezometric heads in the aquifer. Nutbrowne and Downing (1976) states that a single exponential term exists in (2.6) when the shape of the piezometric head in the aquifer is relatively smooth and can be represented by a single normal mode. Generally, more than one normal mode is necessary, and the resultant flow is represented by a sum of exponential terms. They further argue that this result is not in conflict with Singh and Stall (1971), as the equations are valid under different boundary conditions of aquifer characteristics.

2.2.2 Modelling recession as reservoir outflow

The outflow given by equation (2.2) is equivalent to the outflow (Q) from a simple linear storage model with no inflow (I). As the simple exponential equation generally does not satisfactory represent the recession flow over a wide range of flows, the catchment storage should be given a nonlinear representation or conceptually modelled by more than a single reservoir.

The outflow of a lumped storage model can be characterized by a general function of the type:

$$Q = KS^n \tag{2.7}$$

where S is storage and K and n constants. A similar form of this equation with n as a function of S, can account for a continually changing relationship between Q and S:

$$Q = KS^{(1+aS)} \tag{2.8}$$

where a is a constant. The outflow can be calculated given the continuity equation:

$$I - Q = dS/dt \tag{2.9}$$

For nonlinear models, when n=/=1 in (2.7), the outflow is given by:

$$Q_t = Q_0(1+at)^{n/(1-n)} \tag{2.10}$$

where a and n are constants. Equation (2.10) equals the expression in (2.4) for n=2, which shows that the aquifer modelled by (2.4) has the same drainage characteristics as a second order storage model.

Instead of applying a nonlinear drainage equation, the recession curve can be modelled as a combination of linear curves, as the principle of superposition applies at linear solutions. In this way an aquifer might be linearized by modelling it as a set of linear reservoirs with a series of recession constants C_i, determined from the equation:

$$Q_t = \sum_{i=1}^{n} Q_{i0} \exp(-t/C_i) \tag{2.11}$$

This equation states that baseflow is a superposition of many distinct exponential terms, and is often referred to as the superposed exponential equation. It is of the same form as the expressions in (2.5) and (2.6).

2.2.3 Modelling recession as an AR process

Rewriting equation (2.2b) for t=1 and adding an error term, gives the expression for the first order autoregressive process, AR(1):

$$Q_{t+1} = kQ_t + e_{t+1} \qquad (2.12)$$

where e_t are assumed independent normally distributed errors with zero mean and constant variance. This model was used by James & Thompson (1970) and Vogel & Kroll (1988) for modelling base flow recessions. Including two recession constants k_1 and k_2, equation (2.12) can be extended to a second order autoregressive model, AR(2):

$$Q_{t+1} = aQ_t + bQ_{t-1} + e_{t+1} \qquad (2.13)$$

where $a = k_1+k_2$ and $b = - k_1k_2$.

Estimates of the recession parameters of (2.12) and (2.13) can be obtained by a least squares method. If the errors are assumed independent a direct solution can be obtained. James & Thompson (1970) presented an iterative weighted least squares procedure assuming correlated errors, where the weights were functions of the parameters to be estimated.

Spolia & Chander (1974) established in general terms the structural relationship between the parameters of an ARMA model (autoregressive moving average) and a conceptual formulation of linear reservoirs. For two linear reservoirs, the ARMA model equals the AR(2) model presented in (2.13).

2.2.4 Empirical relationships

The applicability of Equation (2.2) has also been shown in many empirical studies, and it is today the most widely used equation in recession analysis. Still, often more complex equations are needed to describe the recession curve for a larger flow range.

Otnes (1953) studied recessions from catchments in southern Norway, and suggested an hyperbola of the form:

$$Q_t = k(t)^{-1} - Q_0 \qquad (2.14)$$

where k is a constant. Based on an emperical study Otnes later found that the equation (Otnes, 1978):

$$Q_t = a(t)^{-n} \qquad (2.15)$$

where a and n are constants (n>1), was generally suitable for Norwegian catchments, which are characterized by a high lake percentage. Untill recently, recession studies in Norway, have commonly been based on Equation (2.15) (Andersen, 1972; Tjomsland et al., 1978). This equation is similar to the "ice melt" hyperbola presented by Toebes and Strang (1964):

$$Q_t = a(t)^{-n} + b \tag{2.16}$$

where b is a constant representing the asymptotical discharge for the curve. As this curve approaches a constant discharge, it was suggested for use in area with snow and ice present. Expressions (2.15) and (2.16) plot as straight lines with slope -n on a log-log paper of Q_t and t, respectively (Q_t-b) and t. This yields proving b has been chosen correctly.

Equations (2.5), (2.6) and (2.11) express the recession curve as a combination of linear curves. Several workers have found empirically that the recessions are adequately represented by a few components of these equations; Equation (2.11) with n=2, was discussed by Boussinesq i 1904 for modelling nonlinear recession curves (Hall, 1968), by Barnes (1939) with n=3, for the separation of the flow into three linear components, and more recently by Pereira & Keller (1982a) and Petras (1986).

2.3 DERIVATION OF A CHARACTERISTIC RECESSION

In humid climate rainfall frequently interrupts the recession period. As a result each discharge series produces a series of recession segments of varying durations. Several methods have evolved to construct a master recession from the selection of shorter recessions. A major problem is the high variability found in the recession characteristics of individual segments.

The master recession methods try to overcome the problem of time variability by constructing a mean recession curve. However, it is also possible to leave this principle and instead obtain a quantitative expression for each segment.

Assume we have n recession segments, then the p recession characteristics, C_p, can be obtained either from the master recession (A) or for each segment separately (B), as illustrated in Figure 2.1. In the latter case a mean value can be calculated to represent average catchment conditions. The two procedures are presented in Section 2.3.3 and 2.3.4, respectively.

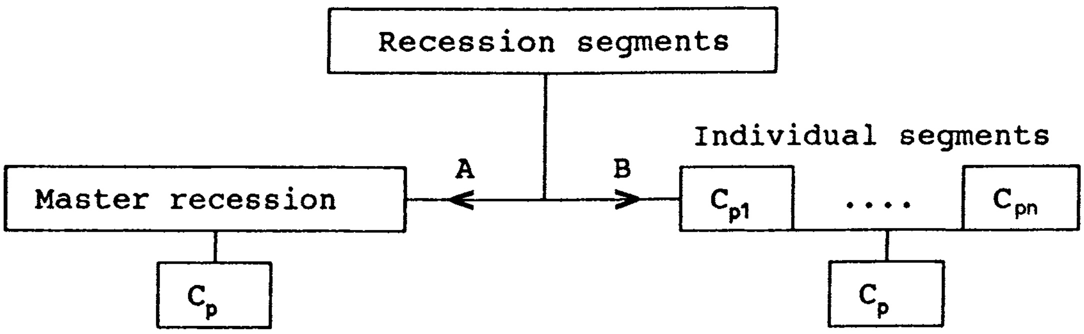


Figure 2.1 The recession characteristics, C_p, can be estimated from a master recession curve (A) or from an ensemble of recession segments (B).

If the recession curve is represented by the simple exponential equation, there is only one constant to be estimated, p=1. The lack of fit of the exponential equation for a wider range of flows has encouraged the use of a superposed exponential equation. Hydrograph separation procedures have commonly been used to define the separate exponential terms, and each components interpreted as indicators of different flow components of the recessions. This subject is given a brief presentation in the next section.

2.3.1 Hydrograph analysis

Interpreting recession flow using graphical techniques as first introduced by Barnes (1939), have frequently been used to distinguish between different flow components of the recession (Hewlett & Hibbert, 1963; Ineson & Downing, 1964; Klassen & Pilgrim, 1975; Kunkle, 1962; Singh and Stall, 1971). The recession curve has traditionally been separated into the linear components of surface, subsurface and groundwater flow.

The change in recession rate has similarly been ascribed to the heterogeneity of an aquifer or the presence of widely different aquifers (Riggs, 1964; Petras, 1986), whereas the single recession curve as expressed in (2.2) is thought to represent homogeneous conditions in terms of transmissibility and storage properties.

In both cases the recession curve is considered to be a composite curve, which has generally been modelled by the superposed exponential equation (2.11). Each term is thought to represent a different flow component, and has traditionally been determined by graphical analysis (Barnes, 1939). If each term dominates at specific times, log Q_t will plot as a series of straight lines (Klassen & Pilgrim, 1975).

Many separation methods employed are highly subjective and are of limited use as indicators of the flow processes operating (Anderson & Burt, 1980; Hewlett & Hibbert, 1967).

In more resent works these subjective methods for analyzing compound recession curves are abandoned in favour of more analytic separation procedures (Browne, 1978; James & Thompson, 1970; Pereira & Keller, 1982a). The hydrograph separation methods discussed in these works are focused on low flow recessions, and do not make any attempt to model a continuous separation.

2.3.2 Recession selection algorithm

In the case of a single linear aquifer the obtained values of the recession constant are independent of the flow or time origin, and the choice of recession segment irrelevant. In practice this is rarely the case, and the time origin of the recessions cannot be chosen arbitrary. It is difficult to find a consistent way of selecting recession from continuous flow records.

Flow data alone or in combination with precipitation records, are used to determine the recession periods. The recession periods last as long as the streamflow does not rise, or precipitation above a given limit occurs. The first days of each recession period are normally deleted to reduce the influence of surface flow, and sometimes also the last days to prevent the influence of the next storm.

The recession segments are selected from the set of recession periods (Figure 1.1) and defined by a starting and duration criteria. Both these criteria have been giving numerous representations in the literature. This section briefly presents some recession selection algorithms encountered.

The **start of a recession** segment, often called initial discharge, can take the form of a constant value or be a variable. It can be represented by one or more values for a catchment, depending on the number of flow components encountered. A variable starting value is a function of the particular method adopted for selecting recession segments, whereas a constant is a fixed value determined prior to the analysis.

A variable starting value can be defined as the discharge at a given time after rainfall, normally between two and five days (Brutsaert and Nieber, 1977; Chidley, 1969; Ishihara & Takagi, 1965; Rorabaugh, 1964; Trainer & Watkins, 1974; Zecharias and Brutsaert, 1988). The starting levels have also been determined from hydrograph analysis, traditionally as introduced by Barnes (1939), or more recently by automatic methods as suggested by Browne (1978) and Singh & Stall (1971).

Vogel & Kroll (1988) defined the recession period to start when a 3-day moving average began to decrease and to end when it started to increase.

A constant value restricts the recession analysis to the range of flow below a given discharge (Institute of Hydrology, 1980; Tallaksen, 1987b; Demuth, 1989). As the discharge value is a variable related to the degree of catchment wetness, one might expect initial conditions of catchment wetness to be similar at a given discharge.

The **recession length** can as start of recession, be a constant or variable value. A minimum length of recession is usually chosen between four and ten days (Bako & Owoade, 1988; Farvolden, 1963; James & Thompson, 1970; Jones & McGilchrist, 1978; Tallaksen, 1987b; Weisman, 1977). Recession periods above ten days have been studied in work by Ando et al. (1986) and Vogel & Kroll (1988).

This study suggests the use of a standard recession where both initial discharge and recession length are constants. This was done in order to reduce the variability in recession characteristics which could be ascribed to limitations in the simple exponential equation applied.

2.3.3 Master recessions

Traditionally, graphical methods have been used to construct a master recession curve, and the two most commonly used methods are the matching strip and the correlation method. Another frequently referred method is the tabulating method, and as pointed out by Hall (1968) these are three somewhat arbitrary hydrograph methods.

In the **tabulating method** (Johnson & Dils, 1956), which is rarely used nowadays, the recession periods are tabulated, shifted until the discharges agree approximately and mean discharges calculated for the period.

In the **matching strip method** (Toebes & Strang, 1964), individual recession segments are plotted and adjusted horizontal until they overlap in the main parts. The master recession curve is then constructed as the mean line by best eye fit through the set of common lines. This method permits a visual control of irregularities in the recession curve, but often telescopes or contracts the true recession.

Nathan and McMahon (1990) presented a semiautomated procedure which automatically selects the recession periods and plot them in descending order on semilogarithmic scales. The operator then interactively shifts the recessions along the ordinate axis until they overlap in the desired fashion. This procedure has made the matching strip method less time consuming, however, it is still subjective.

Petras (1986), Demuth (1989) and Wingård (1976) presented graphical shifting procedures for the recession segments, which enables the master curve to be constructed without any subjective judgments.

In the **correlation method** (Langbein, 1938), the discharge one time (Q_t) is plotted against discharge some time interval later (Q_{t+dt}) for selected recession periods, and a curve fitted to the data points. If the recession rate follows an exponential decay as given by (2.2b), Q_{t+dt} versus Q_t will plot as a straight line with slope k, where:

$$k = (Q_{t+dt}/Q_t) \qquad (2.17)$$

Federer (1973) calculated k for 1-day segments and grouped the values by date and streamflow rate at noon. The mean value for each group was calculated, and seasonal, average recession curves constructed. The method has later been applied by Grip (1977) and Brandesten (1988).

The uncertainties involved in defining recession periods from the hydrograph (Section 2.3.2), have made some workers prefer the concept of the correlation method which eliminates the variable t from the analysis and instead expresses the rate of change in flow for a differential dt. The rate of change can generally be expressed as a function of Q:

$$dQ/dt = f(Q) \qquad (2.18)$$

where f is a function which is characteristic for a given catchment. The equation can for flow data be approximated by differences and the function f(Q) representing the master recession, determined from a plot of dQ/dt against Q. Jones & McGilchrist (1978) chose instead to model the rate of change in river height (dh/dt) as a function of h, which is equivalent to replace Q in Equation (2.18) with h.

The choice of analytical expression to be fitted to the correlation plot is based on the same consideration as for the observed hydrograph (Section 2.2), and some equivalent expressions are presented below.

For the nonlinear flow equation in (2.10), (2.18) takes the form of a power function:

$$dQ/dt = -aQ^b \qquad (2.19)$$

where a and b are constants which can be expressed in terms of the constants Q_0, a and n in (2.10)

For a simplified linear equation as given in Equation (2.2), that is b=1 in (2.19), Equation (2.18) can be written as:

$$dQ/dt = -aQ \qquad (2.20)$$

which is for k = 1-adt, equivalent to the expression in (2.17).

The graphical analysis of Q_{t+dt} against Q_t or the equivalent form of dQ/dt against Q, are often performed by means of the upper and lower envelope of points, representing the maximal and minimal observed recession rates, respectively (Browne, 1978; Brutsaert and Nieber, 1977; Knisel, 1963; Zecharias & Brutsaert, 1988). The function f determined from the envelope curves can be defined as the master recession, and the corresponding flow hydrograph derived from integration of f(Q).

The correlation plot requires high accuracy in the low flow measurements, and it is important that the time interval is selected in accordance with the quality of the flow data. Daily time intervals are frequently used, however, this is often insufficient for the data in question.

Institute of Hydrology (1980) argued for two days interval in the correlation method, as a compromise between shorter periods of low accuracy in the recession, and larger periods which tend to eliminate many recession periods from considerations.

Nathan & McMahon (1990) stressed the importance of selecting as long time interval as possible when using the correlation method, due to the subjective element involved when fitting a curve to the data points. They further stress that a small range in slope represents a significant proportion of the range of base flows, so the uncertainty involved in applying this method might be considerable.

Brutsaert and Nieber (1977) avoided the subjective element of curvefitting by determining the function f by a least squares correlation of the lower envelope of data points. Over most of the range of Q the slopes of the lower envelopes were reasonable constant with b close to 1.5 in equation (2.19), which they showed to be in accordance with the nonlinear Depuit-Boussinesq model.

2.3.4 Individual recessions

The master recession methods try to overcome the problem of time variability in recessions by constructing a mean curve (Figure 2.1). However, it is possible to leave the master recession principle and instead calculate a quantitative expression for each segment (Chidley, 1969; Gottschalk & Perzyna, 1989; Klassen & Pilgrim, 1974; Tallaksen, 1987b; Vogel & Kroll, 1988).

Average recession characteristics can be obtained from the set of n recession curves. Assuming n groups of observations, each with j observations (x_{ij}, y_{ij}), i=1..n, j=1..m. If a separate linear regression line can be fitted to each group of observations by the least squares method, and the sum of squares for variation about each line obtained, four lines can be considered (Brownlee, 1960):

1. the n individual lines
2. the n parallel lines with an average slope k,
3. the least-squares line for the group means $(x_i\text{-mean}, y_i\text{-mean})$
4. the overall regression line which assumes that all observations come from a single population.

The procedure in point 4 is similar to derive a master recession curve from a plot of all observations.

Brownlee presents an expression for the average slope in 2, which adjusts for differences in the number of observations, j, in each group. The average slope can be calculated if the null hypothesis, which assumes that there is not a significant difference between the n slopes, is accepted. This approach was used by Bako & Hunt (1988) to derive a mean baseflow recession constant.

It is necessary to account for the number of observations in each flow sequence to obtain unbiased estimates of mean recession characteristics (James & Thompson, 1970; Pereira & Keller, 1982b). If the number of observations (j) in each group is equal, however, the average slope will equal the arithmetic mean of the n individual slopes.

Tallaksen (1987b) developed a computerbased procedure for calculating individual recession constants. The simple exponential equation was fitted by a least squares method to each segment, which was automatically selected from the flow sequence. The method has been further refined in this study, and is presented in details in Chapter 4. The mean value and coefficient of variation are derived for each catchment from the sample of recession constants. The mean value is calculated by simple arithmetic averaging as the segments are of equal lengths.

To summarize, it is stressed that the method selected for obtaining a characteristic recession should be fast and objective, so to ensure consistency in the derivation and applicability for larger data sets. This is essential in regional studies if intercomparision is to be meaningful.

2.4 OPTIMIZATION OF RECESSION PARAMETERS

Despite the form of the recession plot, as a hydrograph segment or a correlation plot, a functional relationship has to be determined in order to obtain a quantitative expression. The recession model can be selected apriori from theoretical considerations or determined from empirical judgments.

Traditionally, the selected recession equation has been fitted to a set of points by a simply subjective best eye fit of the data, as in the matching strip method. Such a procedure is subjective and liable to human error. In contrast to manual techniques, an automatic method is fast, reliable and objective and should be used both to obtain a characteristic recession as discussed in Section 2.3 and to estimate the recession parameters.

An automatic estimation of recession parameters is commonly performed using a simple or weighted least squares regression for determining the functional relationship of the recession plot (Bako & Hunt, 1988; James & Thompson, 1970; Pereira & Keller, 1982b; Vogel & Kroll, 1988; Tallaksen, 1987b). Jones & McGilchrist (1978) estimated the parameters of the regression model by the method of maximum likelihood.

Automatic methods generally allow for statistical considerations of the model fit and of the estimated parameters. Vogel and Kroll (1988) point to the importance of obtaining minimum variance and unbiased estimates of the recession constant, and Pereira & Keller (1982b) developed a curve fitting procedure which particularly focus on reduced variance of the residuals.

2.5 TIME VARIABILITY IN RECESSIONS

A considerable variation in recession rates has been found for most catchments. It is important that we understand and evaluate, preferable quantitatively, the effect of different factors on the recession rate. The variation is due to both the particular recession model and calculation procedure and to natural factors. It is important to minimize the influence of the former when evaluating the natural causes behind the variation.

The most important factors thought to affect the time variability in recessions are:

Recession model and calculation procedure: Limitations in the recession equation to model a wide flow range will impose variability in the calculated characteristics, and any subjective elements in the method for deriving a characteristic recession will influence the result.

Uncertainties in low flow measurements: In many small catchments records do not exhibit a high measurement precision for low flows, and several days may pass before a lower value is recorded.

Summer and winter curve: Climates where snow and ice are present during the cold season, experiences widely different summer and winter recession curves. In such environments it is preferable to distinguish between periods with and without frost. Gjørsvik (1970) found in a Norwegian study, a slower recession rate for the winter curve, however, limited work has been done on winter recession curves.

Nonhomogeneous aquifers: The presence of several aquifers in a catchment contributes to the variability found in recessions. Both areal and vertical differences in aquifer characteristics cause this complexity. A seasonal change in the proportion of discharge provided by different aquifers might be found.

Recharge or abstraction: Discrepancies in the flow series might be a result of recharge from precipitation or snow melt, or abstraction for i.e. irrigation.

Previous weather conditions: The amount of water stored in the catchment depends on previous weather conditions. Spatial variability in the storm patterns causes differences in the distribution of flow paths in the catchment, which in turn will influence the drainage pattern.

Evapotranspiration: The effect of evapotranspiration on the low flow regime is well documented. A major task of this study is to investigate its influence on the recession rate. This issue is therefore treated separately in the next section.

Quantitative studies of the causes behind the time variability in recessions have generally investigated the effect of evapotranspiration. Works which have tried to relate the variability to other factors have often been of limited success. Chidley (1969) found generally low correlations between a recession constant, start of recession and an 'antecedent precipitation index'. Jones & McGilchrist (1978) were not able to relate the recession characteristics to measures of catchment wetness.

In this study (Part III & Chapter 4), the coefficient of variation of the recession constant was neither related to catchment and climatic parameters nor to low flow indices, which suggests that the recession variance is independent of low flow regime. It is shown, however, that the recession constant calculated from the simple exponential eqation, depends both on start and length of the recession segment.

2.6 THE INFLUENCE OF EVAPOTRANSPIRATION

During warm weather and especially in the active growing season, water loss by evapotranspiration has a marked influence on low flows. This is particularly noticeable in areas with shallow groundwater tables and extensive vegetation.

Evapotranspiration includes transpiration from plants and evaporation from soil and water surfaces. Principles of evapotranspiration are presented in Section 6.2. When evaluating the effect on recession flow, it is important to distinguish between water lost by evapotranspiration that would otherwise become streamflow and water that would not.

Vegetation along stream banks, in areas with shallow water tables and with well developed root systems can have a high water consumption during dry weather. Studies have shown that the effect of evapotranspiration on recession flow is highest in forested catchments (Brandesten, 1988; Federer, 1973).

A drying of the upper soil layer can be succeeded by capillary transport from the groundwater providing a shallow water table. The effect of evapotranspiration is reduced for the lowest discharge values as the source area with potential for evapotranspiration losses from soil and groundwater, recedes during the recession period due to lowering of the water table and drying out of the upper soil layer. Federer (1973) argued that water was lost throughout most of the catchment in order to produce the rapid recession rate found during summer.

The effect of evapotranspiration is to steepen the recession curve, reflecting the increased loss of moisture. Accordingly, many authors have recognized the recovery of low flow in autumn or winter as a result of reduction in evapotranspiration (Croft, 1948; Federer, 1973; Singh, 1969). Croft ascribed the increased rate of flow largely to a decrease in transpiration rather than in evaporation.

Theoretical studies of the interaction between groundwater flow and evapotranspiration losses have been carried out by Singh (1968) & Daniel (1976). Singh evaluated the effect of evapotranspiration losses on the outflow curve. Daniel obtained an analytic solution for the evapotranspiration rate from groundwater by applying the theoretical model for groundwater outflow presented by Rorabaugh (1964), and assuming a constant evapotranspiration rate.

Diurnal fluctuation of streamflow is a result of water being lost by evapotranspiration during daytime at a higher rate than at night, and is a well known effect of riparian transpiration. Normally a pronounced increase in the diurnal fluctuations is observed during the warm season (Croft, 1948; Reigner, 1966; Tschinkel, 1963; Troxell, 1936).

A seasonal form of the recession curve is a result of the flow being more affected by evapotranspiration in the warm season. Many works have demonstrated the seasonal variation of the recession curve (Ando et al., 1986; Brandesten, 1988; Croft, 1948; Federer, 1973; Grip, 1977; Knisel, 1963; Singh & Stall, 1971). Langbein (1942) estimated evapotranspiration losses from baseflow recessions.

Other studies have approached the problem of predicting the amount of water lost by evapotranspiration. The loss has been estimated by constructing a "potential" recession curve, which is thought to represent time of little or no evapotranspiration. Potential baseflow recession curves have been obtained from hydrograph analysis by connecting the highest peaks of a recession period (Reigner, 1966; Tschinkel, 1963), or simply by assuming that the baseflow curve in autumn represents the potential curve (Farvolden, 1963). The evapotranspiration loss is then assumed to be related to the difference between the actual and the potential recession curves. Tschinkel (1963) related the estimated loss to pan evaporation, whereas Reigner (1966) found it to be related to mean daily discharge and a vapour pressure deficit. The method poses problems in defining the potential recession curve.

Weisman (1977) related a recession constant to the average daily pan evaporation during the time of recession. In Chapter 4 and Part III average air temperature during the recession period is used as an index of evapotranspiration. Both high and low correlations with the recession constant are found in the different catchments. In Chapter 6 evapotranspiration losses are calculated using the soil water balance model AMOR, which accounts for vegetation and soil properties in the calculations.

If a satisfactory relationship between an index of evapotranspiration and fluctuations in the recession rate can be established, it means that we can improve our low flow forecasts. It is essential for operational purposes that the evapotranspiration estimate can be routinely calculated. Chapter 6 approaches this problem.

2.7 CONCLUDING REMARKS

Recession analysis generally suffers from the fact that no satisfactory definition of recession characteristics exists. The result is a lack of consistency in obtaining recession characteristics which has limited a wider use.

This study suggests the use of a standard recession in order to reduce the variability in recession characteristics due to the limitations of the simple exponential equation used. In a standard recession both initial discharge and recession length are constants. The method which is automatic, is presented in details in Chapter 4.

It is important that an automatic method both for obtaining a characteristic recession and to estimate its recession parameters is applied. Automatic methods are in contrast to manual techniques, fast and objective, and readily transferable, which ensures consistency in derivation and applicability for larger data sets. This is essential in regional studies if intercomparision is to be meaningful.

In general, the selection of the best method to apply in recession analysis should depend on the purpose of the study. The high time variability in the recession curve, argues against the use of a master recession curve except as an overall approximation which is appropriate for use at the regional scale.

When selecting an expression to fit a recession segment, one has to consider which part of the curve is most important. In a regional study where the recession characteristics are thought to represent catchment storage properties, it is the speed with which the low flow is reached that is important. For regional analysis, a simple expression is preferable as the recession behaviour will vary considerable between the catchments.

Low flow forecasting is concerned with the lower end of the recession curve, and it is necessary to analyze the recession characteristics in a detailed manner where more complicated solutions might be sought. The time variability found in recessions should be incorporated in any low flow forecast, merely as a statistical variance or given as a conditional forecaset with reduced variability.

One of the major natural factors thought to influence the recession variability is evapotranspiration. If a satisfactory relationship between an index of evapotranspiration and fluctuations in the recession rate can be established, it is possible to improve our low flow forecasts. It is essential for operational purposes that an estimate of evapotranspiration can be routinely calculated.

CHAPTER 3

REGIONAL ANALYSIS OF RECESSION BEHAVIOUR

3.1 INTRODUCTION.

The influence of geology, including rock, drift and soil materials, is frequently reported as the major terrestrial influence on low flows. The problem is how to represent this influence numerically. Any direct expression has to incorporate a number of formation characteristics, whose properties vary considerable over even small areas. In any regional studies it seems necessary to make use of indirect measurements.

Many indirect methods have evolved in order to represent the geology of a catchment. The main purpose has been the need for an index of storage in multivariate analyses of both floods and low flows. Improved relationships between low flow indices and catchment characteristics have been attained by adding a storage index.

The recession curve tells in a general way about the natural storages feeding the stream. Accordingly, it holds substantial promise for use as an index of storage, providing a suitable way of quantifying the recession rate exists.

This chapter considers regional aspects of recession behaviour, with special emphasis upon the use of the recession constant as an index of storage. The recession rate characterizes the gradual depletion of moisture stored in a catchment, and represents the integrated effect of terrestrial and meteorological conditions. The most important factors thought to affect the recession rate, and their related parameters are presented, and the relationships between recession, catchment and low flow characteristics investigated. A brief overview of general methods used to derive an expression of geology is given, and the use of the recession constant in this context is discussed separately.

The analysis includes the recession characteristics estimated according to the method presented in this work. The recession characteristics are calculated as the mean value (C-mean) and variance (C-var) of N estimates of the recession constant calculated from individual segments. The recession calculation procedure is generally discussed in Chapter 2, and calculation details are given in Section 4.3. The method involves the use of a standard recession where both initial discharge and length of the recession segments are constants.

The recession characteristics are in Part III included in a regional low flow study of 68 catchments. The main objective of this study was to investigate the possibility to improve the accuracy of the regression equations by including the recession constant. The main results from this analysis are discussed in a general context in the following sections.

3.2 FACTORS AFFECTING THE RECESSION RATE

The recession part of the hydrograph reflects the total effect of various physical characteristics of the catchment. These factors can broadly be characterized as terrestrial and meteorological, and their parameters classified as catchment and climatic characteristics. The catchment characteristics can further be subdivided into morphometric, geological and cover parameters.

The initial input is given by meteorological conditions, whereas the catchment response is determined by terrestrial conditions. In areas with limited storage capacity, the low flow characteristics are largely controlled by meteorological influence, whereas in areas with high storage capacity, terrestrial conditions prevail. The effect of storage is to increase low flows and reduce the recession rate. A slow recession is equivalent to a low recession rate, whereas a fast recession corresponds to a high recession rate.

The recession mean and variance values as defined in this study are calculated for 68 catchments, and the region pattern investigated (Part III). There is no clear pattern in the plots, however, one might recognize a wider range in both mean and variance values for catchments situated along the coast. This result suggests that local, rather than regional factors, govern the recession rate.

Physical expressions of formation characteristics are generally not applicable in regional studies, due to lack of necessary data. This section discusses the influence of parameters relevant at the regional scale, which are generally limited to those which are readily available from maps.

3.2.1 Meteorological characteristics

Precipitation: Areas with high annual precipitation and frequently interrupted recession periods will yield higher recession rates. Precipitation is commonly represented by mean annual or seasonal precipitation.

Evapotranspiration: Areas with high evaporative demand, will yield faster recessions, and the seasonal variations might be pronounced.

3.2.2 Catchment characteristics

Catchment size: An increase in area will increase the routing effect on the flow, and thereby offsetting the recession rate. The main measures of size are catchment area and length of main stream.

Relief: A catchment with high relief and steep slopes, increases the drainage rate and favour a fast recession. Relief can be represented by altitude range, a relief-ratio, slope of main stream or measures of the hypsometric curve.

Drainage network: A dense river network increases the rate of quick runoff and reflects a low infiltration capacity. A coarse network manifests a high infiltration capacity and high groundwater recharge rates which will sustain a slow recession. An index of drainage density has frequently been used as an index of catchment storage properties. The index can be derived in terms of stream length, stream number or stream junctions.

Lakes: The presence of lakes increases the catchment storage and thereby reduces the recession rate. The influence on extreme low flows is more difficult to evaluate as the role of the lakes in runoff formation at this low level of discharge is not clear. Lakes are in low flow analysis commonly represented by the ordinary lake percentage, however, a weighted lake percentage has shown equally applicable for low flow estimation (Moltzau, 1989).

Geology: This term includes bedrock, drift and soil materials, and are often referred to as the dominant factor in determining the low flow behaviour of rivers. Geology of high permeability and storage capacity favours a slow recession rate. Both type and extend of the formations are important. Different methods for indexing geology are presented in Section 3.3 and 3.4.

Vegetation A dense vegetation cover reduces the groundwater recharge due to the water lost by evaporation of intercepted rainfall and transpiration by plants. The immediate effect on the recession rate can, however, be difficult to evaluate, whereas the seasonal variation in evapotranspiration clearly is reflected in the recession pattern.

3.3 DERIVATION OF A GEOLOGICAL INDEX

The influence of geology on streamflow is particularly apparent at low flows when the entire discharge, apart from lake drainage, comes from subsurface storage. The effect of geology has been well documented in the literature, and McMahon (1976) gives a summary of works where the influence of geology on low flows has been reported.

However, not many of these works have made any direct numerical expression for the effect of geology. Any expression has to be multipurpose in characterizing a number of formation characteristics, i.e. infiltration, porosity (the ability to store water), permeability (the capacity to yield water) and local structural effects. These properties vary considerable over even small areas, and data are normally not available at the spatial scale necessary for comparative studies on a regional scale. For these reasons direct measurements are often left out by the hydrologist in favour of indirect expressions. Indirect methods provide an average catchment value, and the problem of obtaining areal values from point estimates is avoided.

Direct measurements of formation characteristics can be substituted by the information of relevant bedrock, drift and soil maps. However, the geological differentiation is usually made on the basis of genesis, whereas the hydrologist needs qualitative hydrogeological information. The geology has to be classified and ranked according to its runoff potential for application in regional analysis. It is possible to use both an absolute scale as for the direct measurements (infiltration, permeability), or rank the rock, drift and soil types according to a relative scale.

A hydrological classification system for soils based on the infiltration rate was introduced by Musgrave (1955), and later refined by Ogrosky & Mockus (1964) by adding drainage class and impeding strata. This scheme was used for soil classification in USA by the Soil Conservation Service (Chiang, 1971). Armbruster (1976) calculated an infiltration index based on a simple numerical weighting of these relative infiltration capacities. Chiang (1971) proposed a rating table based on the soil catena concept, to group soils of similar runoff potential.

One of the first attempt to use soil indices in a regional study in Europe was made by NERC (1975). Based on national soil maps, the soils were allocated to the appropriated "Winter Rainfall Acceptance Potential" (WRAP) class, given the soil and site properties. The classification is based on the infiltration potential, which in reverse reflects the runoff potential. A soil index for each catchment was derived from the five WRAP classes.

Other measurements of geology have also been used in regional analysis. Bedrock permeabilities were used by Pereira & Keller (1982b), Klassen & Pilgrim (1975) tested three different indices of geology, representing surface rock type and alluvial deposits, and Tallaksen (1987b) calculated a storage index based on a numerical weighting of the drift deposits.

3.4 INDIRECT EXPRESSIONS OF STORAGE PROPERTIES

The geological characteristics are normally dominant in determining the storage properties of a catchment, and a storage index is commonly referred to as an index of geology. The use of indirect expressions implies that the effect of a combination of factors influencing recharge and storage conditions, are incorporated in the derived index. Consequently, an indirect expression should be referred to as a storage index, not only representing the influence of geology.

3.4.1 Morphometric characteristics

The most commonly used morphometric measurement in low flow analysis is drainage density (Section 3.2.2). Jacob (1943) studied its relationship to formation characteristics, and Carlston (1963), Farvolden (1963), Moltzau (1990) and Zecharias & Brutsaert (1988) among others, have studied its influence on low flows. A major problem when working with drainage density, is the lack of consistency in its derivation. This is due to differences in scale and quality of maps.

3.4.2 Flow related indexes

These indexes are derived from discharge series, directly from the time series or as indices of the slope of flow duration and frequency curves. Both flow duration and frequency curves have high data requirements, and are not commonly used.

Classical hydrograph analysis involves the use of various hydrograph separation techniques in order to distinguish between the different flow components. These methods have received serious criticism, and hydrograph separation is by Hewlett and Hibbert (1967) described as "one of the most desperate analysis techniques in use in hydrology".

A review of different hydrograph separation techniques is given by Nathan & McMahon (1990). They distinguish between methods aimed at deriving the response for a given event, and automated techniques for the continuous separation of base flow. It is the latter methods which are applicable at the regional scale.

Hewlett & Hibbert (1967) argue for the use of an objective and arbitrary method for separating the flow. They use the flow separation program suggested by Hibbert & Cunningham (1967), which is in contrast to traditionally methods, not based on physical reasoning. It simply divides the flow into a quick and a delayed component using a time based separation. The delayed flow component is thought to represent the runoff that derives from stored sources. Two different response factors are suggested based on the ratio of separated volumes.

A similar index, the base flow index (BFI), was developed during a low flow study in UK (Institute of Hydrology, 1980) for the purpose of indexing the influence of soil and geology. The index is the ratio of base flow (delayed flow) to total flow, calculated using a smoothing minima separation technique. A more detailed presentation of the index is given in Tallaksen (1987a) where it is evaluated for use in Norway, and in Part II where it is included in a regional low flow model for Norway.

Nathan & McMahon (1990) compare the BFI with another index of base flow, calculated using the same flow relationship, but applying a different separation technique. The separation is based upon a recursive digital filter, and differs from the BFI smoothed minima technique by generating higher base flow under flashy peaks. The digital filter yielded similar correlations as the BFI when compared to low flow indices.

The strong influence exhibited by storage capacity on low flows has also been studied by means of the recession curve. The rate of change as illustrated by the recession curve can be look upon as representing the permeability of a catchment, whereas the absolute discharge can be related to the volume of stored water.

Various expressions for recession characteristics have been proposed (Chapter 2), some for the purpose of indexing the catchment's storage capacity in regional regression relationships (Browne, 1981; Institute of Hydrology, 1980; Tallaksen, 1987b; Vogel & Kroll, 1988). This was also the initial purpose of the recession constant, C-mean, introduced in this study. In Part III a regional low flow analysis is performed, and it is concluded that including the recession mean value in a low flow regression model, significantly increased the estimation accuracy. Similar results are obtained when the recession constant is replaced by the BFI.

In principle, one can question the use of flow related indexes as indexes of catchment properties. These indexes introduce uncertainties when evaluating the model results because it is not explicit known which catchment properties are represented by the index. A qualitative evaluation of these techniques is difficult because the methods of calculation are arbitrary, and it is not a known quantity that is estimated.

It is for ungauged catchments necessary to develop a transposition for the flow related indexes, which introduces additional uncertainties in the application. The record length and period will influence the stability of these indexes due to climatic variations. The time variability of a flow related index can be very high, and sometimes of the same magnitude as the total variability of all series.

However, flow related indexes have performed satisfactory in many studies because even a rough estimate of storage properties greatly increases the performance of the estimation equations. Until detailed rock, drift and soil maps are available for larger areas, and satisfactory geological indexes can be developed, there will be a need for this type of index.

3.5 RELATIONSHIPS BETWEEN RECESSION AND CATCHMENT CHARACTERISTICS

The recession characteristics of ungauged catchments can be calculated providing that the recession constant can be satisfactory described by the catchment and climatic characteristics available or by developing regional maps of base flow recessions.

The relationship between geology and recession rates has frequently been reported, but has often, particularly in earlier works, been limited to a qualitative description (Ayers & Ding, 1967; Musiake et al., 1975). Average values of a recession constant have been derived for different physiographical regions or geological formations (Browne, 1978; Knisel, 1963; Trainer & Watkins, 1974; Wright, 1970). Browne (1978) presented an isopleth map of recession values for the study area. Ando et al. (1986) proposed a weighted average method to estimate a recession constant for basins with various geological characteristics.

Quantitative relationships with catchment characteristics have been investigated by a number of workers (Andersen, 1972; Farvolden, 1963; Demuth, 1989; Klassen & Pilgrim, 1974; Pereira & Keller, 1982b; Petras, 1986; Tallaksen, 1987b; Tjomsland et al., 1978; Zecharias & Brutsaert, 1988). Although it has been possible to establish estimation equations for recession characteristics, these works often show that the recession characteristics are inadequately described by the indices available. This is also valid for flow related indexes in general.

The most important indices found to affect the recession rate in these studies are related to geological characteristics (drainage density), relief (main slope) and climate (mean annual rainfall). The most frequently used parameter for each characteristic is given in brackets.

Low correlations between the recession and catchment characteristics are also found in the regional analysis presented in Part III. The highest correlations are obtained with drainage density and mean annual rainfall, which is in agreement with previous results.

It is common to seek the relationships with catchment and climatic characteristics through statistical methods of correlation and regression. Zecharias & Brutsaert (1988) formulated the groundwater outflow based on a hydraulic approach applied to a simple conceptual model. This permitted the recession constant to be calculated both in terms of catchment characteristics and flow data. The highest correlation coefficient obtained between the recession constant of the two calculation methods was 0.68 (N=19).

3.6 RELATIONSHIPS BETWEEN RECESSION CHARACTERISTICS AND LOW FLOW INDICES

Estimates of the recession constant as well as other flow related indexes, have found to be highly correlated with low flow statistics. Gottschalk & Perzyna (1989) made an attempt to incorporate recession characteristics as parameters in a physical based distribution function for low flow.

This section compares relationships obtained in five different studies. Table 3.1 presents the correlation coefficients (r) found between different low flow indices and the base flow index (BFI) and recession constants, respectively. The number of cases (N) is given in brackets. $Q_{90}(D)$ is the D day average flow exceeded 90 % of the time, and MAM(D) the mean annual D day minimum. All flow indices included have been standardized with specific mean annual flow to reduce the effect of catchment area and climate. (The standardized values are in some of the works referred to as STD values).

Table 3.1 Low flow correlations.

REFERENCE	REGION	LOW FLOW INDICES	BFI r (N)	RECESSION r (N)
Tallaksen, 87b	Norway	Q_{90}	.71 (19)	.86 (18)
This study,part III	Norway	MAM(7)	.74 (68)	.91 (68)
Moltzau, 90	Norway	MAM(7)	.71 (51)	.86 (51)
Nathan/McMahon, 90	Australia	Q_{90}	.71 (186)	.40*(186)
Institute of Hydrology, 80**	UK	$Q_{90}(10)$ MAM(10)	.72 (456) .81 (456)	

* Nathan, pers. comm. (1991)

** square root transformations of the variable

A high consistency in the correlation figures between BFI and the low flow indices is found for these data sets, which vary both in size and type of region. The highest correlations with the low flow indices are found for the recession constant as included in the Norwegian studies. Moltzau (1990) applied the recession mean value as defined in this study, whereas Tallaksen (1987b) used the original version of this method. Details in the methods are given in Chapter 4. The results clearly confirm the applicability of the recession mean value in regional low flow analysis.

Vogel and Kroll (1988) compared a similar estimator of recession characteristics, calculated an average of an ensemble of idividual recession constants, with two other estimators based on representation of the recession as an AR(1) and an AR(2) process, respectively (Section 2.2.3). The first estimator proved to explain significantly more of the regional variability of low flows than either of the two autoregressive parameters.

As both the BFI and the recession constant are thought to represent storage properties, they are expected to be related. A correlation coefficient of 0.77 is found between the BFI and the recession constant in this study (Part III), which is slightly above the correlations obtained by Nathan & McMahon (1990) and Beran & Gustard (1977), r=0.60 and 0.61, respectively.

3.7 CONCLUSIONS

Many attempts have been made in the past to derive an expression for geology or storage capacity, applicable at the regional scale. A brief overview of general methods used to derive such an expression is given, and the use of flow related indexes including the recession constant is discussed separately.

The most important factors thought to affect the recession rate, and their related parameters are presented. Earlier works, including this study, often shown that the recession characteristics are inadequately described by the indices available. This is also valid for flow related indexes in general.

The most important indices found to affect the recession rate are related to geological characteristics (drainage density), relief (main slope) and climate (mean annual rainfall). The most frequently used parameter for each characteristic is given in brackets. The best relationship is commonly found with geology. There is a general lack of relevant geological maps in many areas, and improvements in low flow estimations, depend on mapping and hydrological classification of the geology in these areas.

Estimates of the recession constant as well as other flow related indexes, are highly correlated with low flow statistics. Correlations found between low flow indices and recession constants and the BFI, respectively, are compared, including data from four different studies. A high consistency in the correlations between BFI and the low flow indices is found for these data sets which vary both in size and type of region.

The results clearly confirm that the average recession constant as defined in this study, is a powerful tool in characterizing the behaviour of low flows. The mean value represents average conditions for the catchment, and the adoption of a constant is shown to be useful in regional analysis. At the catchment scale, however, where recession analysis is useful for low flow forecasting, it is essential to understand the factors influencing the time variability in the recessions.

CHAPTER 4

RECESSION RATE AND VARIABILITY

4.1 INTRODUCTION

Prior recession analyses have shown great time variability in recession characteristics. A general presentation of factors that might influence the variability pattern at the catchment scale is given in Section 2.5. In order to derive recession characteristics which are representative for catchment storage properties, it is essential to have quantitative knowledge about the main factors influencing the recession variability.

In catchments without human impacts, the variation is either due to natural fluctuations or model limitations. To minimize the variability due to limitations in the recession model, a standard recession is suggested, where both initial discharge and recession length are given as constants. Varibility due to human errors and subjective judgments are minimized using an automatic calculation procedure. Still, low accuracy and measurement errors in the low flow data influence the model fit and cause variability.

Natural fluctuations in the recession pattern are due to initial conditions of catchment wetness and influence of evapotranspiration and slight precipitation during the recession period. The initial discharge of each recession segment is given a constant value, as it is assumed that similar conditions of wetness prevail at similar discharge levels. One of the main interest of this study is to investigate to what degree climate in the recession period can account for the remaining variability.

The climatic influence on recession variability is in Part III studied by incorporating data on precipitation and temperature during the recession period. The aim of this chapter was to perform a more comprehensive analysis of the recession characteristics of a catchment, and to investigate the generality of the poor relationships between recession chacteristics and climatic and catchment characteristics, reported in Part III.

4.2 DATA BASE AND DATA QUALITY

Ten catchments in southern part of Norway are selected, the location of each gauging station is given in Figure 4.1. The sample has been selected to have a wide range in catchment characteristics. In addition the limiting criteria are:

* catchment area less than 75 km^2
* climatic stations located in or near the catchment
* at least 10 years of corresponding runoff-climate records
* no diversion or regulation of streamflow

For each catchment the related catchment, flow and climatic characteristics are presented in Appendix A.1, together with outlines of drainage areas, station data and locations. Map information is generated from the topographic map series (M711), in scale 1:50 000. Climatic stations and data are not presented for catchment 569 and 917, due to the lack of representative stations. The catchments are therefore, only included in the first part of the analysis.

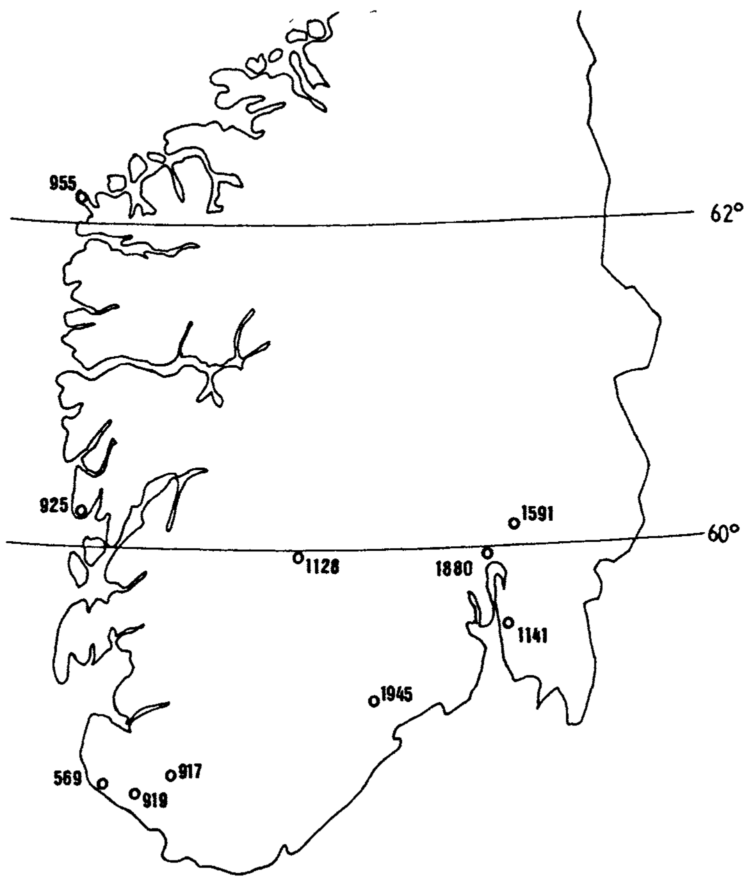


Figure 4.1 Location of gauging stations.

As the aim of the analysis is to study recession characteristics and related storage properties of the catchments, the analysis has been limited to the summer period in order to avoid the influence of snow and ice. The summer months are for each catchment determined based on location, and examination of the hydrograph. The selected summer periods are given in terms of daynumbers, Appendix A.1.

4.2.1 Catchment characteristics

The set of catchment characteristics selected for this study is composed of commonly used morphometric, geology and cover properties. However, the selection has been limited by the characteristics available from the M711 map series. It is considered important that the same map series is used, as cover properties have shown to have widely different representation on different maps, even of the same scale. The area characteristics are given as percentage of total area, lakes included. Computation details and characteristics are given in Appendix A.1.

The selected morphometric characteristics are catchment area (AREA), altitude range (ALT) and relief ratio (RELIEF). The cover properties include lake percentage (LAKE), bog percentage (BOG), percentage of cultivated land (CULT) and forest percentage (FOREST). REST is the percentage of total area not covered by any of these characteristics, and is calculated as the rest term. It includes area of bare rock, bare soil, low vegetation (grass/scrubs) and if explicit values are missing, also cultivated land. A list of variable and related statistics is given in Appendix B.4.4.

The term geology includes in this study, rock, drift and soil materials. The bedrock of these catchments can, as in general for Norway, be looked upon as impermeable. Water is in these rocks stored in, and transmitted through fractures. The drift material has not been mapped for the whole study area, and was therefore not included in the analysis.

Soils can be characterized by the dominant types of loose deposits in the catchment, and allocated to a SOIL CLASS, type 1, 2 or 3, where soils of high, medium and low water capacity are defined. These soil classes are equivalent to the classification system given in MORECS (Section 6.5.2). Values are only given for the two catchments included in the evapotranspiration calculations in Chapter 6.

The flow characteristics obtained are average daily flow (ADF), the base flow index (BFI) and the recession constant

(C-mean). The base flow index (Institute of Hydrology, 1980) is presented and discussed for Norwegian conditions in Tallaksen (1987a) and in Part II, and is given a brief presentation in Section 3.4.2. The recession constant is calculated both with precipitation included (C-mean, P), and with a precipitation limit of 1.0 mm per day (C-mean). The recession calculation procedure is presented in Section 4.3.

4.2.2 Discharge data

Daily discharge data were provided by the Norwegian Water Resources and Energy Administration (NVE).

The data quality is of special importance when analyzing low flows, and all the selected discharge stations have limnigraphs. Still, the accuracy in the low flow measurements is not sufficient to avoid that the low flow data frequently are recorded in a staircase manner, i.e. several equal values follow before a lower value is recorded. As also slight precipitation might offset the recession rate and produce steps in the series, the presence of steps generally complicates the flow analysis.

As steps appear at low discharges, they will commonly be a feature of runoff series with a low average daily flow (ADF). Series with steps will in the following be referred to as stairs series. To avoid steps in the series, the transformed series is introduced. Here equal values in the observed series, are replaced by values resulting from fitting an exponential decay curve between decreasing neighbour points in the series.

4.2.3 Climate data

The climate characteristic chosen for the regional analysis is mean annual precipitation (SAAR), whereas daily precipitation totals (prec) and average temperature (temp) are included for studies at the catchment scale.

Precipitation and temperature data are supplied by the Norwegian Meteorological Institute. Temperature is given as mean daily air temperature, whereas daily precipitation is the recorded 24 hour value, observed 7 AM. To a large extent this is precipitation that has fallen the previous day, but due to the time delay in the catchment, the value is chosen to be valid for the recorded day.

Daily temperature data are normally of high quality during the summer period, the major source of error is how representative the station is. However, as temperature has a stable spatial distribution, a point estimate will satisfactorly represent the relative difference between the recession periods.

Daily precipitation data is due to its high spatial variability, a major source of error in the analysis. Station representativity is of vital importance when determining precipitation free periods. The accuracy of the precipitation measurements is important when evaluating the influence of precipitation on individual recessions. The catchments have been selected from an evaluation of the how representative the precipitation station is. However, considering the high spatial variability of precipitation found in many parts of Norway, the low station density and the small areas in question, the precipitation data remain a major source of error.

4.3 RECESSION CALCULATION PROCEDURE

The calculation of the recession constant is based on the automatic method first presented in Tallaksen (1987b). The method has been slightly modified in this study by the introduction of a standard recession. The choice of recession model and calculation procedure is based on the conclusions given in Chapter 2.

The major advantages of this method are that it is automatic, objective, fast and subject to evaluation of statistical performance. The simple exponential equation is chosen due to its simplicity and wide use. It has only one recession constant to be estimated, which is preferable for regional analysis (Chapter 3). Its limitation for a wide flow range is accounted for by calculating successive values of the recession constant for decreasing starting levels.

The method is discussed in a general context in Chapter 2, whereas a more detailed presentation is given below. Data in the form of average daily flows are used in the following, but other time steps are equally applicable.

Given a continuous discharge series with daily mean values, a computer programme automatically selects recession segments from the time series, providing the following parameters have been chosen:

* Season: which in this study is the selected summer period (daynumber).
* Upper limit of discharge (QUL): which is the maximum discharge level for start of recessions (l/s).

* Length of recessions (LENGTH): which is the constant recession length (days).
* Number of decreasing values (NUM): which is the minimum number of decreasing values required in the recession segment.
* Goodness of fit of theoretical curve (r): which is the minimum required correlation coefficient calculated between the observed and predicted value of runoff.
* Precipitation limit: which is the threshold value for acceptable daily precipitation.

The recession segments are selected as follows:

1) The start of the recession period, Q0, is determined from the time series as the first value below QUL, however, it is required that Q_0 is at least two days from peak of discharge.

2) The recession sequence continues as long as the next discharge value is less than or equal to the last value, and does not reach zero, and providing the number of days in the sequence does not exceed the selected LENGTH. Only segments with the required length, and minimum number of decreasing values are included in further calculations.

3) The simple exponential equation is fitted to each segment by a least-squares method. Equal values in the sequence are left out, and the calculation based on decreasing values only.

4) The correlation coefficient (r) between observed and predicted values of runoff is calculated, and segments with values above the selected limit, are accepted for further analysis.

5) The recession segments are checked against corresponding percipitation data, and segments containing days with percipitation above the given limit are disregarded.

The recession constant (C) of the simple exponential equation $Q_t = Q_0 \exp(-t/C)$ (Equation 2.2), is calculated for each segment. This results in, for each catchment, a distribution of the recession constant rather than one value derived from a master recession, Figure 4.2. The recession characteristics of each catchment are analyzed by looking at the mean value (C-mean) and variance (C-var), of N estimates of the recession constant. C-mean is calculated by simple arithmetic averaging, which will give an unbiased estimate providing the recession segments are of equal lengths.

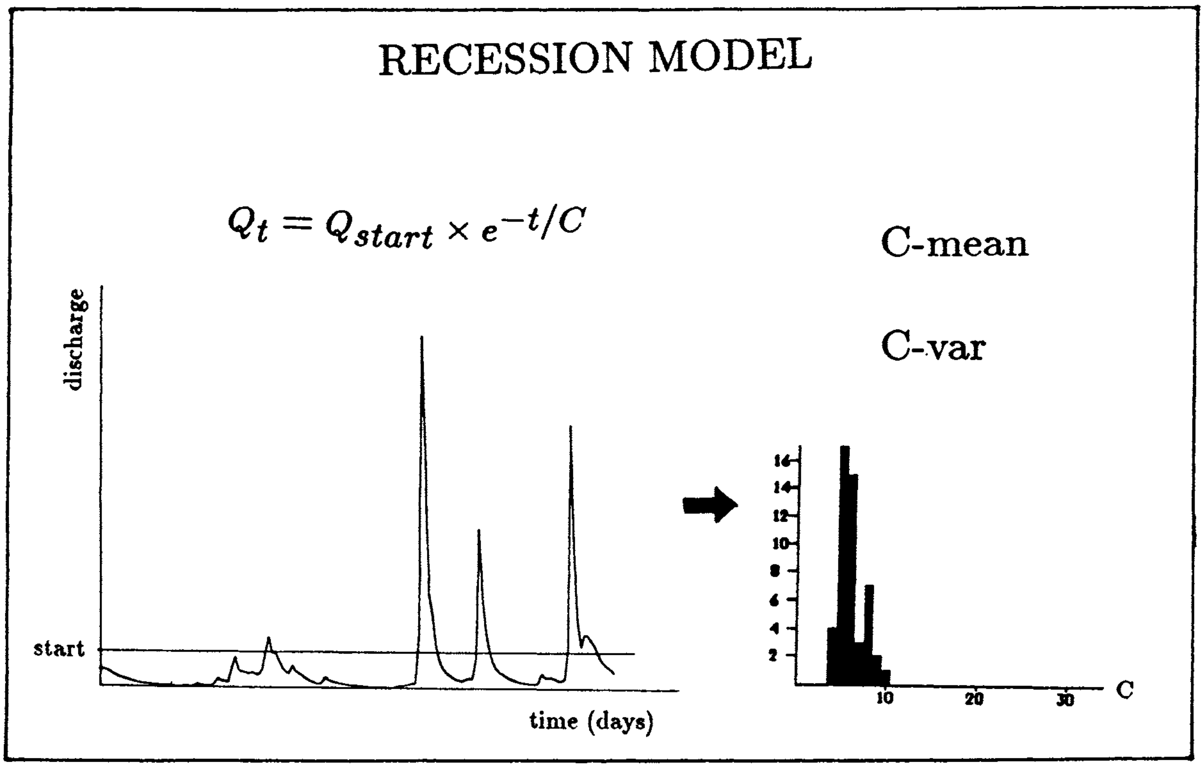


Figure 4.2 Recession calculation procedure.

The curve-fitting equations are derived with respect to the original nonlinearized exponential equation. The sum of residuals squared are calculated using a relative residual, R, which is given by:

$$R = [Q_0 \exp(-t/C) - Q_t]Q_t \qquad (4.1)$$

This expression is preferable to use if it assumed that the data are measured with the same relative accuracy. Newtons method is used in the solution of the resultant nonlinear equations. A more detailed description of the curve fitting procedure is given in Miller (1981). A comparison made between this direct approach and a least-squares fit made to a linearized form achieved by taking the logarithm of the equations, revealed small differences. In case of a steep start of recessions, however, the direct fit produced a slightly lower recession rate (Tallaksen, 1987b).

Goodness of fit of theoretical curve is calculated as the correlation coefficient (r) between observed and predicted value of runoff. In the recession analysis in Part III, the acceptable limit of r was set to 0.90, to avoid segments with large discrepancies in the recession pattern. As the purpose of this study is to analyze the factors that govern the recession variability, this limit is left out and all segments accepted for analysis.

As discussed in Section 4.2.2 the low flow data are frequently recorded in a staircase manner, due to low resolution in the low flow measurements. The recession analysis is performed for both observed series with steps and transformed series where the steps have been modified.

The calculations are in the observed series based on decreasing values only, denoted in Figure 4.3, and equal values ( ) are left out of the calculations. The segments terminate at the last decreasing value, and leaves the flat end of the recession out of the calculation. Stairs series experience increasingly longer steps as the discharge reduces, and the limiting factors for accepting a recession segment will be the recession length and the required number of decreasing values in the sequence. Consequently, the selection of segments will be biased towards the steepest recessions as the step length increases.

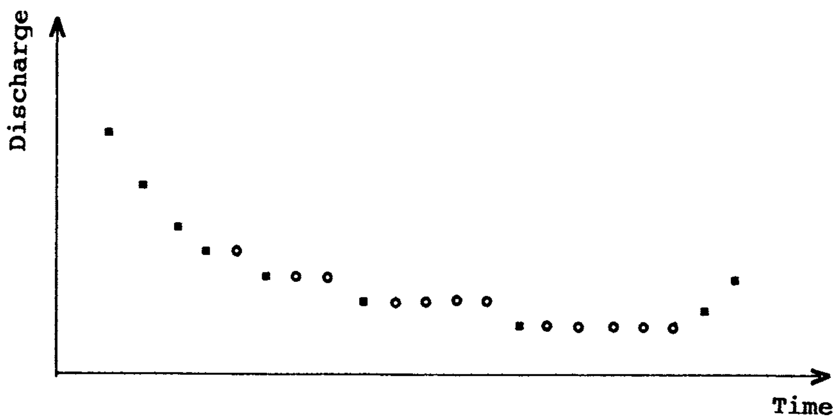


Figure 4.3 Stairs in the discharge series.

In the transformed series, equals values are replaced by decreasing values. The last flat part of a recession period poses a special problem, however, because it is not clear whether it belongs to the recession curve or the rising limb of a new storm. In the transformed series this part is excluded from analysis. This implies a reduction in the recession rate for the lowest starting levels of recessions. The matter is further discussed in the next section.

4.4 RECESSION ANALYSIS

The recession calcualtion procedure presented in the last section is in Part III tested using all recessions below a given threshold discharge, with no restriction to start or length of recessions. The results showed that there is a significant correlation between C-mean and both starting level and length of recessions. A decrease in start and an increase in length of the recessions, results in a lower recession rate. This implies limitations in the generality of the two parameter recession model. To minimize these influences the use of a standard recession as described in the previous section, was introduced, where starting level is fixed and the recession segments of equal lengths.

Mean value and coefficient of variation are calculated for five different starting levels (QUL), all given as a percentage of average daily flow (ADF). The chosen percentages are 100, 75, 50, 30 and 20, and the calculations are carried out for both observed and transformed series. The decreasing starting levels represent successively more advanced stages of the outflow process.

Length of recession period (LENGTH) is chosen to be seven days, whereas the number of minimum decreasing values in the sequence (NUM) is five. The humid climate in western Norway favours short recession periods, due to frequently interrupted recessions. In order to select enough segments, it is necessary to choose a short recession length. In eastern Norway, however, low average daily flows and long recession periods, favour steps in the series. These series require longer recession periods in order to get representative recession segments. The choice of seven days is a compromise between these considerations.

The calculated recession characteristics are listed in Appendix table B.4.1 and B.4.2 and plotted in Figure 4.4 and 4.5. In Table B.4.1 the recession calculations are based on the total discharge period available, and there is normally a large number of recession segments for each catchment. In Table B.4.2 the period is reduced to match the observation period of the climate series. This is done in order to compare the recession values with and "without" precipitation for a consistent period.

The analysis is repeated when recession segments influenced by precipitation are removed. The threshold value for precipitation is set to 1.0 mm per day, which is in range of expected loss by interception. Mean values and coefficients of variance for the reduced data set "without" precipitation, are given in Appendix table B.4.3. The two different data sets are labelled "precipitation free periods" respective "precipitation included".

Figure 4.4 illustrates the trends in mean values as starting level increases, whereas variance is presented in Figure 4.5. Both observed (left column) and transformed series (right column) are presented for complete, reduced and precipitation free periods. It is important to notice the different scales on the Y-axises.

The recession characteristics are expected to be related to the nature of the catchment, quantified through catchment and climatic characteristics, as discussed in Chapter 3. The significance of these relationships is studied by correlation analysis, and the result presented in Table 4.1 and 4.2, and in Appendix table B.4.5.

The climatic influence on the recession variability at the catchment scale, is analyzed by incorporating precipitation and temperature data for the recession period. A statistical analysis of correlations between the recession constant (C) and precipitation and temperature is performed, and the results presented in Table 4.3 and 4.4.

4.5 DISCUSSION

During the discussion that follows it is important to be aware the number of difficulties that arises due to steps in the series. Even though these are modified through the calculation methods, they still influence the results.

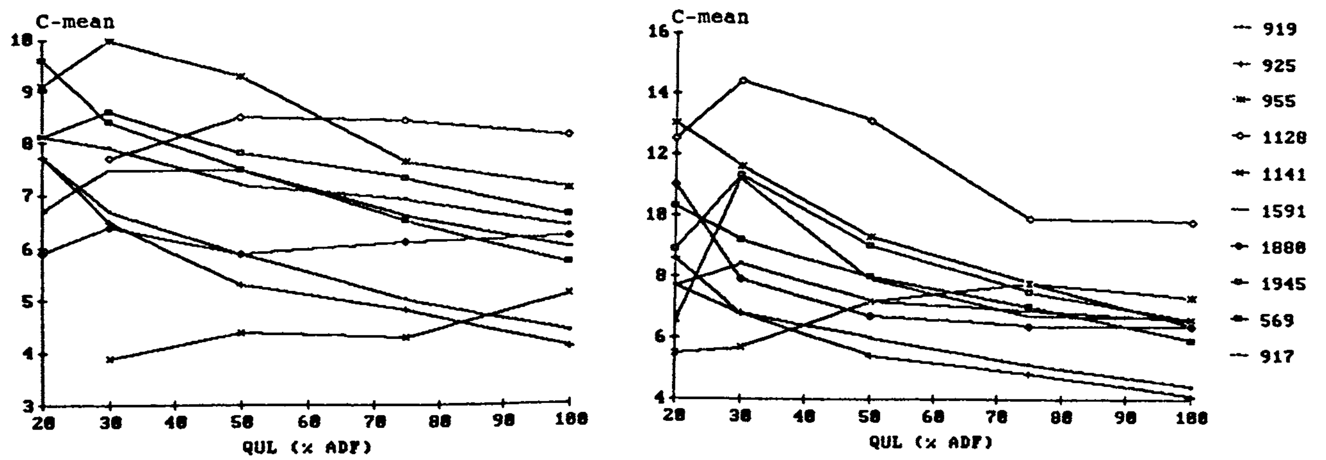
4.5.1 Trends in mean values

Figure 4.4 shows a general increase in mean values as starting level decreases, accomplished by an increase in range of values. This implies that the flow does not follow a simple exponential decay, which is in accordance with previous results (Part III). Except for catchment 1141, the rate of increase is similar for the catchments in each series, but generally higher rates are found in the transformed series.

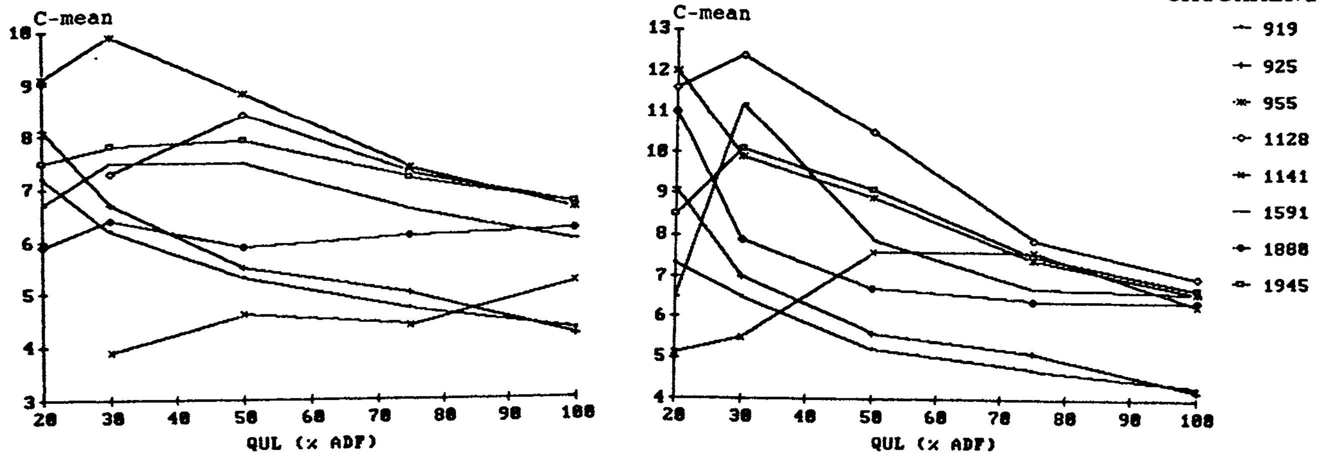
It is common to find a drop in C-mean at starting level 20 % for both the observed and transformed series. This is due to the calculation methods, and is not related to the drainage process. For the transformed series, it is a consequence of excluding the flat part in between storms from the recession. This leads to a steeper recession, frequently appearing at the lowest starting level. In the observed series, equal discharges are left out both within and at the end of a segment. A recession length of seven days with five decreasing values, will cause a reduction in number of selected recession segments as the step length increases. As a result the lowest starting levels only contain the steepest recessions, and are therefore not representative for the catchment.

The difference in the selection algorithms between observed and transformed series also explains the higher increase in means values found in the transformed series.

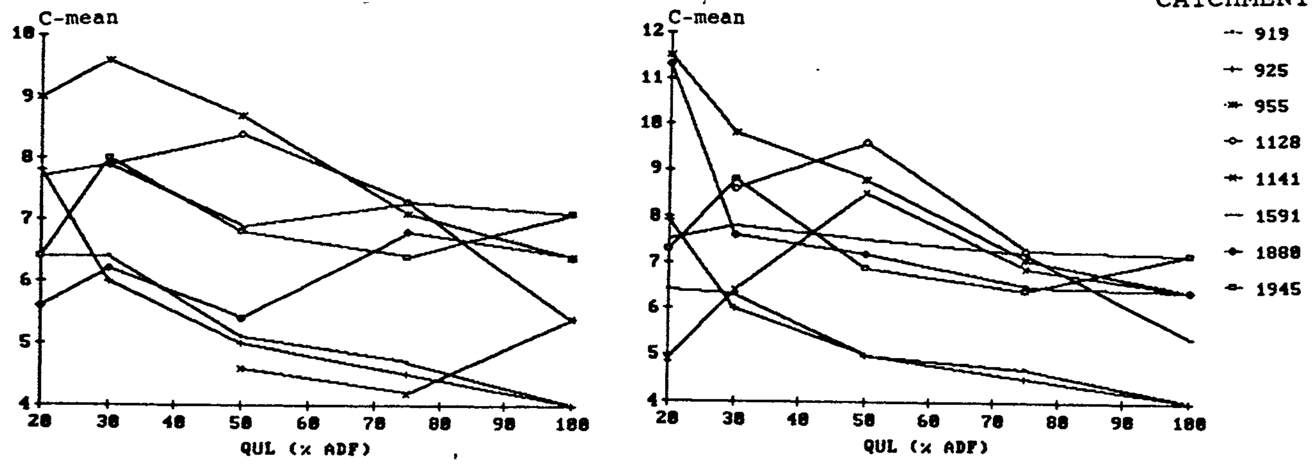
a) Complete period



b) Reduced period



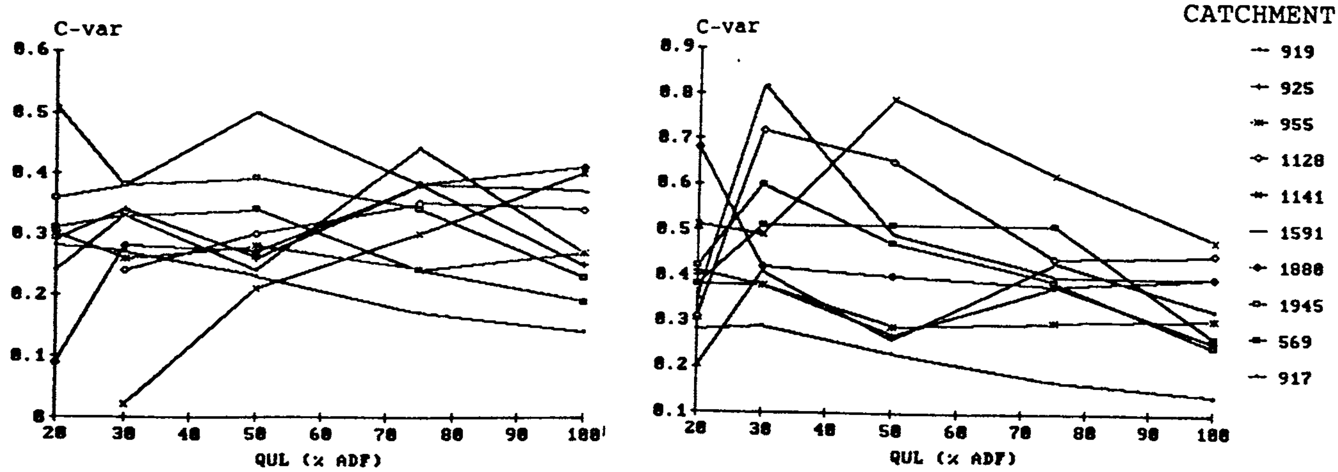
c) Precipitation free period



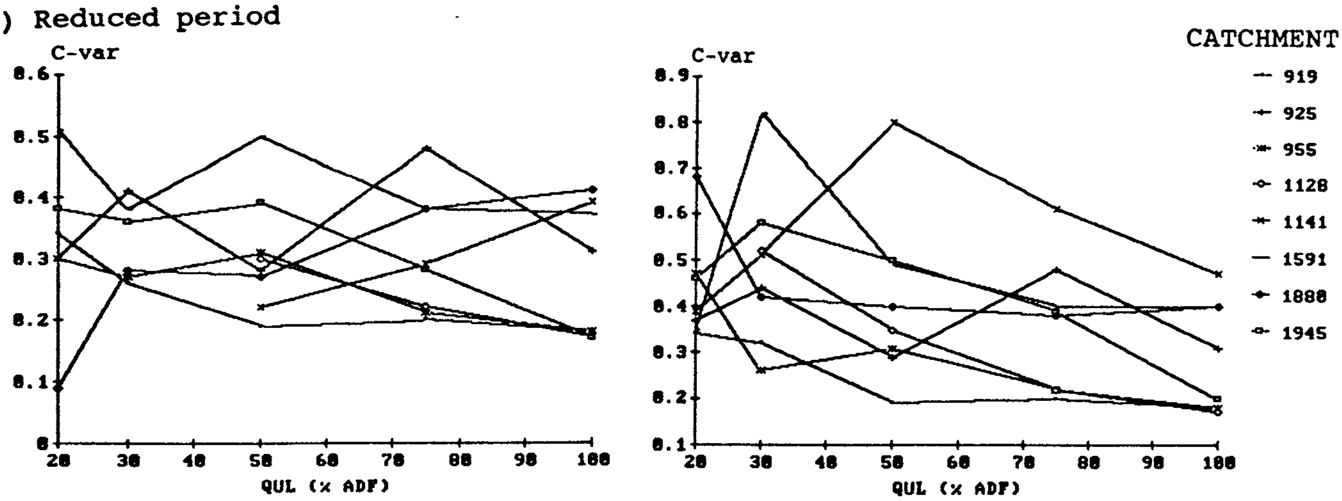
OBSERVED SERIES　　　　TRANSFORMED SERIES

Figure 4.4　Recession mean values (C-mean) for five starting levels, QUL = 20, 30, 50, 75 and 100 % of ADF. Observed (left column) and transformed series (right column) are presented for a) complete, b) reduced and c) precipitation free periods.

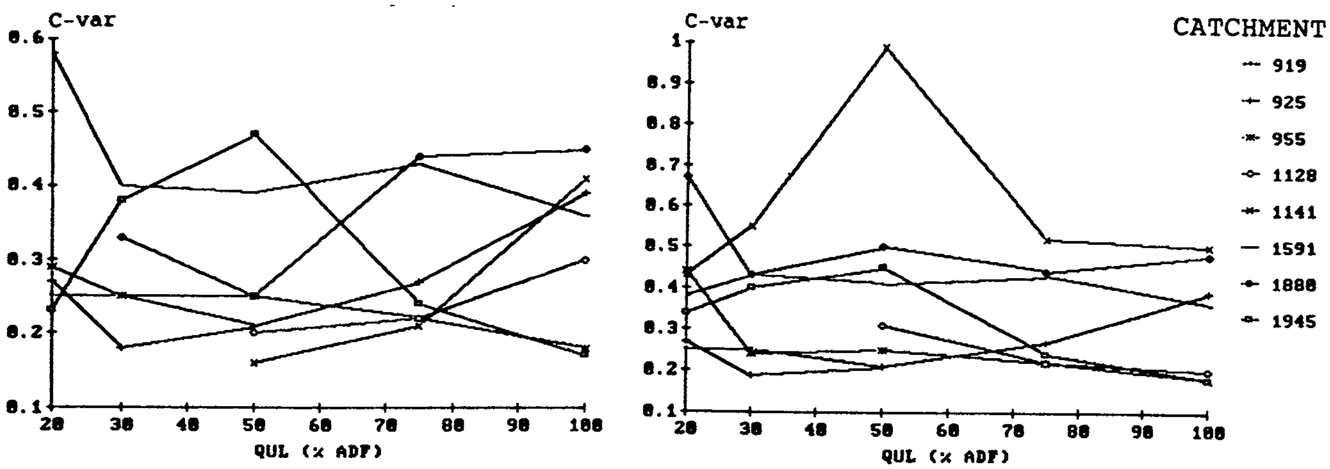
a) Complete period



b) Reduced period



c) Precipitation free period



OBSERVED SERIES TRANSFORMED SERIES

Figure 4.5 Recession variance values (C-var) for five starting levels, QUL = 20, 30, 50, 75 and 100 % of ADF. Observed (left column) and transformed series (right column) are presented for a) complete, b) reduced and c) precipitation free periods.

As all the flat parts of the recessions, apart from the last one, are accounted for in the transformed case, the C-mean values will be generally higher, particularly for low starting levels.

These features will be most noticeable the larger the extent of steps in the original hydrograph. Catchment 1141 is greatest influenced by steps. This is also evident in the mean value trend, where the decrease starts at a high starting level, particular in the observed series. It is possible to achieve a continuously increasing trend in the recession rate for the observed series, providing a sufficient high value of the recession length is chosen. For catchment 1141 this was obtained with a recession length of 10 days, and a minimum number of 3 decreasing values.

Some catchments do not have steps or they do not reach the lowest discharge level within the tested range of starting levels. Consequently, they have a continuing increase in mean values as starting level reduces. The resultant picture for all catchments is an irregular pattern below the 30 % starting level.

To summarize, the transformed series experiences higher mean values, and a wider range in values. The discrepancy between the observed and the transformed mean values depends on the extent and length of steps in the series. Any decrease in the recession mean value for the lowest starting levels, should be disregarded and left out of the analysis. Alternatively, the calculations can be performed with longer recession periods.

Moving from the complete series in a) to the reduced series in b), there are only minor alterations, although the reduction in sample size is considerable for some catchments. This consistency in mean values supports the idea of within year variations, and that number of segments rather than years, is the limiting factor in the calculations.

The precipitation free periods in c) are compared with the reduced periods in b), which cover the same time interval, and it can be seen that introducing a precipitation limit of 1.0 mm each day, only leads to minor reductions in the mean values. Exceptions are the transformed values at 30 % starting level, where high values commonly are found in b). There is no similar reduction in the observed series. However, the range in C-mean in b) is lower and similar to the reduced range in c) for the transformed series. The reduction found in the transformed series suggests that longer steps at the lower discharge levels, are influenced by precipitation. These steps are accounted for in the transformed series, but not in the observed.

4.5.2 Trends in variance values

Figure 4.5 shows no general trend in variance values for the observed or transformed series. Generally higher values of C-var are found in the transformed series, and a slight increase in C-var can be recognized for lower starting levels in a) complete, and b) reduced period. The 20 % values has to be disregarded as for the mean values, due to the special features of the stairs series, as commented on in Section 4.5.1.

Moving from the complete period in a) to the reduced period in b), only minor alterations are found, as for the mean values. The precipitation free periods are presented in c), and C-var in the transformed series is here close to being constant for each catchment, with the largest reduction found at the 30 % starting level. This agrees with the reduction found for the mean values at the same starting level. In the observed series only minor reductions are found, and the two series have in c) a similar range in variance values. Catchment 1141 interrupts this picture due to its particular high number of steps.

The effect of precipitation during the recession period is to a larger extent accounted for in the transformed series. This is particularly noticeable at the 30 % starting level. The difference between the two series is a result of the different segment samples selected. The general influence of precipitation on series with little or no steps can be studied for catchment 919 and 925. Both catchments show a slight reduction in mean and variance values when precipitation is removed, with no preference to particular starting levels. The higher effect of precipitation found at lower starting levels in stairs series, might be a result of low accuracy in the low flow measurements, which also means a slow response to precipitation input.

4.5.3 Mean value and variance as related to catchment characteristics

Regional aspects of recession analysis are presented in Chapter 3, and relationships between recession and catchment characteristics discussed in Section 3.5. This analysis adds to the previous results by incorporating recession characteristics for different starting levels.

The catchment characteristics selected are presented in 4.2.1 and values for each catchment given in Appendix A.1.

The recession characteristics selected are: C-mean (CM) and variance (CV) for observed (O) and transformed series (T), with precipitation (P) and without ( ), with starting level 75 and 30 %, in total eight sets of mean and variance values for each catchment. The recession characteristics are labelled as a combination of these abbreviations, i.e. CMO75P, which equals the mean value for the observed series at 75 % starting level and precipitation included. The complete correlation matrix is presented in Appendix table B.4.5, whereas selected correlation figures are given in Table 4.1 (C-mean) and Table 4.2 (C-var).

As the recession constant can be looked upon as an index of storage, it is expected to be related to characteristics typically reflecting catchment storage capacity. In Part III, this issue was investigated for 68 catchments in Norway and included the variable ADF, SAAR, AREA, RELIEF, ROCK and ASE. ROCK is equivalent to the term REST in this analysis, SAAR is mean annual precipitation and ASE is a weighted percentual lake area index. These variables were related to C-mean and C-var, calculated with starting level 100 %, length 8 days, 4 decreasing values and precipitation included. Significant correlations were only found between C-mean and SAAR.

The sample size included in this analysis is much lower, but more detailed recession characteristics are included. As the sample size is very small (eight or ten catchments) the correlations are expected to have low significance, and can only be interpreted as an indicator of any relationships.

In correlation matrix A in Table B.4.5 (precipitation included), significant correlations of the mean values are only found for CMT75P, which is positive correlated with bog percentage (BOG) and negative correlated with altitude range (ALT). In other words, BOG offset the recession rate, whereas a high range in altitude favours a fast recession.

These relationships are not significant at the 30 % starting level, suggesting the dominance of other factors not represented in this study. As higher starting levels represent the recession in an earlier stage of a dry period, it is likely that the affect of altitude decreases as the dry period increases. Selected correlation figures are given in Table 4.1. Number of cases is 10 when precipitation is included and 8 for the precipitation free data.

For the precipitation free data, correlation matrix B in Table B.4.5 and Table 4.1, the only significant relationship is a negative correlation between ALT and CMT75. A lower correlation with BOG might indicate its importance in offsetting the recession rate in response to slight precipitation, whereas ALT represents the drainage velocity in general.

Table 4.1 Selected correlation coefficients for C-mean.

	CMO75P	CMO30P	CMT75P	CMT30P	CMO75	CMO30	CMT75	CMT30
AREA	-.16	.21	-.54	-.24	-.23	.07	-.58	-.42
RELIEF	.47	.35	.19	.49	.57	.57	.06	.60
LAKE	.45	.56	.20	.32	.31	.62	.13	.41
BOG	.39	-.16	.77*	.51	.24	-.04	.44	.17
FOR	-.23	-.52	.00	-.05	.01	-.45	.20	-.24
ALT	-.20	.32	-.76*	-.27	-.30	.17	-.82*	-.28
BFI	.80*	.53	.67	.74*	.75	.68	.65	.70
ADF	-.27	.25	-.61	-.30	-.41	.14	-.74	-.26

number of cases 10(8), 1-tailed Signif: * .01

The correlations between BFI and the recession mean values are also given in Table 4.1. The coefficients are similar to the result in Part III, where a correlation coefficient of 0.77 was found between CMO100P and BFI (Section 3.6).

The recession mean values are not significantly correlated with ADF, which is important to notice as starting level is given as a function of ADF. Similar result was found in Part III. Although a negative trend in the correlations for high starting levels, can be recognized in both studies, the influence of general climatic conditions on the recession mean value is low.

Due to the low number of catchments in the analysis, only limiting conclusions can be drawn. For recession mean values, significant correlations with catchment characteristics are only found at the 75 % starting level, for the parameters BOG and ALT. The most important factors thought to influence storage properties, and thereby the recession rate, are geology. Indexes of geology, where the effect of rock, drift and soil materials are included, were not available in this study, but have previously shown to be correlated with the recession constant (Tallaksen, 1987b). This is due to the lack of relevant geological maps for the catchments, which have been selected based on the qriteria listed in Section 4.2. In order to improve the accuracy of the estimation equations for the recession constant, it is necessary that rock, drift and soil maps are available on a national basis.

Recession variance (C-var) is not related to any of the catchment characteristics included, as also found in Part III. Selected correlation figures are presented in Table 4.2, whereas the complete correlation matrix is given in Appendix table B.4.5. The variance values in precipitation free periods are left out of Table 4.2 due to the low number of cases.

Table 4.2 Selected correlation coefficients for C-var.

	CVO75P	CVT75P	CVT30P
AREA	-.09	-.24	-.19
RELIEF	.08	-.47	.07
LAKE	-.17	-.27	-.16
BOG	.08	.34	.51
FOR	-.38	.21	.47
ALT	-.06	-.55	-.46
BFI	.22	-.01	.39
ADF	-.35	-.55	-.65

number of cases 10, 1-tailed Signif: * .01

One might recognize the negative correlation between CVT75P/CVT30P and ADF, although it is not significant. It suggests that lower ADF values yield higher variance, which can be related to an increase in steps at low flows. The positive correlations between the variance values at 30 % and BOG and FOR suggest higher sensitivity to climatic variables in areas with high bog and forest percentage. However, more data are necessary to draw any conclusions.

4.5.4 Statistical analysis of recession variability

Recession variability at the regional scale was discussed in the last section. This section analyzes the climatic influence on the variability at each starting level of discharge in the catchment.

As a first step to link the variability to climatic influence, a statistical analysis of correlation between the recession constant (C) and precipitation and temperature is performed. Average values of temperature and total precipitation during the recession period are included. The analysis is repeated given a precipitation limit of 1.0 mm per day. This is similar to the analysis performed in Part III. The results from these two studies might deviate of two reasons: there is no defined limit for the goodness of fit of theoretical curve in the present work, and the minimum number of decreasing values in a sequence (NUM) is five instead of four. (In Part III NUM is erroneously referred to as five).

The results are given in Table 4.3 and 4.4, where the correlations between the recession constant (C) and precipitation (prec), temperature (temp), starting day (std) and curve fitness (r) are presented for the five different starting levels defined in Section 4.4.

Curve fitness is measured as the correlation coefficient (r) between observed and predicted value of runoff. Any significant correlation between C-mean and r is negative, which suggests a better fit of the simple exponential curve for the steepest recessions in these catchments.

The influence of precipitation on mean and variance values found at lower starting levels in the transformed series, is also reflected in the correlation figures in Table 4.3. High correlations with precipitation are found for catchments 1128, 1591 and 1945 at the 30 % starting level. Correlations at high starting levels are only found for catchment 919. By removing segments influenced by precipitation, the correlations at low starting levels disappear, and there are no major differences between observed and transformed series (Table 4.4).

Except for the above mentioned figures, the correlation between C and precipitation is low, and shift between positive and negative sign. The correlation is expected to be positive as precipitation during the recession phase offset the recession rate, and cause a lower recession rate. A minor storm and corresponding peak, prior to the recession period, however, might cause an increase in the recession rate. The recession selection algorithm requires that the start of recession is at least two days from peak of discharge, still, it is possible that recessions include fast drainage. This effect of precipitation might have a marked influence on the recession variability which has not been accounted for in the analysis, particularly for catchments with frequently interrupted recessions.

High evapotranspiration losses will increase the recession rate, and thereby reduce the value of the recession constant, C. The influence of evapotranspiration on recession variability is indicated by the relationship found between recession variance and average temperature during the recession period. Temperature show significantly higher

Table 4.3 Correlation coefficients between the recession constant C, and precipitation (prec), temperature (temp), starting day (std) and curve fitness (r).

CATCHM.	QUL=	OBSERVED SERIES					TRANSFORMED SERIES				
(period)	%ADF	no	prec	temp	std	r	no	prec	temp	std	r
919	100	8	.93**	.17	.09	.56	8	.93**	.17	.09	.56
(68-84)	75	10	.34	-.65	.61	-.01	10	.34	-.65	.61	-.01
	50	17	-.33	-.45	.40	-.27	16	-.31	-.56	.44	-.40
	30	19	-.31	-.71**	.68*	-.63*	20	-.17	-.44	.32	-.68**
	20	20	-.21	-.52*	.36	-.11	20	-.21	-.52*	.36	-.11
925	100	42	.12	-.19	-.38*	-.02	40	.16	-.21	-.40*	-.02
(57-72)	75	42	.02	.12	-.45*	-.26	39	.06	.06	-.44*	-.34
	50	48	.20	-.05	-.37*	-.15	48	.25	.09	-.34*	-.19
	30	48	.01	-.10	-.25	-.25	48	.11	.02	-.33*	-.17
	20	36	.16	-.14	-.24	-.13	36	.56**	-.16	-.02	-.45*
955	100	36	.23	-.19	.04	-.28	35	.24	-.19	.03	-.28
(57-86)	75	37	.27	-.31	-.13	.02	36	.30	-.33	-.12	.04
	50	38	.24	-.19	.01	-.51**	37	.23	-.19	.02	-.54**
	30	26	-.19	-.29	.15	.05	26	-.20	-.28	.17	.03
	20	13	.27	-.21	.15	-.56	14	.14	-.36	-.24	-.18
1128	100	9	-.41	-.01	.10	.42	7	-.28	-.18	.06	.34
(63-76)	75	5	-.11	-.39	.32	.43	7	.56	-.34	-.38	.53
	50	7	.08	-.64	.70	-.48	7	.70	-.73	.12	.06
	30	3					6	.95*	-.25	-.25	-.86
	20	1					3				
1141	100	19	-.37	-.60*	.59	.20	24	-.23	-.68**	.69**	-.12
(57-74)	75	13	-.37	-.02	.08	-.13	25	-.15	-.32	.62**	.20
	50	11	-.25	-.30	-.17	-.30	20	-.17	-.19	.49	.10
	30	3					20	-.20	.21	.29	-.79**
	20						20	-.06	.32	.29	.14
1591	100	11	.65	-.49	.46	-.17	13	.26	-.49	.42	-.25
(66-81)	75	13	-.17	-.61	.45	-.13	14	-.06	-.54	.36	-.28
	50	12	.68*	-.31	.10	-.39	13	.58	-.43	.22	-.44
	30	10	-.33	-.38	.54	.17	11	.91**	-.20	-.03	-.72*
	20	11	-.21	-.88**	.81*	.38	10	-.27	-.27	.63	-.39
1880	100	26	-.06	-.73**	.72*	.07	28	.03	-.76**	.75**	.04
(71-88)	75	23	-.23	-.66**	.60*	.04	23	-.03	-.73**	.69**	.02
	50	18	.12	-.27	.14	-.06	23	-.19	-.74**	.65**	-.03
	30	17	.15	-.41	-.17	-.04	21	-.03	-.73**	.57*	-.33
	20	6	.68	.06	.42	-.31	16	-.12	-.74**	.54	-.10
1945	100	11	-.42	-.84**	.73*	.13	12	-.35	-.80**	.70*	.04
(72-87)	75	14	.44	-.69*	.53	-.38	17	.25	-.68*	.58*	-.45
	50	10	.59	-.59	.19	-.39	12	.30	-.78*	.61	-.30
	30	7	.01	-.93*	.90*	.07	10	.60	-.60	.63	-.88**
	20	9	.55	-.58	.58	.53	11	.51	-.57	.74*	-.08

1-tailed Signif: * .01 ** .001

Table 4.4 Correlation coefficients between the recession constant C, and precipitation (prec), temperature (temp), starting day (std) and curve fitness (r). Precipitation limit of 1.0 mm per day.

CATCHM. (period)	QUL= %ADF	OBSERVED SERIES no	prec	temp	std	r	TRANSFORMED SERIES no	prec	temp	std	r
919	100	4	.98*				4	.98*			
(68-84)	75	3					3				
	50	10	.10	-.60	.48	-.16	9	-.43	-.78*	.61	-.50
	30	14	-.20	-.85**	.79**	-.62*	14	-.20	-.85**	.79**	-.62*
	20	10	-.03	-.54	.60	.30	10	-.03	-.54	.60	.30
925	100	18	-.32	-.06	-.41	-.14	18	-.32	-.06	-.41	-.14
(57-72)	75	15	-.34	-.07	-.59	.23	15	-.33	-.08	-.57	.29
	50	20	-.19	-.24	-.36	-.20	21	-.16	-.24	-.36	-.14
	30	20	.12	-.44	-.45	-.29	19	.13	-.45	-.46	-.30
	20	19	-.09	-.40	-.45	.09	19	-.11	-.39	-.45	.09
955	100	15	.15	-.45	-.43	-.43	15	.15	-.45	-.43	-.43
(57-86)	75	16	.40	-.71*	-.31	.01	16	.40	-.71*	-.31	.01
	50	15	.12	-.25	.18	.26	15	.12	-.25	.20	.26
	30	14	-.17	-.25	.22	.30	14	-.15	-.23	.22	.23
	20	7	.49	-.19	-.57	-.66	9	.68	-.16	-.12	-.26
1128	100	5	-.66	-.12	.15	.79	5	-.73	-.07	.12	.92
(63-76)	75	5	-.12	-.39	.32	.43	5	-.12	-.39	.32	.43
	50	7	.08	-.64	.70	-.48	6	.33	-.78	.50	-.39
	30	2					4				
	20						1				
1141	100	10	-.04	-.83*	.61	.19	11	-.21	-.89**	.69*	-.10
(57-74)	75	6	-.02	-.39	-.03	.36	10	.21	-.87**	.69	.20
	50	6	-.54	.68	-.63	-.43	9	-.31	-.68	.51	.14
	30	1					11	.20	-.82*	.46	-.93**
	20						9	.56	-.23	.15	-.55
1591	100	7	.44	-.34	.45	.10	7	.43	-.33	.44	.14
(66-81)	75	7	-.37	-.77	.82	.19	8	-.37	-.74	.78	.17
	50	9	-.17	-.62	.63	-.77*	10	-.27	-.73*	.69	-.72*
	30	8	-.20	-.80*	.75	-.07	7	-.26	-.81	.77	-.05
	20	6	.14	-.99**	.84	.45	5	.93	-.64	.73	-.59
1880	100	9	.56	-.78*	.75*	.18	9	.56	-.78*	.75*	.33
(71-88)	75	10	-.14	-.74*	.80*	.30	9	.01	-.70	.78*	.35
	50	8	.29	-.06	-.25	-.50	10	.03	-.82*	.69	.01
	30	12	.46	-.48	-.38	.12	14	-.12	-.84**	.48	-.26
	20	4					8	-.44	-.84*	.77	-.03
1945	100	8	-.30	-.82*	.75	.00	8	-.11	-.79*	.74	-.36
(72-87)	75	7	.37	-.91*	.86*	-.29	7	.38	-.92*	.86*	-.26
	50	5	.87	-.82	.85	-.56	5	.87	-.82	.85	-.49
	30	6	.34	-.93*	.90*	-.04	7	.09	-.95**	.94**	-.58
	20	5	.23	-.55	.19	.83	6	.37	-.48	.19	.79

1-tailed Signif: * .01 ** .001

correlation coefficients with the recession constant than found in Part III. Still, there is a large scatter in the correlation figures, probably due to differences in climate and catchment characteristics.

Particularly high correlations are found for catchment 1880 and 1945, which both are primarily forested. The same picture is evident when precipitation is removed, even showing an increased trend for most of the other catchments, particularly catchment 1141 and 1591. These catchments also have a high forest percentage, and common for all four catchments are their location in the eastern part of Norway.

The variance values in precipitation free periods, reveal that catchments with high correlations with temperature also experience the highest variance values. This suggests that the higher variability found for these catchments can be ascribed to a higher range in evporatranspiration losses. Consequently, the recession constant can be estimated with higher accuracy, providing an index of evapotranspiration exists.

Starting day (std) is recorded as daynumber from the selected summer period, which is defined as the months without frost. Due to warmer climate in the first part of the summer period, the correlation between starting day and the recession constant is expected to be positive. This is valid for most catchments and often accompanied by a high correlation between temperature and starting day.

Catchment 925 deviates from this trend and has a significant negative correlation with starting day when precipitation is included, i.e. the fastest recessions are found in early autumn. Autumn recessions commonly follow a series of storms that results in a high degree of catchment wetness. As catchment 925 has a particular high average daily flow (ADF), the recession segments generally have high starting levels. It is suggested that a highly saturated catchment, accompanied by a high starting level and frequently interrupted recessions, might involve recession segments which include faster drainage. There is no correlation with starting day at the lowest starting level, which agrees with this reasoning.

When returning to the major question of how the climatic parameters can account for the variability in the recession rate, evidently temperature is the most promising factor. However, there is a large spread in the correlation figures, probably because of differences in climate and catchment characteristics. The influence of temperature is particularly marked for catchments being mainly forested and situated in eastern Norway. The influence is evident for both high and low starting levels. In order to quantify the water lost by evapotranspiration, an appropriate model for application on a local scale is required. This topic is adressed in Chapter 6.

It has to be noted that no account has been taken of any possible delay in catchment response to precipitation input or evapotranspiration losses. As all catchments in this analysis is below 75 km^2, this is not expected to be a major source of error. It might, however, be responsible for part of the difference found bewteen the catchments. More detailed analysis is necessary to draw any conclusions.

4.6 APPLICATIONS

Recession analysis as a tool in hydrological analysis is generally presented in Section 2.1. This section briefly outlines areas where the recession calculation procedure developed in this study is applicable or has been evaluated for use.

This method produces for each catchment a distribution of the recession constant which depends on the sample selection criteria. If a probability distribution adequately fits the recession sample, any **low flow forecast** can be made with a given probability of occurence. In this study the conditional distribution of the recession constant is obtained, given start and length of recessions, however, no theoretical distribution has been fitted so far. The analysis could be extended to study a joint probability function for a variable recession start or length.

A recession constant has in many studies represented the integrated influence of catchment **storage properties**. A general presentation of numerical expressions for storage capacity is given in Section 3.3 and 3.4. The recession mean value calculated according to the recession calculation procedure introduced in this study, were in Part III included in a regional low flow regression model. This resulted in a significant increase in the accuracy of the estimation equations.

The calculation method has revealed great time variability of recessions. In Chapter 5 the recession distribution from an observed series is compared with the distribution produced by the conceptual HBV rainfall-runoff model. Recession analysis can in this way enable the low flow part of the model to be modelled more closely and thereby improve **the low flow model performance**.

The recession analysis is in Chapter 6 used in combination with an evapotranspiration model to study the **influence of evapotranspiration** on the low flow regime. This part of the study was initiated by the results from this chapter, where the influence of evapotranspiration is indicated by the relationship found between recession variance and temperature.

4.7 CONCLUSIONS

The recession characteristics of ten rivers are presented and discussed with respect to climatic and catchment influences, both at the catchment and a regional scale. The low flow data are frequently recorded in a staircase manner, due to low accuarcy in the low flow measurements. In the transformed series steps in the discharge series have been modified, and both observed and transformed series are included in the recession analysis.

There is a general increase in mean values as starting levels decreases, indicating that the flow does not follow a simple exponential decay. A higher rate of increase is found for the transformed series due to differences in segment selection criteria. There is a high consistency in mean and variance values for different sample selections and sizes. The introduction of a precipitation limit of 1.0 mm per day only leads to a minor reductions in the mean values, except for the high mean values found at lower starting levels in the transformed series.

There is no recognizable trend in variance values with starting level for the two series, but generally higher values of C-var are found in the transformed series. Removing segments influenced by precipitation involves less difference between the two series.

The number of catchments in the statistical analysis between recession and catchment characteristics is low, and only limiting conclusions can be drawn. Mean values at the 75 % starting level are influenced by BOG and ALT when precipitation is included. The correlation with BOG is reduced when precipitation is removed. A lower correlation with BOG might indicate its importance in offsetting the recession rate in response to slight precipitation, whereas ALT represents the drainage velocity in general. The relationship with ALT is not significant at the 30 % starting level, suggesting that the effect of altitude decreases as the dry period increases.

The most important factor thought to influence the recession rate is geology. Indices of geology, where the effect of rock, drift and soil materials are included, were not available for the study area. This is due to the lack of relevant geological maps for the selected catchments. In order to improve the accuracy of the estimation equations for the recession constant, it is necessary that relevant geological maps are available on a national basis.

The correlation between the recession constant and total precipitation during the recession period is generally low, and shift between positive and negative sign. The correlation is expected to be positive as precipitation offset the recession rate. The influence of precipitation on mean and variance values found at lower starting levels in the transformed series, is, however, reflected in significant correlations. By removing segments influenced by precipitation correlations at the low starting levels disappear, and there are no major differences between observed and transformed series.

High evapotranspiration losses will increase the recession rate, and by that reduce the value of the recession constant, C. The influence of evapotranspiration on recession variability is indicated by the relationship found between recession variance and average temperature during the recession period. Temperature show significantly higher correlation coefficients with C than was found in Part III. Still, there is a large scatter in the correlation figures, probably due to differences in climate and catchment characteristics. The influence of temperature is most noticeable for the four forested catchments situated in eastern Norway, and is evident for both high and low starting levels.

The influence of evapotranspiration on the flow regime, will be most noticeable in areas with high evaporation demand and with a surface cover that can meet this demand. These conditions are met in forested catchments in eastern Norway, and as found in this study, the evapotranspiration loss might even influence the recession pattern at very low flows. This might be a result of a shallow groundwater table which favour capillary transport from the groundwater zone subsequent to the water lost by evapotranspiration. This matter is further discussed in Chapter 5 & 6.

A major problem in interpreting the results from the recession analysis in a consistent manner, is due to difficulties that are caused by steps in the series. The transformed series was introduced to modify the steps, but the lowest values before a new storm still pose a problem. In the observed series, equal values are left out of the calculations, and the main question is how to select segments with increasingly longer steps at lower flows.

With a constant recession length and a fixed number of minimum decreasing values in the series, the selection of segments will be biased towards the steepest recessions as the length and extent of steps increases. From these considerations, it is concluded that the transformed series are preferable to use in recession analysis. A better representation of the last flat part of the recessions, is however, requiered.

CHAPTER 5

RECESSION ANALYSIS OF HBV SIMULATED SERIES

5.1 INTRODUCTION

The recession calculation procedure presented in Chapter 4 has revealed high time variability in recessions. This might be as result of natural fluctuations, as well as model limitations. In this chapter the recession distribution from observed series is compared with the distribution from a synthetic series, simulated using the conceptual HBV rainfall-runoff model.

There is a particular interest in studying the model's capability of reproducing the variability in the recession rate, and to compare the main mechanisms behind the variability in each series. It has to be noted that the HBV model was not developed for low flow modelling. Still, it is important to evaluate its general low flow performance.

Parameters in conceptual models are not directly related to physical properties and can not be given a strict physical interpretation, nor can they be measured in the field. The dynamic part, however, is based on our knowledge of the drainage system and should include representation of the major processes. In areas with shallow groundwater table, soil moisture deficits in the root zone may be compensated by capillary transport from the groundwater zone. This effect of evapotranspiration on the groundwater level has not been incorporated in the present HBV model. Evapotranspiration is in this analysis indexed by temperature, and its influence on the recession variability investigated for both observed and simulated data.

5.2 DATA BASE

Four catchments in southern part of Norway are selected for analysis. Their basic catchment data are presented in Appendix A.1 and locations given in Figure 4.1.

Catchment 1945 and 1591 are primarily forested, but differ in size and lake percentage. Catchment 917 consists mainly of low vegetation, bare rock and lake, whereas 1128 has a composition of lakes, bog, bare rock and forest. Three precipitation stations have been used in the HBV calibration of catchment 917. This resulted in a very low number of precipitation free periods for the catchment, and it was therefore left out of analysis that required climatic data.

For the other three catchments discharge, temperature and precipitation data are collected. High representativity of climatic data is important, and particularly for precipitation due its high spatial variability. The catchments are represented by one precipitation and temperature station, locations are given in Appendix A.1.

5.3 THE HBV MODEL

The HBV model has been widely used for hydrological simulation and forecasting in Norway and Sweden. It was developed at the Swedish Meteorological and Hydrological Institute (Bergström, 1976). The model simulation in this study was done using the HBV model that is presently part of the Karmen system at the Norwegian Water Resources and Energy Administration, NVE, (Sælthun & Taksdal, 1988).

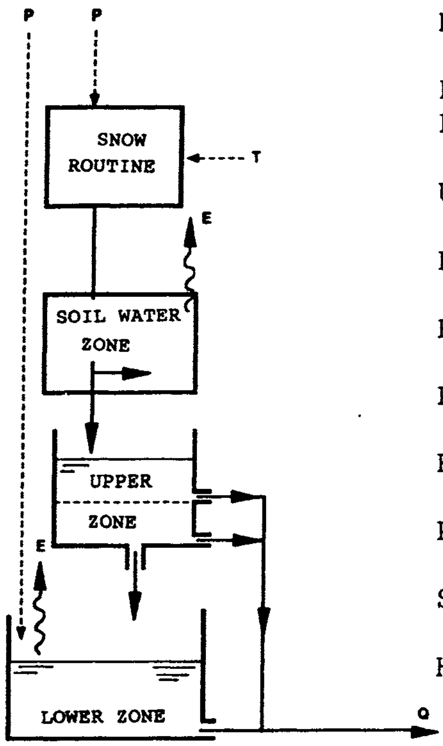
The model simulates runoff continuously with daily time steps, and with precipitation and mean air temperature as inputs.

5.3.1 Model structure

The main components of the dynamic part are a nonlinear soil moisture submodel and a piecewise linear storage system, Figure 5.1. The three main modules are the soil water zone, upper zone and lower zone. Lakes are regarded as an integrated part of the lower zone. Lake area precipitation and evaporation are represented as direct input or output to the lower zone.

The soil water zone has a nonlinear retention that is governed by two parameters, FC (zone water content at saturation) and Beta (nonlinearity constant). Water is removed from the zone by throughflow to the upper zone and by evapotranspiration. The ratio of actual evapotranspiration to potential, varies linearly with zone water content. Potential evapotranspiration is given as monthly values.

The upper zone drains at a constant rate, PERC, to the lower zone. Runoff is generated from the upper zone through a piecewise linear response where KUZ and KUZ1 are runoff coefficients for slow and rapid response respectively, and UZ1 the threshold value for rapid response.



MODEL PARAMETERS

Beta : nonlinearity root constant
FC : soil water content at saturation (mm)
UZ1 : threshold value for rapid response, upper zone (mm)
KUZ1 : drainage coefficient, upper zone, rapid response (1/t)
KUZ : drainage coefficient, upper zone,low water content (1/t)
PERC : percolation to lower zone (mm/t)
KLZ : drainage coefficient, lower zone (1/t)
PKORR: precipitation correction factor
SKORR: additional snow correction factor
HKORR: altitude gradient for precipitation

Figure 5.1 HBV model structure (P: Precipitation, E: evapotranspiration, Q: discharge, T: temperature).

The lower zone generates runoff at a linear rate, KLZ, with maximum lower zone water content LZmax, given by PERC/KLZ and maximum drainage by PERC.

5.3.2 Model calibration

Parameter values for catchment 917 and 1128 were provided by NVE, whereas catchment 1591 and 1945 were calibrated as part of this study. Catchment 1945 is given two different parameter sets, labelled 1945 and 1945*, where slow and fast recessions are modelled, respectively.

The same calibration scheme has been applied for all catchments. It combines a subjective judgement with analysis of volume differences and model efficiency, R^2, which is the proportion of the initial variance accounted for by the model (Nash & Sutcliffe, 1970). On average three years were used for calibration, whereas the total period was used for simulation. Normally, more than three years are required for calibration. However, as this study looks at the low flow model concept in general, and not at details in the model fit, three years are acceptable. Selected parameter values are presented in Table 5.1.

Table 5.1 Selected HBV data.

Catchment	917	1128	1591	1945	1945*
Beta	2.0	2.0	2.0	2.0	2.0
FC (mm)	150	170	100	100	100
UZ1 (mm)	30	30	15	10	10
KUZ1 (1/time)	.80	.50	.60	.80	.90
KUZ (1/time)	.15	.10	.15	.20	.20
PERC (mm/time)	.90	.60	.80	.80	.20
KLZ (1/time)	.01	.01	.01	.02	.05
PKORR	1.00	1.03	1.10	1.02	1.05
SKORR	1.40	1.10	1.04	1.20	1.15
HKORR	.04	.04	.04	.02	.02
LZMAX (PERC/KLZ,mm)	90	60	80	40	4
Q at LZmax (l/skm2)	10.42	6.94	9.26	9.26	2.31
Calibration period	57-61	84-86	67-69	82-84	82-84
Model eff. R^2	.55	.83	.84	.57	.55
Simulation period	57-70	64-75	66-81	72-86	72-86
Model eff. R^2	.65	.85	.75	.62	.60

The model efficiency (R^2) for catchment 1945 is low due to difficulties when calibrating snow periods. As only summer-data are analyzed, model fit during the summer period was emphasized. Consequently, the lack of fitness during winter months was neglected for this catchment, resulting in a low R^2 value.

5.4 RECESSION ANALYSIS

The recession procedure presented in Section 4.3 is applied at both simulated, observed and transformed series. The recession calculations are limited to the same subperiod in each catchment. Recession mean value (C-mean) and coefficient of variation (C-var) are calculated for five different starting levels. The upper limit (QUL) for start of recession is given as a percentage of mean annual flow (ADF) as in Chapter 4, and the same percentages is used: 100, 75, 50, 30 and 20. Length of recession period is seven days.

The transformed series was introduced in Section 4.2.2 in replacement of the observed series with steps. The main features of the observed and transformed series are discussed in Section 4.3. Both series are included in this analysis in order to compare directly with the HBV series. The simulated series can also contain steps due to figure rounding at low flows. Catchment 1945 is the only catchment in this analysis which has sufficient low discharge values to experience steps in the simulated series.

The calculated recession characteristics are listed in Appendix table B.5.1 and plotted in Figure 5.2 and 5.3. Figure 5.2 illustrates the trends in mean values as starting level increases, whereas variance is presented in Figure 5.3.

The analysis is performed for recession segments both with and "without" precipitation. The threshold value for precipitation is 1.0 mm per day. Mean values and coefficients of variance for the precipitation free data are given in Appendix table B.5.2, and the trends illustrated in the right column of Figure 5.2 and 5.3. The general trends in mean and variation values for observed and transformed series are discussed in Section 4.5. This chapter concentrates on special features of the HBV series.

The recession constant, C, are correlated with both average temperature and total precipitation during the recession period, similar to the analysis in Section 4.5.4. The results are presented in Table 5.3 and 5.4. In contrast to the real world, the HBV model has a known precipitation input, and true precipitation free periods can be defined.

5.5 DISCUSSION

5.5.1 Trends in mean values

The observed, transformed and simulated series in Figure 5.2, have all similar mean values for the higher starting levels. The general trend in the observed and transformed series is discussed in Chapter 4. The simulated series clearly deviate from this pattern. Catchment 1128 and 1591 experience a minor drop in mean values before a marked rise, resulting in very high values of C-mean at the 20 % starting level. For catchment 1945 the rise starts already at the 75 % level.

Both the observed and the transformed series have a drop in mean values at the 20 % starting level, which is due to steps in the discharge series (Section 4.5.1). A similar drop in value is found for the second simulation of catchment 1945 (labelled 1945*), which agrees with the minor amount of steps in this series. Runoff generating at the lower starting levels in the simulated series, yields drainage mainly from the lower zone. A drainage coefficient

PRECIPITATION INCLUDED PRECIPITATION FREE PERIODS

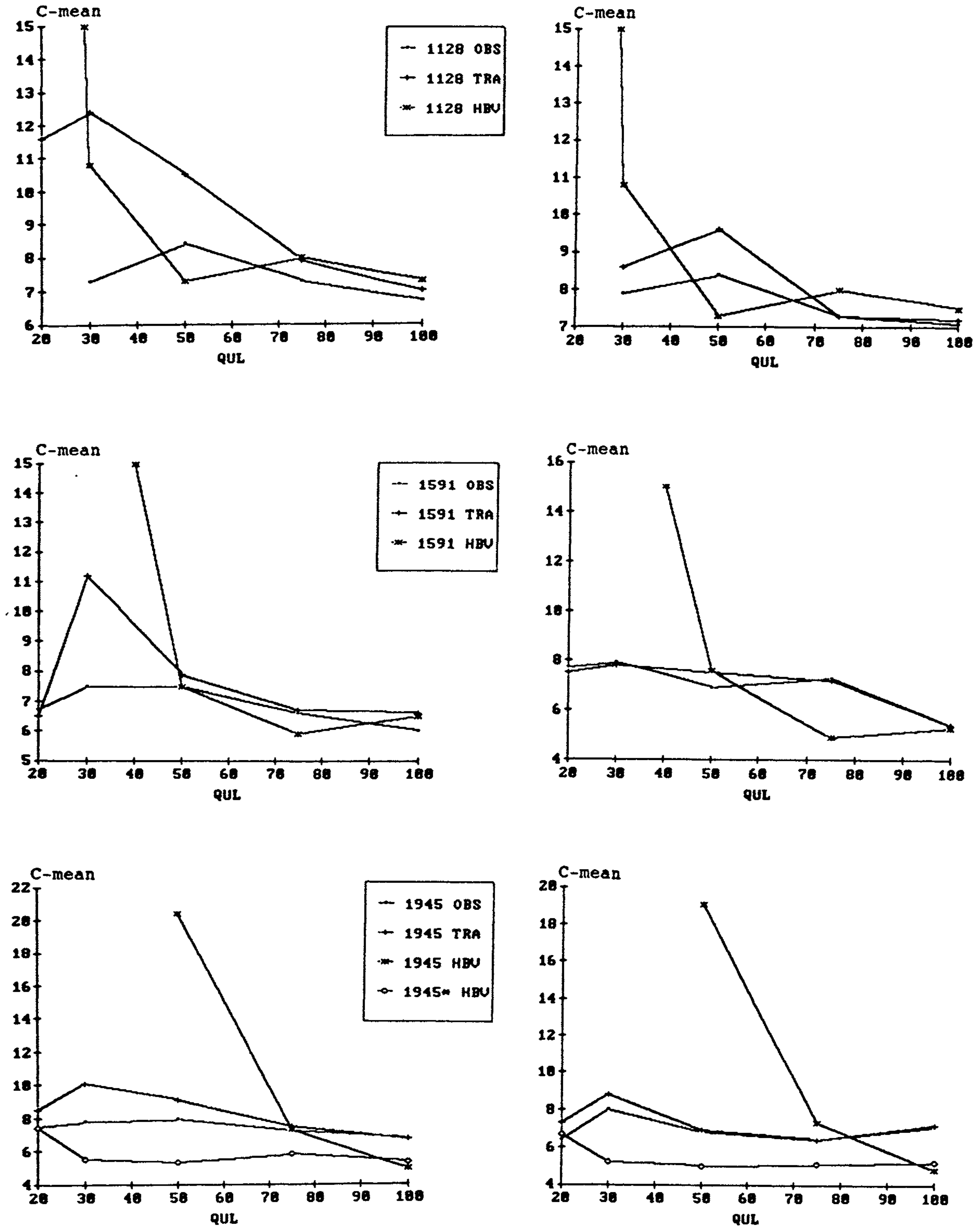


Figure 5.2 Recession mean values (C-mean) for five starting levels, QUL = 20, 30, 50, 75 and 100 % of ADF. Precipitation included (left column) and precipitation free periods (right column) are presented for catchment 1128, 1591 and 1945 for observed, transformed and simulated series.

PRECIPITATION INCLUDED PRECIPITATION FREE PERIODS

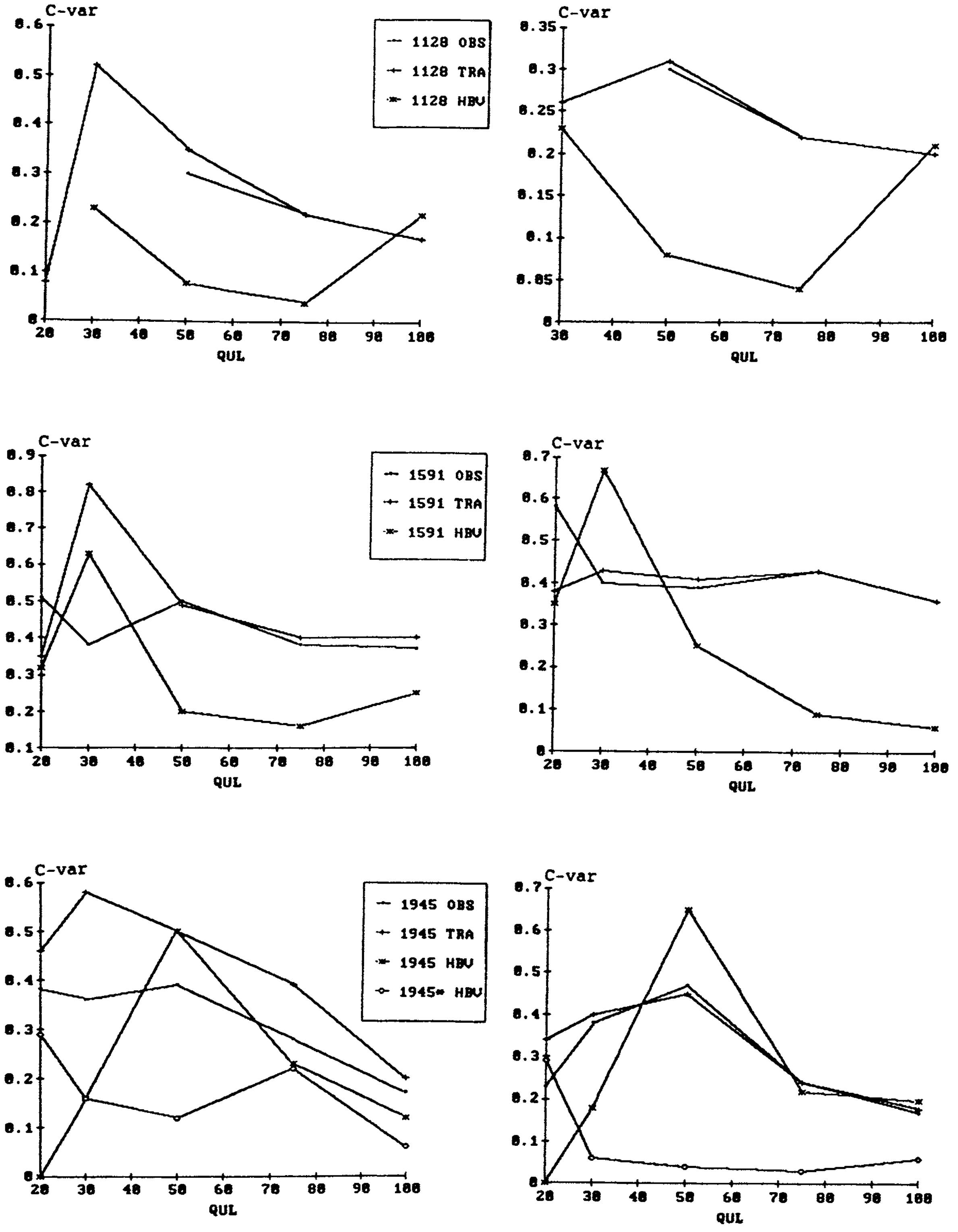


Figure 5.3 Recession variance values (C-var) for five starting levels, QUL = 20, 30, 50, 75 and 100 % of ADF. Precipitation included (left column) and precipitation free periods (right column) are presented for catchment 1128, 1591 and 1945 for observed, transformed and simulated series.

(KLZ) of 0.01 is commonly used for the lower zone, and results in very slow recession rates and high C-mean values.

Catchment 1945 was recalibrated, specially paying attention to model steeper recessions. The result is presented as catchment 1945* in Table 5.1. In order to achieve a faster recession rate, an increase in drainage rate was combined with a reduction in lower zone water capacity. An average C-mean of 5.1 is found for the four highest starting levels in this second calibration, which corresponds to a drainage coefficient of 0.82. This agrees with the KUZ1 value of 0.90 in the model, as the total discharge will yield a drainage rate somewhat lower than 0.90. At the 20 % starting level, lower drainage coefficients dominate and the mean value increases.

A general increase in the recession rate, i.e. lower mean values, is found for catchment 1945*. The effect is particularly noticeable for the lower starting levels. A comparison with the mean values of the observed and transformed series suggests that the increase in recession rate has been too high. The trend in the observed and simulated series is now similar, apart from a slight increase in mean values at 20 % in the simulated series. The reduction in recession rate at this low level is due to the dominance of lower zone drainage.

Introducing a precipitation limit of 1.0 mm per day generally leads to minor changes in the HBV mean values. A reduction in mean values can, however, be recognized for catchment 1945* and for the higher starting levels of catchment 1591. The model parameters of catchment 1945*, yield a faster response than the original calibration of catchment 1945, and runoff will be more directly influenced by precipitation. This can also be seen from increased correlations between recession mean values and precipitation.

5.5.3 Trends in variance values

The general trend in variance values for observed and transformed series is discussed in Section 4.5.2. In both series, high variance appears in connection with increased climatic influence revealed in significant correlations with temperature or precipitation.

Figure 5.3 shows generally lower variance values in the simulated series for higher starting levels. To reveal why a maximum in variance occurs for lower starting levels, individual segments for catchment 1591 are studied. Table 5.2

presents two segments with the same starting level (30 %), but widely different recession constants, C. Average temperature and total precipitation during the recession period are given, along with the total precipitation 10 days prior to the start of recession.

Table 5.2 Two simulated recession segments for catchment 1591, starting level 30 %.

C	year	std	temp °C	prec mm	10 days prec
I 69.8	1968	210	17.0	0.0	23.9 mm
II 7.0	1976	263	6.4	0.0	33.3 mm

DISCHARGE SEGMENTS :								
I	349	344	338	334	329	325	320	l/s
II	327	228	115	113	112	110	108	l/s

The two discharge segments illustrate the large difference between the recession constants. Segment I yields a higher lower zone water content than segment II, and the slow drainage of the lower zone will start at a higher discharge level. The maximum lower zone drainage is 514 l/s. Segment II shows the model's response to a storm after a prolonged dry spell. The lower zone was not able to restore its water capacity during the storm.

The transition to lower zone drainage will produce widely different recession constants. The range in values depends on the difference between the drainage coefficients of the upper and lower zone. The transition is for catchment 1591 too abrupt. The maximum in variance will occur at different starting levels, depending on the model parameters. The second parameter set for catchment 1945, shows how the recession variability is reduced due an increase in drainage rate and a reduction in lower zone water capacity.

When runoff is dominated by lower zone drainage, the recession variability reduces to a minimum as for catchment 1945. This catchment has no lakes and is therefore not influenced by external factors in the model at this low level of discharge. The result is a recession rate directly linked to the drainage coefficient of the lower zone. KLZ equals 0.02, which corresponds to a C value of 49.5. This agrees with the calculated 20 % value of 47.6. The other catchments do not reach this minimum in variance within the selected discharge range.

It is only if the transition effect discussed above, can be avoided or is of minor influence, that removing segments influenced by precipitation will have any influence on the variability pattern. A drop in variance is only found where precipitation is the major source of the variability. The effect of precipitation is commonly detected at high starting levels, as also reflected in the correlation figures (Section 5.5.3).

Catchment 1945* has very low variance values in precipitation free periods, which is due to the fast model response. Lower zone drainage constitutes only minor part of the discharge, due to the low value chosen for PERC. The recession discharge will be dominated by rapid drainage from the upper zone, and slight precipitation be the dominant factor in influencing the recession rate at high starting levels. The resulting variance will be very low in precipitation "free" periods. The transition from upper to lower zone drainage is succeeded by an increase in recession mean and variance values at the 20 % starting level.

Observed series can also experience transition effects due to the presence of several aquifers or water baring layers in a catchment. Neither a simple nor a composite recession curve, is limited to follow an exponential decay. The abrupt change in drainage rate modelled in the simulated series, is, however, only occasionally experienced in nature.

5.5.3 Statistical analysis of recession variability

This section looks at the climatic influence on the recession variability at each starting level of discharge. The correlations coefficients between the recession constant C, and temperature (temp) and precipitation (prec) during the recession period are calculated. The analysis is repeated given a precipitation limit of 1.0 mm per day, and the result presented in Table 5.3 and 5.4.

Significant correlations between C and temperature are not found in the simulated series. This is contradictory to the results in the observed and transformed series, where significant correlations are obtained for catchment 1591 and 1945. Climatic influence on these series is generally discussed in Section 4.5.4.

The simulated series of catchment 1128, 1591 and 1945*, have significant correlations between C and precipitation at a few high starting levels. By removing segments influenced by precipitation, there is a drop in variance and corresponding correlation figures. Catchment 1945*

Table 5.3 Correlation coefficients between the recession constant C and precipitation (prec) and temperature (temp).

CATCH-MENT	QUL= %ADF	OBSERVED SERIES no	prec	temp	TRANSFOR. SERIES no	prec	temp	HBV SIM. SERIES no	prec	temp
1128 (64-75)	100	9	-.41	-.01	7	-.28	-.18	11	.39	-.66
	75	5	-.12	-.39	7	.56	-.34	10	.67	-.19
	50	7	.08	-.64	7	.70	-.73	12	.88**	-.32
	30	3			6	.95*	-.25	7	.10	-.52
	20	1			3			3		
1591 (66-81)	100	11	.65	-.49	13	.26	-.49	14	.47	.06
	75	13	-.17	-.61	14	-.06	-.54	20	.57*	-.23
	50	12	.68*	-.31	13	.58	-.43	19	.06	.35
	30	10	-.33	-.38	11	.91**	-.20	28	-.22	.08
	20	11	-.21	-.88*	10	-.27	-.27	18	.39	-.39
1945 (72-86)	100	11	-.42	-.84**	12	-.35	-.80**	15	-.19	.20
	75	14	.44	-.69*	17	.25	-.68*	14	.19	.33
	50	10	.59	-.59	12	.30	-.78*	17	.08	.04
	30	7	.01	-.93*	10	.60	-.60	19	.15	.03
	20	9	.55	-.58	11	.51	-.57	3		
1945* (72-86)	100							12	.00	.08
	75							17	.56*	.13
	50							12	.26	-.07
	30							17	.31	.09
	20							12	.24	-.07

1-tailed Signif: * .01 ** .001

Table 5.4 Correlation coefficients between the recession constant C and precipitation (prec) and temperature (temp). Precipitation limit of 1.0 mm per day.

CATCHM. (period)	QUL= %ADF	OBSERVED SERIES no	prec	temp	TRANSFOR. SERIES no	prec	temp	HBV SIM. SERIES no	prec	temp
1128 (64-75)	100	5	-.66	-.12	5	-.73	-.07	6	-.09	-.56
	75	5	-.12	-.39	5	-.12	-.39	9	.73	-.46
	50	7	.08	-.64	6	.33	-.78	12	.88**	-.32
	30	2			4			7	.10	-.52
	20							3		
1591 (66-81)	100	7	.44	-.34	7	.43	-.33	6	.74	-.54
	75	7	-.37	-.77	8	-.37	-.73	7	.45	.33
	50	9	-.17	-.62	10	-.27	-.73*	10	.14	.35
	30	8	-.20	-.80*	7	-.26	-.81	18	.00	.11
	20	6	.14	-.99**	5	.93	-.64	15	.71*	-.40
1945 (72-86)	100	8	-.30	-.82*	8	-.11	-.79*	5	.64	.80
	75	7	.37	-.91*	7	.38	-.92*	7	.38	.62
	50	5	.87	-.82	5	.87	-.82	9	.00	.28
	30	6	.34	-.93*	7	.09	-.95**	10	.47	-.56
	20	5	.23	-.55	6	.37	-.48	2		
1945* (72-86)	100							5	.97*	-.65
	75							8	.82*	-.45
	50							7	.98**	-.57
	30							11	.83**	-.47
	20							8	.25	.09

1-tailed Signif: * .01 ** .001

shows, surprisingly, an increase in the correlation with precipitation. This catchment has a fast response in its model structure, and experiences very low variance values when precipitation is removed. Still, the correlations suggest that the model responsed even to minor precipitation amounts. The model does not account for interception losses. The increase in correlations is merely a result of very low variance in the recession rate and precipitation values.

5.6 MODEL IMPLICATIONS

To summarize, the major disadvantages regarding low flow modelling in the present HBV model structure are:

* The transition between drainage of the upper and lower zone is too abrupt, and

* The effect of evapotranspiration on low flows is not accounted for.

To limit the influence of the transition effect, the model parameters should be chosen carefully and within a reasonable range. One the other hand, it might be better to modify the model structure by substituting the different zones with only one saturated zone. This zone could follow a nonlinear drainage or drain at several different levels within the zone.

Any choice of model structure has to consider the number of parameters to be estimated. A large parameter set increases the subjective influence in the calibration process, by introducing a range of parameter combinations which give acceptable results. This is possible due to intercorrelations between parameter values, which makes it difficult to find the optimal values, and complicates the interpretation of model results. To some extent these problems can be avoided by limiting the parameter range. Anyhow, choice of model should be guided by model application, available data and needed accuracy, and the simplest model possible, be chosen.

Increased evapotranspiration losses can be modelled by introducing an upward flux from the upper zone to the soil water zone. Mørk (1989) suggested a capillary transport which depended on potential evapotranspiration (EPOT) and groundwater depth. When the groundwater lies above a certain transition zone, the transport equals EPOT, when it lies below, transport is neglected. In the transition zone, the transport varied linearly with groundwater depth, from zero to EPOT.

The next sections briefly present some resent model works which address these issuses.

5.6.1 The PULSE model

The PULSE model (Bergstøm et al., 1985), is based on the HBV model structure and developed to model hydrochemical properties. A modified version of this model has been tested on a Norwegian catchment by Lindström et al. (1990).

Runoff in the PULSE model generates from a single saturated zone representing groundwater, either situated close to the surface or deeper depending on the hydrological situation, Figure 5.2. Total drainage from the saturated zone (QGEN) increases in steps as the water content increases. QGEN depends on zone water content LZ, and is determined through four recessions coefficients, K0 - K3, and corresponding water threshold levels, UZL, LZL and DZL.

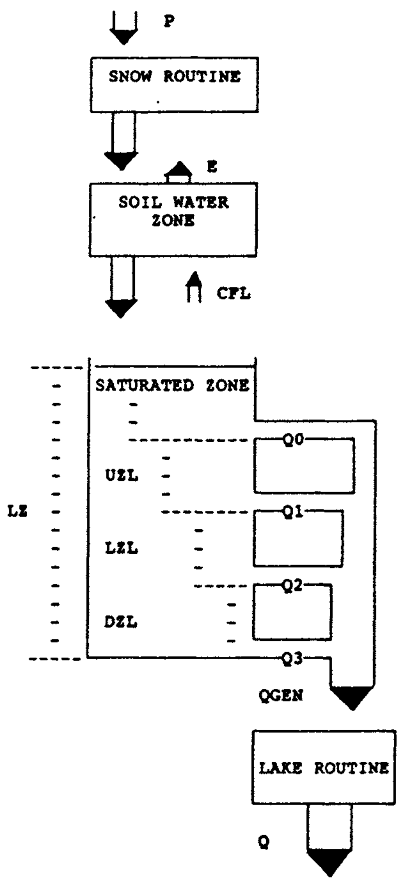


Figure 5.2 PULSE model structure (P: Precipitation, E: evapotranspiration, CFL: capillary transport, Q: dis-charge).

This modification of the response function is also part of an upgraded HBV model (Bergström & Sandberg, 1983). If major lakes exist, the calculations are done for subcatchments where the lake outlet terminates the catchment. In these catchments QGEN passes through a lake routine.

The soil moisture routine in the HBV model is modified in the PULSE model to allow capillary transport (CFL) from the groundwater zone to the soil water zone. CFL is given by:

$$CFL = CFLUX(1 - SM/FC) \qquad (5.1)$$

where CFLUX is a parameter, SM soil water zone content and FC soil water zone content at saturation. CFL/CFLUX varies linearly with SM. This is similar to the capillary transport model suggested by Mørk (1989), only CFLUX is replaced by EPOT.

The PULSE model has four different recession coefficients and corresponding water levels. The increased complexity and parameter interactions of a larger parameter set, course problems in parameter estimation and reduce the applicability of the model. Lindström et al. (1990) reduced the number of parameters in the response function by replacing the original function of the PULSE model with a nonlinear relationship between storage and outflow.

The modifications of the HBV model structure introduced in the PULSE model, agrees with the conclusions from this analysis. The gradual depletion of only one saturated zone, reduces the transition effect on the recession variability, and the evapotranspiration process is given a better representation through the possibility of increased water losses due to capillary transport.

5.6.2 Improved HBV model

The HBV model as applied in Norway, has recently been subject to new developments (Killingtveit et al., 1990; Sælthun, 1990). Modifications of the snow melt and evapotranspiration algorithms are suggested. The evapotranspiration calculations are improved through a better calculation of potential evapotranspiration using a temperature index method. It is also suggested that the HBV model should include an upward transport of water from the groundwater to the soil water zone. At present this has not been implemented in the model.

5.6.3 Further research

A project has been proposed in cooperation with NVE, to improve the evapotranspiration routine in the HBV model. The evapotranspiration algorithms of the AMOR model presented in Chapter 6, will be linked with the soil moisture routine in the HBV model. Andersson (1989) found that the influence of different evapotranspiration routines on the model fit of the HBV model generally was small. Howeve, in order to account for the effect of evapotranspiration on low flows, it is essential that a capillary transport is included in the soil moisture routine.

The model results will be evaluated against the original HBV model in a comparative analysis. This project is presented in more details in Section 7.2.

5.7 APPLICATIONS

The general usefulness of recession analysis has been discussed in the foregoing sections. This section looks at areas where recession analysis is applicable in combination with conceptual models.

Recession analysis can be used to evaluate the low flow performance of the simulated series in general, and in particular to monitor hydrological changes, including impact of land use and climate change on low flows.

Recession analysis can also be used before and during the calibration process, to update model parameters or obtain initial estimates of model parameters. The obtained information can reduce the subjective aspect of the calibration process. Harlin (1990) presents an automatic calibration scheme for the HBV model. Initial parameter estimates of the recession parameters KUZ1, KUZ and KZL are obtained from recession analysis of runoff in different flow intervals. The intervals are determined from analysis of the flow duration curve.

The recession analysis of the HBV simulated series in this study revealed a too slow recession rate of the lower zone (KLZ). KLZ is recommended to be within the range 0.01 to 0.05, which corresponds to a recession constant C, between 99.5 and 19.5. The observed recession rate of the catchments included in this study, never achieve such a slow drainage rate. It is important to account for this in the calibration process. Analysis of recession rates from the lowest starting levels can guide the estimate of KLZ and PERC, which control the low flow values.

A better understanding of which factors control the recession process can enable model parameters to be estimated from catchment characteristics. The relationship between catchment and recession characteristics is discussed in Section 3.5 and 4.5.3.

5.8 CONCLUSIONS

Returning to the questions and hypothesis raised in the introduction, the simulated series will to some extent reproduce the recession variability in the observed series. However, there is a fundamental difference in the origin of these variabilities.

The major course of variability in the simulated series is due to the transition effect between different drainage coefficients of the upper and lower zone in the HBV model. The difference in magnitude between these coefficients determines the variability pattern. Precipitation and temperature are to a much lesser extent responsible for the variability, and their effect is only measurable if the transition effect is negligible.

In the observed series, however, there is an evident link to the climatic parameters. Particularly important is the correlation with temperature which link the variability to evapotranspiration losses. It is more difficult to relate precipitation to the recession rate, probably because of its high spatial variability. Contradictory to the simulated series, the true input is not known.

Mean values of the recession constant are for high starting levels satisfactory represented by the simulated series. For lower starting levels it is common to find a marked rise in HBV mean values. This is due to the choice of lower zone model parameters, which favour a very slow recession rate and a high lower zone water content.

Generally, low flow modelling needs more attention. Improved simulations can be obtained through a better model structure or simply by an increased emphasis upon optimization of low flow related parameters. Recession analysis is a valuable tool when verifying the model's low flow performance, and guide the choice of parameters before and during the calibration process.

CHAPTER 6

MODELLING EVAPOTRANSPIRATION AT THE CATCHMENT SCALE

6.1 INTRODUCTION

The influence of evapotranspiration on recession variability is in Chapter 4 indicated by the relationship found between recession variance and temperature. Chapter 5 points to the importance of including the influence of evapotranspiration in low flow modelling. In order to quantify the water lost by evapotranspiration, an appropriate model for application on a local scale is required. This chapter presents a soil water balance model which accounts for the effect of vegetation and soil properties in the caclulations. The model is a tool for assessing the real water loss by evapotranspiration, and can simply replace the soil moisture zone in existing rainfall-runoff models.

Evapotranspiration calculations have to take into account the interface processes of water transport through the atmosphere-vegetation-soil system. Major uncertainties in this part of the hydrological cycle include the role of vegetation.

There are two main factors affecting the evapotranspiration process, the external meteorological conditions and the soil/vegetation characteristics. The meteorological factors determine the evaporative capacity of the atmosphere, whereas the soil/vegetation characteristics determine the capillary movement of water through the unsaturated soil and the transmissibility of the vegetation. The relative importance depends upon water table location, type of vegetation and capillary rise height of the soil.

In areas with shallow groundwater, the groundwater level may vary strongly. Soil moisture deficits in the root zone due to evapotranspiration, can be compensated by capillary transport from the groundwater zone. Groundwater table close to the land surface is commonly found in moraine or clay terrain, and is typical for Scandinavia. Available literature reveals that only limited data are available on the actual rates of evapotranspiration from soils overlying shallow water tables (Rasheed et al., 1989).

This chapter discusses principles of evapotranspiration in general. Different approaches to modelling evapotranspiration are presented, with special emphasize on works which include the effect of vegetation.

Choice of model was guided by both the need to find a model structure which is based on the physical processes involved, and at the same time is applicable to areas with normal data coverage. The model has to account for the effect of vegetation and soil properties in the calculations, and at the same time be applicable for use in areas with normal data coverage.

There was no model available in Norway for this purpose. In close collaboration with research scientist S. Lystad at the Norwegian Meteorological Institute, the soil water balance model MORECS from the Meteorological Office in Great Britain was selected. It is based on the Penman-Monteith equation for calculating evapotranspiration and accounts for vegetation and soil properties in the calculations. This requires a certain complexity in the model, which is inevitable however, when assessing the variability in daily evapotranspirations rates. In this study the model has been adjusted to operate on data routinely observed at climatic stations in Norway. The model work has been done in cooperation with S. Lystad.

AMOR is applied at two widely different catchments, and the variability in the estimated evapotranspiration rates is compared with the variability observed in the recession rate. The comparison is made for different levels of soil moisture deficits. The object is to study the variability in evapotranspiration estimates for different vegetation types, and in particular to relate the magnitude of the mean catchment loss during the recession period to the observed discharge variability.

6.2 PRINCIPLES OF EVAPOTRANSPIRATION

In general, evapotranspiration is composed of evaporation from soil and intercepted rainfall and transpiration from plants. The value of evapotranspiration varies according to vegetation type and to the availability of water in the soil. Transpiration is a necessary component of the plant production process. In order to assimilate CO_2, the stomata open and water is lost through transpiration.

Both evaporation and transpiration are influenced by the general meteorological conditions. These can adequately be represented by radiation, temperature, vapour pressure and wind speed. Actual evapotranspiration falls below the potential rate at a point which depends on the soil moisture and of the hydraulic properties of the moist soil.

Transpiration from a dry surface (no intercepted rainfall) is limited by the energy available to evaporate water and by the ability of the soil to supply water to the evaporating surface. Water loss from the plant canopy can be characterized by a resistance analogue. Water that transpires has to overcome the internal and surface resistances of the plant, whereas the transport of water vapour to the atmosphere is determined by the aerodynamic resistance.

The aerodynamic resistance depends on the effect of the physical roughness of the vegetation on the transfer of energy and water vapour from the surface to a reference level in the atmosphere. It is a function of wind speed, aerodynamic roughness of the vegetation and atmospheric stability.

Plant resistance is composed of internal and surface resistances, and describes the vegetational control over the rate of water supply for transpiration. It depends on meteorological and enviromental factors such as type and age of plant, ambient carbon dioxide concentration, vapour pressure deficit, temperature, light intensity and soil moisture status. The surface resistance depends both on stomatal resistance and leaf area.

Compared with a grassland site, forested catchments normally experience lower water table elevations, soil moisture and runoff due to higher evapotranspiration losses. This difference can probably be attributed to the greater interception loss from a forest canopy (Holmes & Wronski, 1981; Petch, 1988). The evaporation rate of water held upon wet grass is similar to the transpiration rate from dry grass, whereas evaporation from the wet foliage of trees proceeds at a faster rate than transpiration.

Holmes & Wronski (1981) reviewed some present work on the water yield from different plant communities, and concluded that the evaporation rate from a wet forest canopy can exceed by 1.5 to 3 times the rate of transpiration that would have prevailed if the canopy was dry. It is therefore essential that evaporation of intercepted precipitation and transpiration are modelled separately in forested areas. The interception loss is a function of the storm character and vegetation type and age. Stewart (1977) found that the annual interception loss of a pine forest accounted for 34 % of the total evapotranspiration, whereas Bringfelt (1982) estimated it to be 22 % for an old, mainly coniferous, forest stand in Sweden.

Rutter (1967) found that actual evapotranspiration from a forest site can exceed the water lost from an open water surface. This can probably be ascribed to the effect of advective sensible heat, which might be an important source of energy for evaporation of intercepted water (Holmes & Wronski, 1981). Stewart (1977) studied the energy budget of a pine forest, and in many occasions of wet canopy the latent heat flux exceeded the net radiation. The additional energy was provided by a downward flux of sensible heat from the air. Shuttleworth and Calder (1979) estimated the total evapotranspiration loss from a forest to be approximately 12 % higher than the total radiant energy input.

Rutter et al. (1971) formulated the "Rutter" model for describing the rate and magnitude of inputs, stores, interchanges and losses from a forest canopy during and after a rainstorm. The model has shown that for temperate regions the structure of the forest plays only a minor role in determining **interception** loss when compared to the frequency and duration of storms (Rutter & Morton, 1977). For modelling purposes this means that it is possible to operate with a simple interception model.

It is far more complicated to model **transpiration** due to a large number of influencing factors and lack of knowledge of their relative importance. Moving from short grass to forest, aerodynamic resistance decreases, whereas surface resistance increases. The reduction in aerodynamic resistance is due to an increase in wind speed with height (neutral conditions). The aerodynamic resistance in forests is small in comparison to the surface resistance, and this explains the larger difference between evaporation and transpiration rates from wet and dry surfaces found for forests. Dry forest canopy transpiration is generally lower than transpiration from grassland sites (Beven, 1979; Roberts, 1983).

Roberts (1983) found that annual values of transpiration for different forest stands in Northern Europe generally yielded similar results, and the annual totals were low compared with formulae such as that of Penman for potential evaporation (Section 6.3). Four processes were considered as maintaining annual transpiration at similar, rather low levels: i) Understoreys in forests are regarded as effective buffers to any tree canopy differences, ii) a marked negative feedback response of surface resistance to climate, restricts the range of transpiration losses, iii) variations in soil water content, in most circumstances, have negligible effects on transpiration rates, and iv) forests have requirements for water which do not exceed its availability at the site in dry years.

6.3 MODELLING OF EVAPOTRANSPIRATION

There are two major approaches in calculating evaporation. The mass transfer method calculates the transfer of heat and water vapour from the evaporating surface to the atmosphere, whereas the energy method considers an energy budget at the earth's surface. Using both energy budget and transport equation, the combination method (Penman, 1948) and its several modified and improved versions (i.e. Monteith, 1965), express evaporation as the sum of a radiation and a ventilation term.

The relative importance of the radiation contra the ventilation term has frequently been discussed. The radiation and ventilation term of the Penman (1948) equation will have the same weight when the air temperature is approximately 9 °C. For air temperatures above 9 °C, the radiation term will dominate, whereas the ventilation term will have most effect for lower temperatures. Thom & Oliver (1977) suggested that Penman's equation, calibrated for water surfaces, underemphasizes the importance of the ventilation terms relative to radiation for rougher surfaces. They derived a modified equation for evapotranspiration valid for rural, lowland areas of moderate aerodynamic roughness. The equation predicts an enhancement of evaporation due to ventilation effects at the expense of evaporation governed by radiation.

Evapotranspiration is a complex process where biological responses can limit or even reduce the rate of evaporation in spite of increasing atmospheric demand. Small scaled physical models based on experimental data, are very complex and unsuitable for routinely estimation of areal evapotranspiration. Their high data requirements prohibit their use for management purposes.

Owing to the difficulties of obtaining field measurements, crop evapotranspiration prediction is generally based on climatic parameters. The dependence of evapotranspiration on soil moisture is commonly accounted for through a soil moisture deficit model that operates by solving a simple water balance equation. Precipitation data are given as input, and actual evapotranspiration calculated in terms of potential evaporation, which is reduced by a regulating function according to the prevailing soil moisture content. This way of using weather records to estimate soil moisture, is a commonly used alternative to field measurements.

Calder et al. (1983) assessed what improvements in prediction of soil moisture deficits could be made by incorporating successively more detailed equations for potential evaporation and regulating functions. The regulating function incorporates the effect of many different mechanisms which may modify the soil moisture content, i.e. interception, soil-moisture drainage, deep abstraction and evaporation from the soil surface. The study concludes that until these effects are incorporated explicitly, little advantage can be gained from further developments and increased sophistication of the meteorological aspects of these models. The potential evaporation equations incorporating either the climatological mean or the Penman equation, were most successful in this study, which included six grassland sites.

Models which only require climatic parameters, often perform satisfactory for low vegetation, typically agriculture and grassland sites. However, evaporation from taller vegetation is much more sensitive to surface factors (Shuttleworth & Calder, 1979). Calder (1977) recommends for tall crops such as forests, the use of a modified form of the Penman equation (Thom and Oliver, 1977), or a more general form (Monteith, 1965), including factors which depend on the characteristics of the vegetation type. A general review on methods used to measure and model forest evapotranspiration is given in Spittlehouse and Black (1981).

The equation by Monteith (1965) is commonly referred to as the Penman-Monteith form of the combination equation. It includes aerodynamic and surface resistances, which represent the effect of vegetation on the rate of evapotranspiration. An increase in surface resistance is accompanied by a reduction in evapotranspiration. Aerodynamic resistance, r_a, occurs both in the numerator and denominator of the Penman-Monteith equation, so its influence on the evapotranspiration depends on the relative importance of the radiation and ventilation terms.

The use of the Penman-Monteith equation for a vegetated area, requiers a simple representation of the vegetation. It is common to look at the sample of leaves as one big leaf, which is represented by a bulk surface and aerodynamic resistance.

Its use has been limited by the lack of knowledge of surface and aerodynamic resistances, and by the availability of the necessary meteorological data. It is at present one of the most recognized methods for calculating areal evapotranspiration. Increased knowledge about the necessary data, has recently encouraged a wider use. The equation yields (Monteith, 1965):

$$\lambda E = \frac{\Delta (R_N - G) + \rho c_p (e_s - e)/r_a}{\Delta + \gamma (1 + r_s/r_a)} \tag{6.1}$$

where E = rate of water loss (Kg $m^{-2}s^{-1}$)
Δ = rate of change of saturated vapour pressure with temperature (mb $°C^{-1}$)
R_N = net radiation (Wm^{-2})
G = soil heat flux (Wm^{-2})
ρ = air density (Kg m^{-3})
c_p = specific heat of air at constant pressure (1005 J Kg^{-1})
e_s = saturation vapour pressure at screen tempera ture (mb)
e = screen vapour pressure (mb)
λ = latent heat of vapourisation ($\approx$2465000 J Kg^{-1})
γ = psychrometric constant ($\approx$0.66 mb $°C^{-1}$)
r_s = bulk surface resistance (sm^{-1})
r_a = bulk aerodynamic resistance (sm^{-1})

At the international workshop 'Estimation of areal evapotranspiration' held at Vancouver, Canada 1987, the question of routinely calculation of areal evapotranspiration was raised. The conclusions were summarized as follows (Black ed., 1987):

"For many applications areal evapotranspirations will have to be obtained by summing area-weighted point estimates for representative vegetative cover types and topographic positions within the area of interest. However, the method used to calculated evapotranspiration should be based on the Penman-Monteith equation, or a Priestley-Taylor type of equation with the incorporation of the capability to restrict evapotranspiration when the soil is dry".

The Priestley-Taylor method was designed as for large scale relationships, measuring in the order of ten and thousands of square kilometers (Priestley & Taylor, 1972). They assumed that on this space scale evaporation is largely a radiation controlled process, and suggested an equation based on the radiation term of the Penman (1948) equation. The equation assumes no advection, and the equation constant is valid for saturated land surfaces. Shuttleworth & Calder (1979) tested the Priestley-Taylor formula for a forest site, and they warned against the indiscriminate use of the equation, due to the high variability in evaporation from forest in response to precipitation.

Dolman et al. (1988) follow the conclusions by Black et al. (1987) in a discussion of forest evaporation, by stating "the best tested model at present is the physically based Monteith version of the Penman equation", and further adds "this model has been successful in the prediction of evaporation from both dry and wet forest canopies".

The use of the Penman-Monteith equation involves selection of appropriate models for calculating interception, aerodynamic and surface resistances. Actual evapotranspiration for dry conditions can be estimated from the Penman-Monteith equation by adjusting the surface and aerodynamic resistance according to the environmental conditions. Actual evapotranspiration for wet conditions can be estimated as evaporation of intercepted water, assuming that the surface resistance is zero. In the forest situation this can result in evaporation rates that are up to three times the calculated transpiration rates (Holmes & Wronski, 1981). Shuttleworth (1975) has shown theoretically that the surface resistance is negligible when the canopy is wet.

The Penman-Monteith equation has frequently been used for modelling evapotranspiration with a variety of suggestions for model representation, some of which is outline below.

Calder (1977) developed a forest evapotranspiration model based on the Penman-Monteith equation. Aerodynamic resistance, surface resistance and the canopy parameters required by a Rutter type of interception model, were obtained using optimizing techniques. A constant value was assumed for aerodynamic resistance, whereas surface resistance was given as a function of season and vapour pressure deficits. The model predictions were much improved by including vapour pressure deficits in the estimation of surface resistance.

Bringfelt (1982) followed in a study of forest evapotranspiration, the suggestion by Calder & Newson (1979) and estimated the number of hours the canopy is wet, to be 1.5 times the number of rain hours. Rainfall amount was reported twice a day, and the length of rainfall related to the rainfall amount. A forest interception model was derived from the equation proposed by Rutter et al. (1971). Transpiration was calculated using a simplified version of the Penman-Monteith equation, where the aerodynamic resistance term was neglected for dry conditions, and assumed constant for a wet forest.

Dolman et al. (1988) presented a model for prediction of forest transpiration. Aerodynamic resistance was assumed constant, whereas surface resistance was given as a function of solar radiation, temperature, specific humidity, leaf area index and soil moisture deficits. The parameters of the surface resistance model were obtained by optimization. It was found that transpiration calculated with a constant surface resistance tended to be much higher than transpiration calculated using a variable resistance. Under very dry condition, the influence of soil moisture deficit was dominant over the humidity deficit feedback.

A more general method for calculating surface resistance, expressed in terms of stomatal conductance, is suggested by Jarvis (1976). Stomatal conductance is modelled as a function of photon flux density, leaf temperature, leaf-air vapour difference, leaf water potensial and ambient carbon dioxide concentration. Scaling up from the leaf to a vegetated area, these variables are not generally available. The type of model described by Jarvis (1976) has frequently been used with other variables. Roberts et al. (1984) found that radiation, specific humidity and soil moisture were the principal factors controlling stomatal conductance in bracken. Stewart (1988) replaced the variables in the Jarvis model by measurements of solar radiation, atmospheric specific humidity deficit, air temperature and soil moisture deficit.

Humidity deficit has in many works shown to be the most important feedback mechanism on the forest transpiration rate, whereas soil moisture deficit has been found to have insignificant effect (Roberts, 1983; Bringfelt, 1982). Dolman et al. (1988) restated these conclusions as follows:

"Up to a value of 60-75 % of the available water, the soil moisture deficit is unlikely to have a significant effect on forest transpiration and transpiration is regulated predominantly by the atmospheric humidity feedback. If the soil moisture content falls below this level, transpiration is reduced drastically and the atmospheric humidity influence become much less significant".

The MORECS (Meteorological Office (UK) Rainfall and Evaporation Calculation System) soil water balance model (Thompson et al., 1981) was chosen as the basis for this study. It uses a modified version of the Penman-Monteith equation (Appendix A.2). Actual estimates of evapotranspiration are obtained using a soil moisture extraction model.

MORECS is modified to adjust to the set of input variables routinely observed at automatic weather or climatic stations in Norway. A major difference between the two models is that MORECS estimates areal evapotranspiration based on smoothed input variables, whereas the modified version, AMOR, calculates point estimates.

6.4 PRESENTATION OF MORECS

MORECS an acronym for Meteorological Office Rainfall and Evaporation Calculation System, was introduced in 1978 by the Meteorological Office in Great Britain. It was designed to provide estimates of weekly and monthly evaporation and soil moisture deficit in the form of averages over 40 * 40 km grid squares, using daily synoptic weather data as inputs. MORECS was extensively revised in 1980/81 and this version constitutes the basis for the personal computer model, AMOR, presented in this study.

The presentation given will be brief, and the reader is referred to Appendix A.2 and Thompson et al. (1981) for further details.

6.4.1 The MORECS system

The MORECS system has five main components:

1. Data collection of meteorological variables called the Penman variables (sunshine, temperature, vapour pressure, wind speed) and rainfall. Interpolation to obtain grid-square average values of each variable.

2. Calculation of daily potential evapotranspiration (PE) for each grid square for different surface covers, using a modified form of the Penman-Monteith combination, Equation (A.2.1).

3. Estimates of PE are converted to estimates of actual evapotranspiration (AE), by adjusting the bulk surface resistance according to the magnitude of the soil moisture deficit. The soil moisture is calculated using a soil moisture extraction model. The calculations are made for soils with high, medium and low available water content.

4. Calculation of daily water balance for each grid-square, using the relative proportions of the various surfaces in each square.

5. Data output are weekly averages of the Penman variables, PE, AE, soil moisture deficit (SMD) and excess rainfall (HER).

The calculations are made for various types of surfaces, and an areal average obtained from the relative proportions of each surface. The amount of intercepted precipitation is determined from the leaf area index and rainfall amount. The time surface is wet depends on the evaporative demand and the amount of intercepted water. Aerodynamic resistance is given as a function of wind speed and effective height of the vegetation, whereas surface resistance depends on the leaf area index and soil moisture deficit. An additional vapour pressure deficit and temperature dependence is introduced for conifers.

6.4.2 Model estimation errors

The major sources of error involved in an evapotranspiration model like MORECS can be identified as: instrument errors, errors related to obtaining areal averages, errors in estimating model parameters, and modelling errors, both related to model structure and parameter representation.

It is at present impossible to evaluate the significance of the expected errors in the overall predictions of evapotranspiration. Thompson et al. (1981) stated that the modelling errors involved in the simplifying treatment of physical processes in MORECS, can be made negligible by comparison with shortcomings in the meteorological dataset and difficulties in specifying the magnitude of necessary crop physiological variables.

Beven (1979) made an assessment of the relative errors in input data and parameter values in the Penman-Monteith equation. Calculations were performed for dry conditions only, aerodynamic resistance, r_a, was given a constant value, whereas surface resistance, r_s, was assumed a seasonal distribution. A sensitivity analysis showed that estimates of evapotranspiration were more dependent on the values of the aerodynamic and surface resistance parameters, than on climatic difference between sites in a broadly humid temperate climate. For forests, where r_s is much larger than r_a, estimates of evapotranspiration are particularly sensitive to surface resistance.

Calder (1977) modelled transpiration and interception losses based on the Penman-Monteith equation and a Rutter type of interception model. Model estimates of r_a and r_s was derived using an optimizing procedure. Calder concluded from a sensitivity analysis of model prediction to experimental errors, that little advantages could be gained from further development of the transpiration and interception models without corresponding development in the accuracy of the measurement of the meteorological variables.

These works point to the importance of including the role of vegetation in the calculation of evapotranspiration. However, the model results depend upon the confidence we can place in estimates of vegetation parameters.

6.4.3 Model verifications

MORECS has been verified against neutron probe measurements taken at test sites in Great Britain. The measured soil moisture deficits (SMD) were compared with estimates obtained using the MORECS model, and it was concluded that MORECS gives generally acceptable values of SMD (Thompson et al., 1981).

The MORECS model has been tested for moorland and grassland sites and evaluated against other soil moisture deficit models, in work by Gardner & Field (1983) and Lockwood et al. (1989). They generally conclude that a MORECS type water balance model gives satisfactory estimates of soil moisture deficits. Gardner & Field (1983) found a bias towards overestimating the SMD, except under very dry conditions. Lockwood et al. (1989), tested the model for a seasonal variable crop and similar found that underestimation by MORECS is most significant in markedly dry periods. They ascribed the underestimation to low maximum available soil moisture content for the upland version of the model. Including an energy balance allowing for the effects of atmospheric stability on aerodynamic resistance, did not produce significant differences on a weekly time scale.

6.5 OUTLINE OF AMOR

The AMOR (AutoMORecs) model, which is a modified version of MORECS, was originally designed by S. Lystad at the Norwegian Meteorological Institute, to operate on hourly observations from automatic weather stations in Norway. The Norwegian Meteorological Institute has tested the AMOR model on an agricultural site, Kise in Hedemark, with satisfactory results (Lystad, pers. comm.). Hourly recorded meteorological data were available from an automatic weather station located at the site. The model calculation of soil moisture content was evaluated against weekly soil moisture measurements using neutronmeters.

In this study the AMOR model has been extended to operate on routine observations made at climatic stations in Norway. The model work has been done in cooperation with S. Lystad. Model details are given in the AMOR users manual (Lystad & Tallaksen, 1991).

Meteorological variables are at the climatic stations recorded from three to eight times a day. It was necessary with an hourly resolution of the input variables to meet the data requirement of AMOR. This implied that special interpolation routines had to be applied for each input variable; temperature, precipitation, wind, humidity and cloudiness. AMOR only considers stations with three recordings a day, but the interpolation routines can easily be adjusted to fit more observations. Dolman et al. (1988) present similar conversion algorithms for available energy, temperature and specific humidity deficits, whereas cloudiness is assumed constant over the day.

The calculations in MORECS are done separately for day- and nighttime periods, with mean values of radiation, resistances, temperature and wind speed for each period. Daily mean values of wind and temperature are adjusted empirically according to which period is considered. In AMOR the mean values for each period are calculated from the hourly input values. A flow chart of the AMOR model structure is given in Appendix A.3.3.

6.5.1 Meteorological input variables

The AMOR model is designed to operate on hourly values of precipitation, temperature, wind speed, relative humidity and cloudiness. A free cubic spline interpolation routine is applied for the variables temperature, wind, humidity and cloudiness, all recorded at 07 AM, 01 PM and 07 PM. The interpolation routine constructs a smooth curve through the three data points given. For further details of the spline function see Borland Int. (1987).

The interpolation routine can result in both higher maximum and lower minimum values than in the observed case. In order to avoid non-existing or unrealistic values, upper and lower bounds were selected following the natural range of each variable. Wind speed was given a lower bound of 0.1 m/s, cloudiness varies between zero and eight, whereas relative humidity was limited to values between zero and 100 %.

MORECS and AMOR both require values for global radiation, which is the sum of shortwave radiation from the sun and atmosphere measured on a horisontal plane. Global radiation is only recorded at a few locations, but can be estimated from clear sky shortwave radiation using empirical relationships which includes cloudiness or relative sunshine duration. Clear sky global radiation is given by location and time.

MORECS calculates the global radiation in terms of relative sunshine duration, whereas AMOR calculates it as a function of cloudiness, following the expression by Ångstrøm (1916). This expression has been extensively used for computations and found appropriate for most situations (Painly et al., 1974). Hourly values of global radiation is obtained from the interpolated cloudiness values. Cloudiness is also required in AMOR for the transformation of net clear to actual longwave radiation, whereas MORECS applies sunshine duration for this purpose.

Average daily values of calculated global radiation at Dønski (station no. 1948) were compared with values observed at Blindern, located about 20 km east of Dønski. The comparison shows a trend towards higher daily values in the observed case, as also confirmed in higher mean monthly values. This result is in line with an investigation carried out at Ås, situated south-east of Oslo, where several empirical equations were compared with observed values of global radiation (Heldal, 1970). The analysis generally concludes that daily values of the global radiation may be estimated by relatively small errors, however, many of the expressions, including Ångstrøm, underestimated the radiation.

Average daily values for temperature, wind and relative humidity obtained from the interpolated hourly values for Dønski, were compared with the mean daily values given by the Norwegian Meteorological Office. The comparison showed satisfactory results with only minor, random deviations.

Precipitation is only recorded once a day, at 07 AM. Even with more recordings, it would not be recommendable to obtain hourly values using a spline function, due to the non cyclic nature of precipitation. In a forest evapotranspiration model by Bringfelt (1982) day- and nighttime rainfall occur during a centered time interval which are given a length related to the rainfall amount. The function obtained for rainfall duration shows very large scatter, reflecting among other effects, the different types of rainfall.

A new model for hourly distributing of rainfall is developed in this study (Part IV). It applies data from climatic stations, were precipitation is only measured once a day. However, the weather is recorded three times a day using weather symbols. This additional information guides the distributing of precipitation into three time intervals. Two weather symbols related to precipitation are selected, WW, which represents the weather at the time of observation and W1, which reports on the weather since last observation. Besides reporting on precipitation/no precipitation, the symbols contain information on type of precipitation, which guides the distribution of precipitation hours within a time interval.

The precipitation simulations show satisfactory results when compared with hourly recording stations, and was accepted for use in AMOR. It is important to note that no attempt is made to model hourly evapotranspiration values. However, hourly values are necessary for estimating the time distribution of day- and nighttime rainfall. The rainfall model therefore focus on the time distribution of rainfall hours, whereas rainfall amount is given a simple representation.

MORECS and AMOR require information on the number of dry and wet hours, which is calculated as a function of evaporation demand and amount of intercepted water. AMOR permits calculation of the number of dry and wet hours directly from the hourly precipitation series, but this has not been implemented in the model yet.

The AMOR model calculation scheme is illustrated in Figure 6.1. After obtaining hourly values for the six input variables, the series are collected on one file by the programme SAMLE. AMOR is run for each cover type in the catchment, and a catchment average calculated as the weighted mean. These procedures can automatically be run for all climatic stations in Norway. It is important to note that the AMOR model calculations are point estimates, which are not valid for larger areas.

6.5.2 Model parameters

The vegetation types in MORECS are in AMOR given a Norwegian equivalent, Appendix A.3.1. Surface types adjusted for use in this study are deciduous forest, conifers, riparian, grass, cultivated land, bare soil and water. Riparian vegetation is used for areas with bog. Basic information for each vegetation type is maximum leaf area index (LAI), albedo, effective crop height, daytime values of surface resistance for dense crops freely supplied with water and available water capacity of the soil. These parameters are defined for each crop type in the model, and values are given in Appendix A.2.4 (MORECS) and Appendix A.3.1 (AMOR).

The required phenological data are: date of spring growth, date of maximum height and harvest date. Initial dates given in AMOR are based on information on longitude, latitude, elevation and coastal distance (Lauscher & Printz, 1955). The given dates can be altered interactively when running the model. Cultivated crops require additional information on sowing and harvest dates.

The soil types are similar to in MORECS, divided into three SOIL CLASSes, of high (1), medium (2) and low (3) soil water capacities. The available water capacity is defined for each surface cover and corresponds to the value for

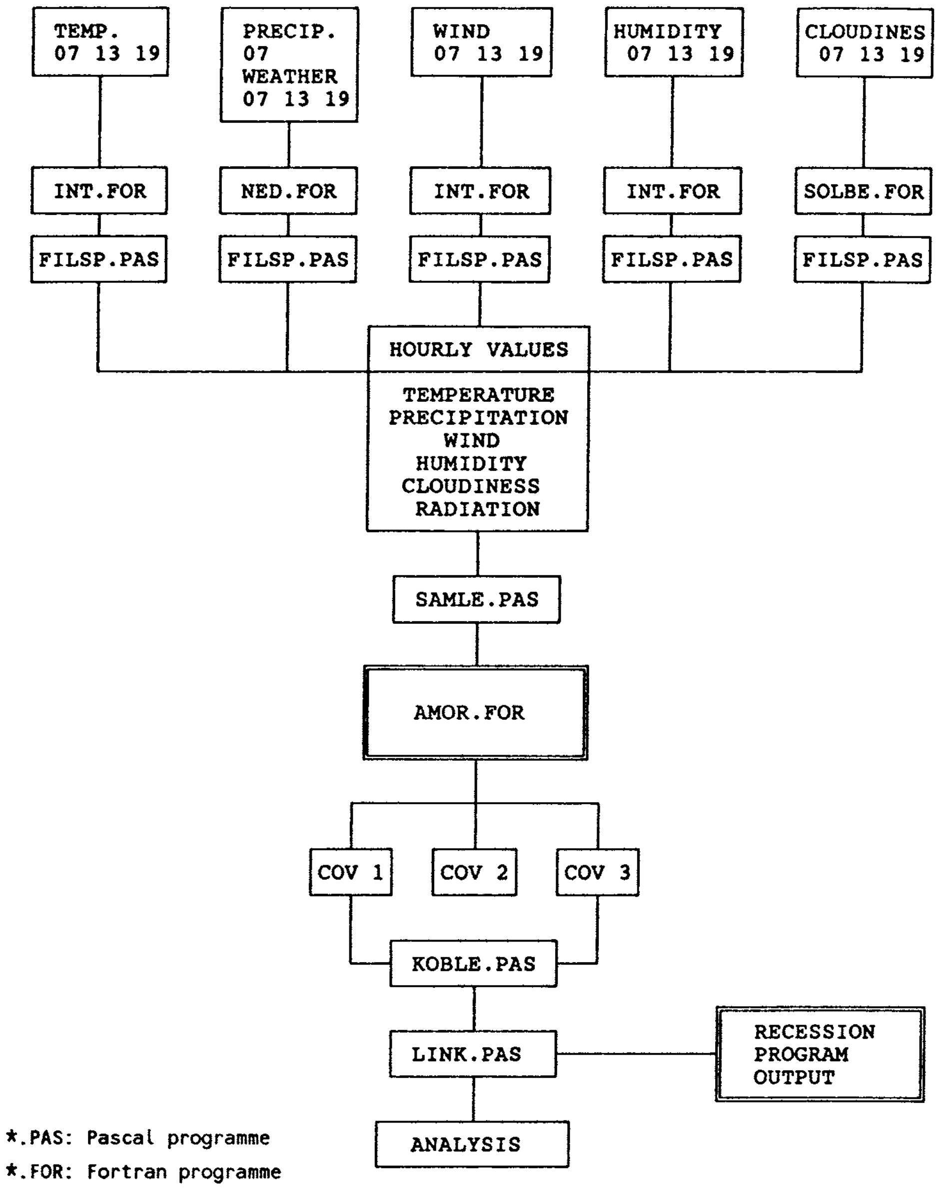


Figure 6.1 AMOR model calculation scheme.

soils of medium capacity. Values 25 % larger and smaller are used to arbitrarily define soils of high and low capacity. Any other value of soil water capacity may be chosen.

6.5.3 Model output

The AMOR model output has been divided into three parts; a main table of evapotranspiration estimates, a test file for selected variables and a graphic file for presentations.

The main table of evapotranspiration rates offers a selection of ten estimates of potential evapotranspiration, and two estimates of actual evapotranspiration (Appendix A.3.2). The test and graphic files have a selection of 51 variables, including vegetation parameters, meteorological input variables and calculated evapotranspiration rates. Variables with a diurnal variation are given as daytime, nighttime and diurnal totals.

6.5.4 Model errors

This section discusses uncertainties in the model calculations which is related to the AMOR model in particular. The general discussion of model errors in a scheme like MORECS was presented in Section 6.4.2.

Random errors in the simulated hourly values are reduced in the calculation procedure as the data are averaged over day- and nighttime periods. Comparison with observed mean daily values show that the meteorological variables temperature, humidity, wind and cloudiness experience random rather than systematic errors. The errors involved in the use of the hourly interpolation procedure are unlikely to be large for these variables. The estimated daily global radiation values are both higher and lower than observed values, but there is an emphasis upon lower values, which is reflected in underestimation of average monthly values. Consequently, there might be an underestimation of evapotranspiration losses.

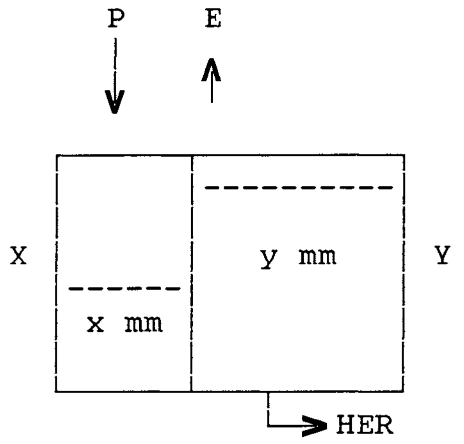
Errors may also result from using the simulated hourly values of precipitation. As these values are averaged for day- and nighttime periods, the errors involved will be of less importance.

Calculations in AMOR are restricted to the summer period, June to October. Soil moisture deficit (SMD) in the model is initial zero, and this may course errors in the estimations during the first period of calculation. As the soil is saturated at the end of the snow melt season, errors involved in estimates of initial SMD are avoided if the calculation starts at this time. This requires snow cover observations or extension to a all year model.

6.5.5 Model improvements

The AMOR model structure is in its main features equal to the MORECS model (Appendix A.2). This section presents three optional routines in the AMOR model, which it is suggested might improve the model. The routines have not been incoorporated in the model simulations in this study.

MORECS uses the simplifying assumption that the available water is held in two reservoirs X and Y which contains reserves of x and y mm (Figure 6.2). All water in X is freely available, while that in Y becomes increasingly difficult to extract as y decreases. The maximum available water is distributed 40 % in X and 60 % in Y. Water is drawn from X until it is completely exhausted, when extraction from Y begins. Recharge replenishes Y only when X is filled.



P = Precipitation
E = Evapotranspiration

Figure 6.2 MORECS soil moisture extraction model.

It is suggested that the soil moisture routine in MORECS could be improved by introducing an interaction between the two reservoirs X and Y. If X and Y are thought of as two discrete soil layers, a concept deliberated avoided in MORECS, the interaction can be looked upon as gravitational and capillary transport. A gravitational transport from X to Y can be modelled assuming high values of X and low values of Y, and a similar capillary transport from Y to X for high values of Y and low values of X. The purpose of varying the soil water model formulation is to obtain a more realistic behaviour of the soil moisture model. Soil moisture measurements are required in order to calibrate the drainage parameters in the transport routines, and to evaluate any model improvement.

MORECS allows soil moisture extraction to take place until the X and Y reservoirs are emptied. It is unrealistic to experience a completely extraction of the Y reservoir and following cessation of evapotranspiration, and it is suggested that a lower limit is imposed on Y. In physical terms it can looked upon as capillary transport from the groundwater zone.

MORECS estimates the 'hydrological effective rainfall' (HER), as the excess rain after the X and Y reservoirs have been replenished. It is suggested that HER also might include excess rain following a very heavy storm, without X and Y being completely filled. The excess rain is included in calculation of intercepted water, but can not replenish the reservoirs.

6.6 DATA BASE AND DATA QUALITY

Data from two sites are used in this analysis, located in the extreme west and east of Norway. Location is given in Figure 4.1, whereas the basic catchment data are given in Appendix A.1. Catchment 1880, situated in the east, has a high forest percentage and experiences a wide range in evaporation demand during the period of calculation (June to October). Catchment 955, is located on the western coast, and is dominated by a maritime climate with a lower and less variable evaporative demand. A big lake terminates the catchment outlet, and the vegetation is dominated by grassland.

The location of the climatic stations is given in Appendix A.1. The climatic station of catchment 1880, Dønski (no. 1948) is located closer to the catchment than the climatic station of catchment 955, Kråkenes Fyr (no. 5910). Catchment 1880 applies the precipitation observations of the climatic station, whereas the representativitity of the precipitation observation of the climatic station no. 5910 is not acceptable for identifying precipitation free periods in catchment (955). Instead a separate precipitaion station (no. 5945) located within the catchment, is used for this purpose.

Data from two sites are used in a preliminary testing of the AMOR model. These catchment are widely different with respect to climate, surface cover and recession variability. The purpose at this stage, has been to demonstrate the applicability of the model for these widely different environments, and investigate the relationship between evapotranspiration losses and recession variability.

The climatological data were provided by the Norwegian Meteorological Institute.

6.7 RESULTS - MODEL SIMULATIONS

Diurnal values of evapotranspiration are calculated for each type of surface cover using AMOR (Figure 6.1). A catchment average is calculated as the weighted mean with respect to the percentage of each cover type (KOBLE.pas).

AMOR permits calculation of evapotranspiration by several recognized methods apart from the Penman-Monteith formula, see Appendix A.3.2. Four methods for calculating potential evapotranspiration (PE) have been selected in this study, together with one estimate of actual evapotranspiration (AE). AE is calculated by the Penman-Monteith formula (P-Mon AE), with allowance for modifications due to environmental conditions.

The selected formulas for potensial evapotranspiration are the Penman (1948) equation (P-48), Penman-Thom (P-Thom), Penman-Monteith (P-Mon PE) and Priestley-Taylor (Pri-Tay). The Penman-Thom formula refers to the equation by Thom & Oliver (1977). The methods are generally discussed in Section 6.3. The Priestley-Taylor equation is a regional equation, generally not applicable at the local scale. It has only been included for comparison purposes.

The difference in evapotranspiration estimates for catchment 1880 is illustrated in Plate 1. The upper figure presents data for a relative dry period (04.09-23.09 1977), whereas the following wet period (24.09-13.10 1977) is given in the lower figure. The highest evapotranspiration rates are in dry periods normally given by the P-Thom equation, followed closely by P-48. The very high values given by P-48 and P-Thom in the upper figure, covers a period of three days with wind speeds above 5 m/s, which is approximately twice the values the other days. The moderate variation in P-Mon PE & AE estimates during this period, is due to the high forest percentage of the catchment. The low estimates of the regional expression by Pri-Tay can probably be ascribed to the fact that the equation only accounts for the radiation term in the calculations.

The lower figure represents a wet period with low atmospheric demand. The PE estimates are low, and negative values are given by P-48, P-Thom and Pri-Tay. This is due to a negative net radiation. The P-Mon equation for PE represents the potential values for transpiration, which is the value obtained given minimum surface resistance and no SMD. During this wet period the P-Mon PE estimates are close to zero. P-Mon AE estimates can, however, exceed PE in wet days due to high interception losses, as also seen in the figure.

Both catchments are represented by four different cover types. Catchment 1880 is covered by forest (87%), bog (7%) and cultivated land (cereals 5% and grass 1%), whereas catchment 955 includes lake (12%), bog (1%), forest (4%) and the rest term, which is predominantly grassland (83%). Soil class 3 (low soil moisture capacity) is selected for all surface types in both catchments.

The relative difference in P-Mon PE and AE estimates of the different vegetation types is shown in Plate 2 for catchment 1880, and in Plate 3 for catchment 955. The figures also include the P-48 estimates. P-Mon PE estimates of grass and water follow the P-48 values closest. The P-Mon PE estimates of water can be both higher and lower than the P-48 values. The estimated P-Mon PE rates for grass are slightly higher than the P-48 values, whereas P-Mon AE rates may fall below the P-48 values, as seen in Plate 2. The higher P-Mon PE estimates for grass, agrees with the modification introduced in the P-Thom equation.

Forest P-Mon PE estimates are rather low compared with the Penman formula (P-48), as also observed in a study by Roberts (1983). P-Mon AE rates of forest evapotranspiration can exceed grassland and water rates in wet periods due to higher interception losses (Plate 2 and 3). These results correspond with observations reported from similar environments, as discussed in Section 6.2.

Bog is modelled as riparian land, and differs from grass in two aspects. The effective height of the vegetation is for grass assumed constant (0.15 m), whereas the bog has a linear increase in height from 0.15 m to a maximum of 2.0 m for sallow (Appendix A.3.1). The maximum value must be chosen in accordance with the type of bog vegetation. A higher effective height means lower r_a values for bog than grass. The influence of arerodynamic resistance on the evapotranspiration estimates, depends on the relative importance of the radiation and ventilation terms as discussed in Section 6.3. Consequently, it is possible to get both higher and lower evapotranspiration estimates for bog compared with grass, despite the larger r_s values for bog. Values for cultivated land will experience a similar variation.

Prior to the periods plotted in Plate 2 and 3, catchment 1880 experiences a soil moisture deficit of 40 % for the forested area, whereas catchment 955 is nearly saturated. Below a deficit of 40 % the soil water is no longer freely available. Consequently, P-Mon AE is noticeable lower than P-Mon PE for catchment 1880 during the dry part of the period, whereas small differences are found for catchment 955.

6.8 RECESSION VARIABILITY AND EVAPOTRANSPIRATION ESTIMATES

The catchment average rate of evapotranspiration is calculated as the weighted mean of each cover type in the catchment. An example of the resultant output file is given in Appendix A.3.2. Evapotranspiration is calculated by the

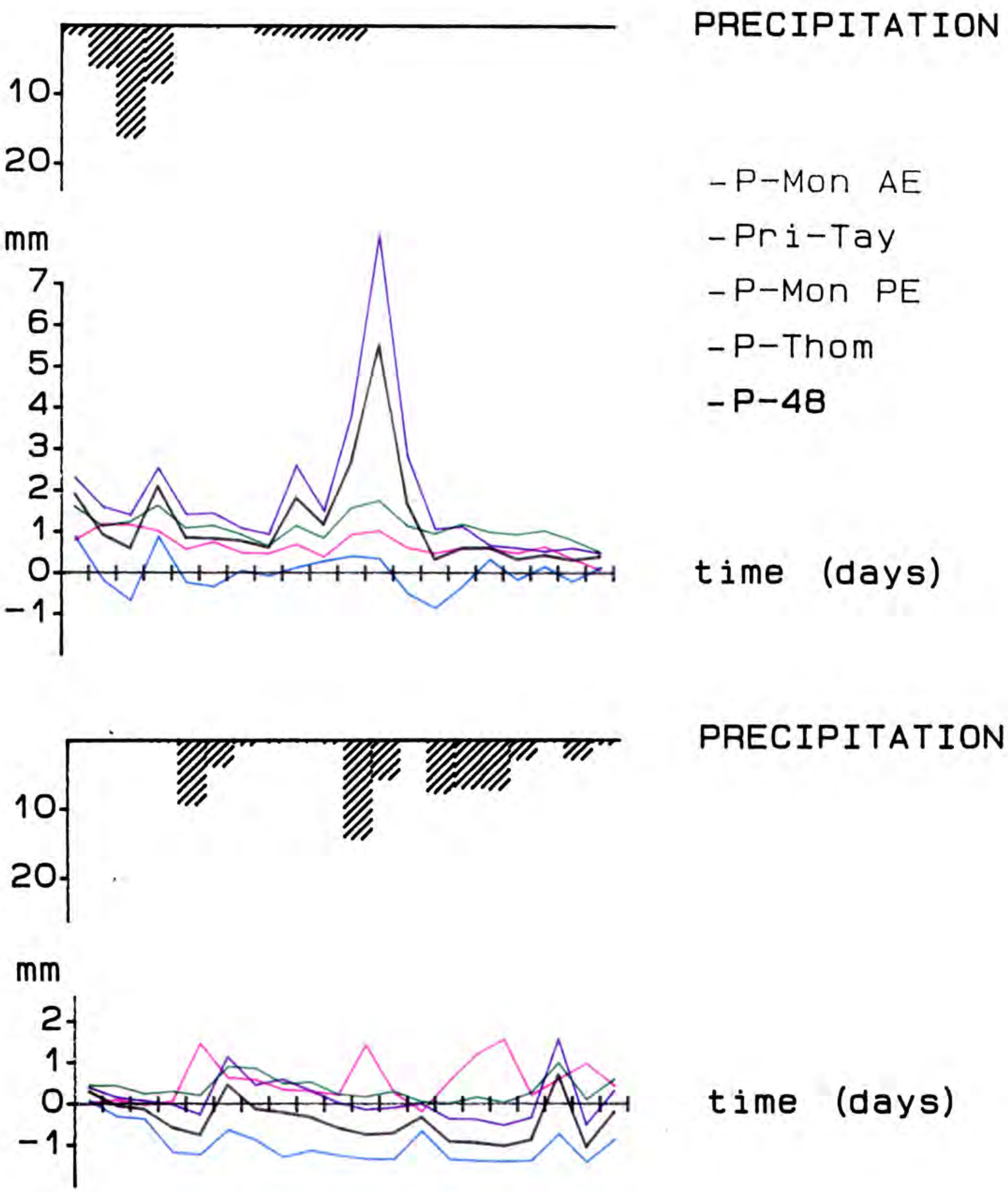


Plate 1

Various evapotranspiration estimates, calculated by different methods, for catchment 1880 in the period 04.09 to 23.09 1977 (upper figure) and from 24.09 to 13.10 1977 (lower figure).

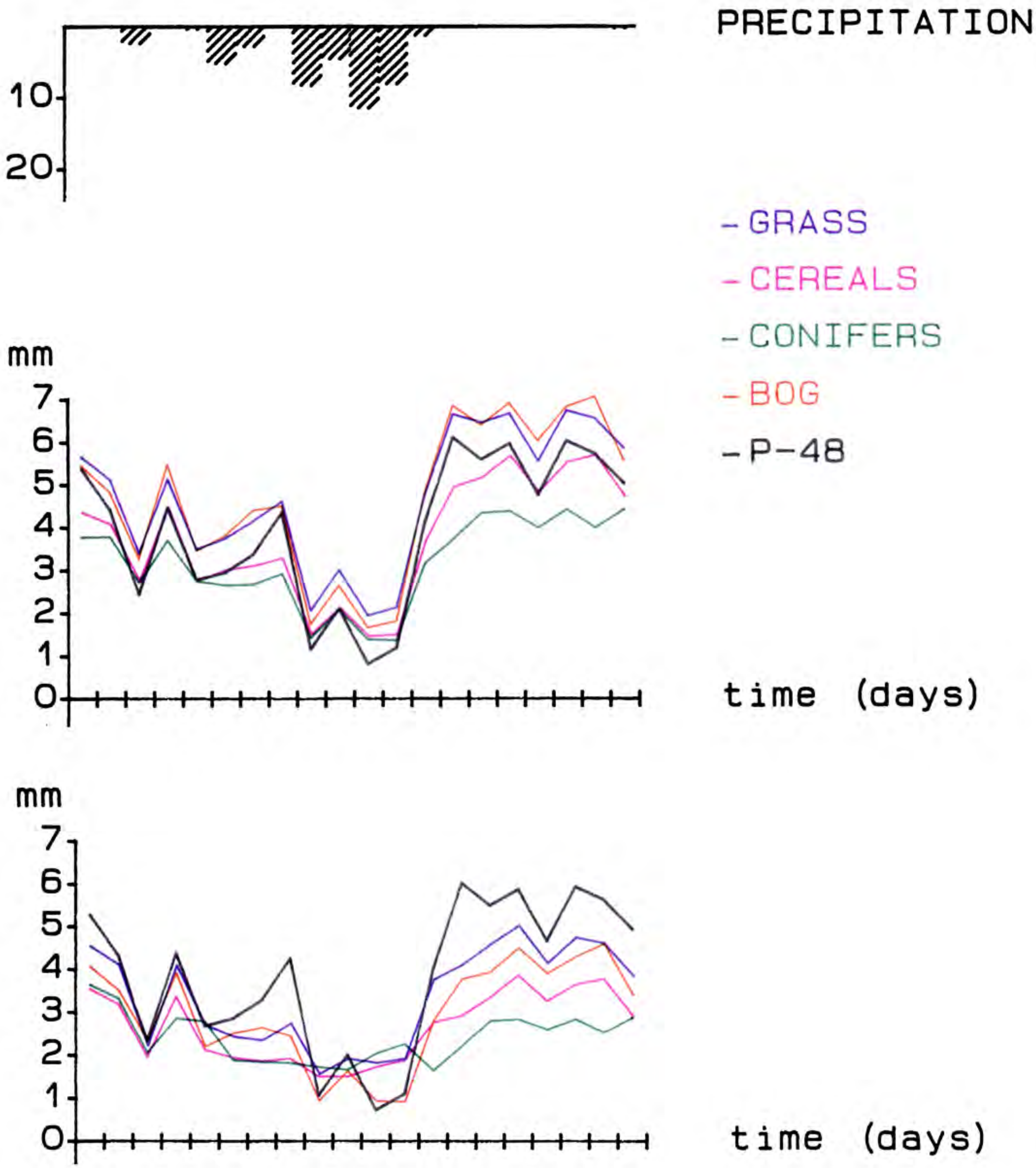


Plate 2

Penman-Monteith potential (upper figure) and actual (lower figure) evapotranspiration estimates of different vegetation types in catchment 1880.

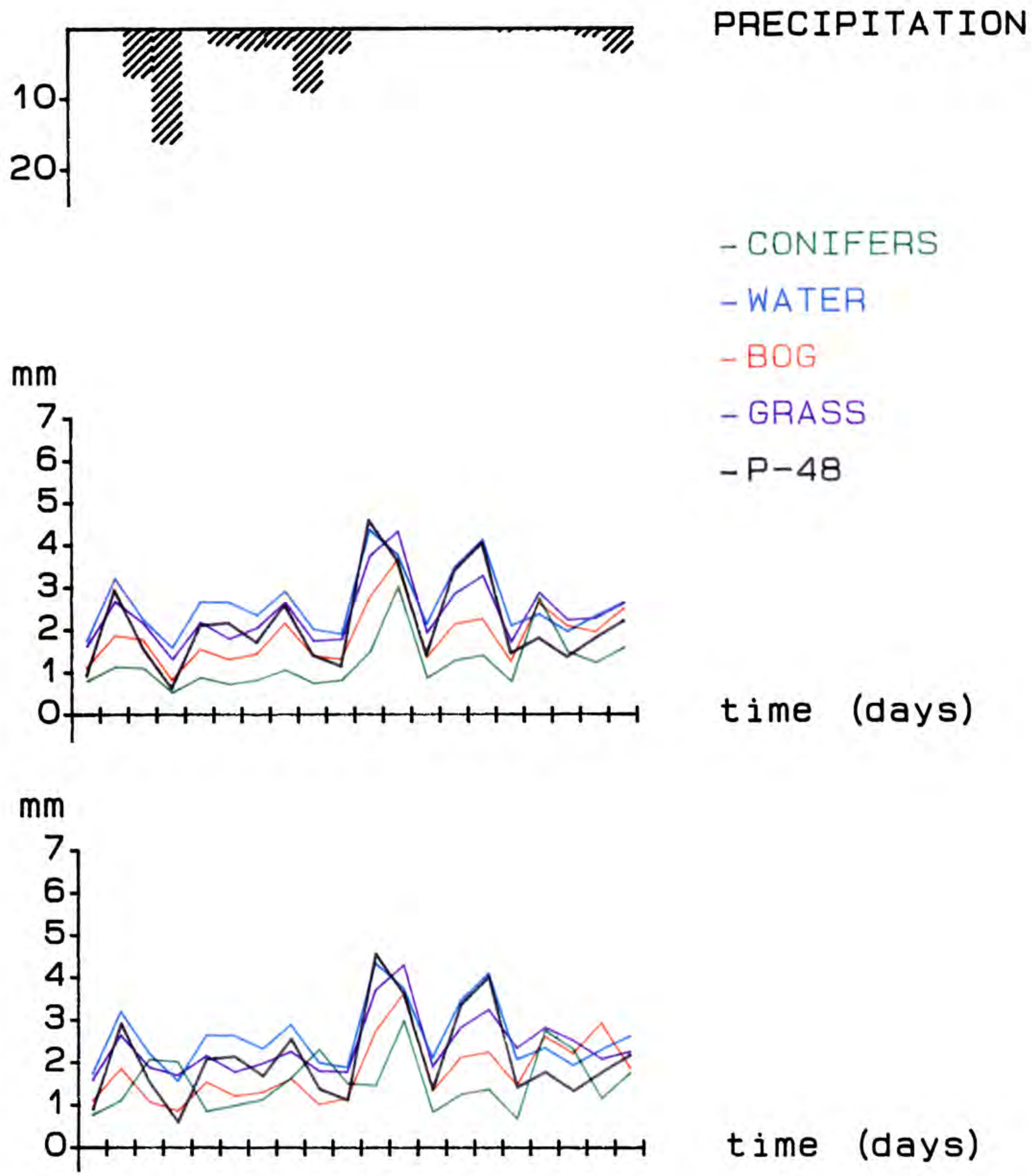


Plate 3

Penman-Monteith potential (upper figure) and actual (lower figure) evapotranspiration estimates of different vegetation types in catchment 955.

five different methods referred in the last section.

The evapotranspiration output file is linked with the recession programme output using Link.pas (Figure 6.1). The recession output consists of the observed daily discharges of the selected recession segments, along with the calculated recession constant, C. The recession segments are selected from the transformed series, as recommended in Section 4.7, and the recession constant calculated according to the method introduced in this study.

The evapotranspiration estimates are averaged for each recession segment, and a statistical analysis of the correlation between the recession constant, C, and the evapotranspiration values performed. The analysis has not considered any delay in the response time between evapotranspiration losses and discharge values. The caclulations are repeated with a precipitation limit of 1.0 mm per day, and the results are presented in Table 6.1 and 6.2. The four PE estimates included are P-48 (PE1), P-Thom (PE2), P-Mon PE (PE3) and Pri-Tay (PE4), and AE is estimated by P-Mon AE.

This analysis is similar to the statistical analysis of recession variability presented in Chapter 4, where average temperature during the period was correlated with the recession constant (Table 4.3 and 4.4). Number of segments is reduced when evapotranspiration calculations are included, due to shorter common series of the climatic variables. Table 6.1 and 6.2 reflect the same trends as found for temperature, with high correlations for catchment 1880 and low for 955.

A second set of values is given for catchment 1880, labelled 1880*, where SOIL CLASS is changed from class 3 of low, to class 1 of high soil water capacity. The change of soil class implies for conifers, a change in soil moisture capacity from 131 to 219 mm.

The high correlations for catchment 1880 are primarily related to a marked seasonal variation in evaporative demand. Both temperature and evapotranspiration estimates will satisfactory reflect this variation, and there is no significant difference between the set of correlation figures, apart from a slightly lower correlation for AE in case of the lowest starting level of recession. Due to model limitations in general, it is not realistic to expect a much higher degree of explained variance than found for temperature alone.

Table 6.1 Correlation coefficients between the recession constant C, and precipitation (prec), starting day (std), four estimates of potensial (PE) and one of actual evapotranspiration (AE).

CATCHM. (period)	QUL= %ADF	no	prec	std	PE1	PE2	PE3	PE4	AE
		TRANSFORMED SERIES							
955 (68-84)	100	23	.45	.31	-.32	-.20	-.32	.03	-.26
	75	22	-.02	-.11	-.29	-.41	-.23	-.10	-.25
	50	25	-.26	-.18	-.03	-.11	-.07	.09	-.04
	30	13	-.07	-.28	-.14	-.16	-.26	-.14	-.14
	20	8	.38	-.47	-.20	-.36	-.30	.01	-.14
1880 (57-72)	100	19	-.26	.73**	-.83**	-.84**	-.81**	-.77**	-.74**
	75	16	-.32	.73**	-.83**	-.84**	-.79**	-.77**	-.74**
	50	16	-.26	.73**	-.79**	-.78**	-.75**	-.77**	-.67*
	30	12	.02	.49	-.69*	-.72*	-.64	-.62	-.52
	20	7	-.02	.29	-.71	-.72	-.66	-.68	-.30
1880* (57-72)	100	19							-.77**
	75	16							-.75**
	50	16							-.77**
	30	12							-.72*
	20	7							-.65

Table 6.2 Correlation coefficients between the recession constant C, and precipitation (prec), starting day (std), four estimates of potensial (PE) and one of actual evapotranspiration (AE). Precipitation limit of 1.0 mm per day.

CATCHM. (period)	QUL= %ADF	no	prec	std	PE1	PE2	PE3	PE4	AE
		TRANSFORMED SERIES							
955 (68-84)	100	5	-.16	-.80	.79	.81	.80	.68	.83
	75	8	.28	-.47	-.47	-.66	-.48	-.08	-.49
	50	8	-.11	-.63	-.10	-.41	-.02	.29	-.04
	30	6	.49	-.04	-.34	-.57	-.55	-.24	-.53
	20	4							
1880 (57-72)	100	7	-.47	.56	-.74	-.76	-.70	-.65	-.65
	75	5	-.26	.91	-.94*	-.94*	-.86	-.93*	-.86
	50	7	-.14	.84*	-.84*	-.83	-.83	-.85*	-.77
	30	7	-.10	.60	-.79	-.80	-.78	-.79	-.70
	20	4							
1880* (57-72)	100	7							-.58
	75	5							-.88
	50	7							-.85*
	30	7							-.86*
	20	4							

Calder (1977) found in a study of evapotranspiration from a spruce forest that it was not necessary to invoke a soil moisture dependence even for SMD in access of 100 mm. For conifers with low and high soil moisture capacity, AMOR simulates a soil moisture dependence at a deficit of 52 and 88 mm deficit, respectively.

A minor increase in correlations figures are found for catchment 1880*, particularly for the lowest starting levels. This suggests that the soil moisture capacity of the original model is set too low or that allowance of groundwater evaporation through capillary transport is not considered. Consequently, model estimates of evapotranspiration will be too low to influence the lowest discharge rate.

The correlation figures for catchment 1880 demonstrate the influence of evapotranspiration on the recession rate, and evidently water is lost through evapotranspiration that otherwise would become streamflow, at all levels of flow in this catchment. This suggests a shallow groundwater table, as also observed in the catchment (Erichsen & Myrabø, 1990), where an upward transport from the groundwater is possible due to capillary rise. Johansson (1987) estimated that capillary transport could account for more than 30 mm during single years in a sandy till area in Sweden.

Plate 2 shows typical summer evapotranspiration rates for catchment 1880. AE is in the range of 2-4 mm, whereas values of about 0.5-1.0 mm are estimated in autumn. Similar values were observed by Federer (1973) in a study of forest transpiration in New Hampshire, USA. The magnitude of the P-Mon AE estimates is for catchment 1880 two or three times the discharge value in the summer low flow periods, and not in the range of error of discharge measurements.

The recession variability in catchment 955 can not be related to the evapotranspiration estimates. Similar low correlations were found for temperature, and it was not possible to improve the correlation by introducing more advanced calculations of evapotranspiration. The seasonal variation in evaporative demand is low in this area, and it is suggested that this may explain the low recession variability and corresponding low correlations with evapotranspiration, observed in the catchment. The recession variability is governed by other factors than evapotranspiration (Section 2.5).

In order to evaluate the success of the evapotranspiration estimates of AMOR, the model calculations have to be verified against soil moisture measurements, or discharge measurements, providing AMOR is extended to a complete rainfall-runoff model. This is the aim of a continuing project, presented in Section 7.2.

6.9 CONCLUSIONS

The main objectives of this chapter was to arrive at a evapotranspiration model which considers vegetation and soil properties in the calculations, and to investigate the relationship between recession variability and evapotranspiration losses.

Based on a general review of evapotranspiration principles and modelling concepts, it is concluded that the Penman-Monteith equation for calculating evapotranspiration provides the most promising formula. It was required that the selected model for calculating evapotranspiration was based on this equation and could operate on standard climatological observations.

The soil water balance model MORECS, which originates from the Meteorological Office in Great Britain, was chosen for this study. It is based on the Penman-Monteith equation for calculating evapotranspiration and accounts for vegetation and soil properties in the calculations. A modified version, AMOR, which operates on standard meteorological data in Norway, has been developed in this study.

AMOR permits evapotranspiration to be estimated from the routine observations of temperature, precipitation, wind, humidity and cloudiness. Evapotranspiration is estimated for each type of vegetation, and a catchment average calculated as the weighted mean. The model is tested on two catchments, and the model's estimates of evapotranspiration rates for different cover types correspond well with observations reported from similar environments.

Data from two sites are used in a preliminary testing of the AMOR model. These catchment are widely different with respect to climate, surface cover and recession variability. The purpose at this stage, has been to demonstrate the applicability of the model for these widely different environments, and investigate the relationship between evapotranspiration losses and recession variability.

The influence of evapotranspiration on the recession rate, is investigated through a correlation analysis of evapotranspiration estimates and recession variability. High correlations are found for catchment 1880, which is forested and located in eastern Norway. This is primarily related to a marked seasonal variation in evaporative demand. The evapotranspiration estimates as well as average temperature, reflect this variation satisfactory, and there is no significant difference between the correlation figures.

A minor increase in correlations is found for catchment 1880 if higher soil moisture capacity is selected, particularly for the lowest starting levels. This suggests that the soil moisture capacity of the original model is set too low, or that allowance of groundwater evaporation through capillary transport is not considered. Consequently, model estimates of evapotranspiration will be too low to influence the lowest discharge rate.

The influence of evapotranspiration on the recession rate is demonstrated by catchment 1880. Evidently water is lost through evapotranspiration that otherwise would become streamflow at all levels of flow in this catchment. This suggests a shallow groundwater table, as also found in this catchment, where an upward transport from the groundwater is possible due to capillary forces.

The recession variability of catchment 955, which is located on the west coast, can not be related to evapotranspiration losses. Similar low correlations were found for temperature, and it is not possible to improve the correlation by introducing more advanced calculations of evapotranspiration. The seasonal variation in evaporative demand is low for this catchment, and it is suggested that this can explain the low recession variability and corresponding low correlations with evapotranspiration, observed in the catchment. The recession variability is governed by other factors than evapotranspiration.

In order to evaluate the success of the evapotranspiration estimates of AMOR, the model calculations have to be verified against soil moisture measurements, or discharge measurements, providing AMOR is extended to a complete rainfall runoff model. An important application of the model will be to evaluate the effect of land use and climatic change on the flow regime.

A final conclusion of this analysis, is that the soil water balance approach provides a promising method for estimating evapotranspiration based on routinely observed climatic data. An objective of future investigations is to prove the general applicability of the AMOR model. This matter is further discussed in Section 7.2, Suggestions for further research.

CHAPTER 7

MAIN CONCLUSIONS AND SUGGESTIONS FOR FURTHER RESEARCH

7.1 MAIN CONCLUSIONS

This thesis has studied recession rate and variability in in general, and the relationship between time variability in recessions and evapotranspiration losses in particular.

Recession analysis generally suffers from the fact that no satisfactory definition of a catchment characteristic recession exists. This is mainly due to the high time variability found in recessions. The result is a lack of consistency in obtaining recession characteristics, which has limited a wider use. The first chapters address these issuses, and presents a new, automatic method for calculating recession characteristics. The recession rate and variability are studied both on the catchment and regional scale.

The last chapter aims to quantify the water lost by evapotranspiration and thereby be able to evaluate its influence on the recession rate. The quantification of evapotranspiration losses is a problem relating to the use of several hydrological tools, i.e. groundwater models, stream forecasting and rainfall-runoff models.

7.1.1 Recession rate and variability

In order to calculate a recession constant which is representative for catchment storage capacity, it is essential to have quantitative knowledge about the main factors influencing the recession variability. In catchments without human impacts the variation is either due to natural fluctuations or model limitations. In order to limit the influence of the latter, a standard recession is suggested, where both initial discharge and recession length are constants.

An automatic method is developed for obtaining a characteristic recession and to estimate its recession parameters. The recession rate is quantified by the recession mean value, calculated as the arithmetic mean of the recession constants C, of individual segments. To each segment the simple exponential equation is fitted and the recession constant calculated. The recession variability is represented by the coefficient of variation of the sample of segments.

The low flow data are frequently recorded in a staircase manner, due to low accuracy in discharge measurements. In the transformed series steps in the discharge series are modified, and the recession analysis is carried out for both observed and transformed series. There is a general increase in mean values as starting levels decreases, indicating that the recession flow does not follow a simple exponential decay curve.

In the regional analysis of recession behaviour, the recession mean value is found to be highly correlated with low flow statistics. The mean value represents average catchment conditions, and the adoption of a constant is shown to be useful in regional analysis. Earlier works, including this study, often show that the recession characteristics are inadequately described by the indicies available. The most important characteristics found to affect the recession rate are related to geology, relief and climate. In order to improve the accuracy of the estimation equations for the recession constant, it is essential that an index of geology exists. This requiers that relevant geology maps, including rock, drift and soil materials, are available on a national basis.

As a first step to link the recession variability to climatic influence, a statistical analysis of the correlation between the recession constant C, and precipitation and temperature is performed. Average values of temperature and total precipitation during the recession period are included. The correlation with recorded precipitation during the recession period is generally low. The influence of evapotranspiration on recession variability is indicated by the relationships found between recession variance and temperature.

Temperature show significantly higher correlation coefficients with C-mean than found in Part III. Still, there is a large scatter in the correlation figures, probably due to differences in climate and catchment characteristics. The influence of temperature is most noticeable for the four forested catchments situated in eastern Norway, and is evident for even the lowest starting level. This might be a result of a shallow groundwater table, which favour capillary transport from the groundwater zone subsequent to the water lost by evapotranspiration.

The recession calculation procedure is applied on HBV simulated series, and the recession distribution from the observed series compared with the distribution from the simulated series. The simulated series do to some extent, reproduce the recession variability in the observed series. However, there is a fundamental difference in the origin of the variabilities.

The major cause of variability in the simulated series is due to the transition effect between the different drainage coefficients of the upper and lower zone in the HBV model. The difference in magnitude between these coefficients determines to a large extent the variability pattern. Precipitation and temperature are to a much lesser extent than in the observed series, responsible for the variability, and their effect is only measurable if the transition effect is negligible.

Generally, low flow modelling needs more attention. Improved simulations can be obtained through a better model structure, or simply by an increased emphasis upon the optimization of low flow related parameters. Recession analysis is a valuable tool when verifying a model's low flow performance, and guide the choice of parameters before and during the calibration process.

7.1.2 Recession variability and evapotranspiration losses

The influence of evapotranspiration on recession variability is in the first part of this study indicated by the relationship found between recession variance and temperature. In order to quantify the water lost by evapotranspiration, an appropriate model for application on a local scale was required. The model has to account for the effect of vegetation and soil properties in the calculations of evapotranspiration, and at the same time be applicable for use in areas with normal data coverage.

There was no model available in Norway for this purpose. However, the MORECS model, which originates from the Meteorological Office in Great Britain, had been adjusted for use at automatic weather stations in Norway by S. Lystad at the Norwegian Meteorological Institute. This model constituted the basis for this study, which has adjusted the model to operate on data routinely observed at climatic stations in Norway. The model work has been done in cooperation with S. Lystad.

The modified version, AMOR, permits evapotranspiration to be estimated from the routine observations of temperature, precipitation, wind, humidity and cloudiness. Evapotranspiration is estimated for each type of surface cover, and a catchment average calculated as the weighted mean. The model's estimates of evapotranspiration rates for different cover types and their relative differences, correspond well with observations reported from similar environments.

Data from two sites are used in a preliminary testing of the AMOR model. These catchment are widely different with respect to climate, surface cover and recession variability. The purpose at this stage, has been to demonstrate the applicability of the model for these widely different environments, and to investigate the relationship between evapotranspiration losses and recession variability.

The influence of evapotranspiration on the recession rate, is investigated through a correlation analysis of evapotranspiration estimates and recession variability. High correlations are found for catchment 1880, which is forested and located in eastern Norway. This is primarily related to a marked seasonal variation in evaporative demand. The evapotranspiration estimates as well as average temperature, reflect this variation satisfactory, and there is no significant difference between the correlation figures.

A minor increase in correlations is found for catchment 1880 if higher soil moisture capacity is selected, particularly for the lowest starting levels of recession. This suggests that the soil moisture capacity of the original model is set too low, or that allowance of groundwater evaporation through capillary transport is not considered. Consequently, model estimates of evapotranspiration will be too low to influence the lowest discharge rates.

The influence of evapotranspiration on the recession rate is demonstrated by catchment 1880. Evidently, water is lost through evapotranspiration that otherwise would become streamflow at all levels of flow in this catchment. This suggests a shallow groundwater table, as also found in this catchment, where an upward transport from the groundwater is possible due to capillary forces.

The recession variability of catchment 955, located on the west coast, can not be related to evapotranspiration losses. Similar low correlations are found for temperature, and it was not possible to improve the correlations by introducing more advanced calculations of evapotranspiration. The seasonal variation in evaporative demand is low for this catchment, and it is suggested that this might explain the low recession variability and corresponding low correlation with evapotranspiration, observed in the catchment. The recession variability is dominated by other factors than evapotranspiration.

In order to evaluate the success of the evapotranspiration estimates of AMOR, the model calculations have to be verified against soil moisture measurements, or discharge measurements, providing AMOR is extended to a complete rainfall runoff model. An important application of the model will be to evaluate the effect of land use and climatic change on the flow regime.

It is concluded that the soil water balance approach provides a promising method for estimating evapotranspiration based on routinely observed climatic data. An objective of future investigations is to prove the general applicability of the AMOR model. This matter is further discussed in the next section.

7.2 SUGGESTIONS FOR FURTHER RESEARCH

The recession calculation procedure presented in this study holds substansial promise both for use at the local and regional scale. At the regional scale the recession mean value adequately represents the average catchment conditions. Further research should concentrate on developing satisfactory relationship between catchment and recession characteristics to permit estimation at ungauged locations. The success depends on mapping and hydrological classification of the geology, including rock, drift and soil materials.

At the local (catchment) scale, the knowledge of natural factors influencing the recession variability, will permit the recession constant to be estimated with higher accuracy. This is valueable for regional analysis, as well as for low flow forecasting at the catchment scale. This study has looked at the influence of climatic factors, precipitation and evapotranspiration during the recession phase, and has demonstated the need for incorporating these factors in recession analysis. Further research should include a larger data set, and investigate possible ways of quantitatively incorporating these factors in low flow forecasting.

This thesis introduces the AMOR model for calculating evapotranspiration using data from automatic weather or climatic stations. Limited data are available on evapotranspiration rates from the widely different natural environments that exist in Norway. This model could be a valuable tool in a regional study of evapotranspiration rates in Norway. However, the model needs further testing and verification. The model calculations can be verified against soil moisture or discharge measurements, the latter preferable by extending AMOR to a complete rainfall runoff model.

Some improvements in the AMOR structure are suggested in Chapter 6, whereas a present research project working with verification and testing of AMOR is presented below.

In the project 'Spatial distribution of meteorological and hydrological variables' AMOR calculations will be verified against soil moisture as well as discharge measurements. The project contributes the international FRIEND (Flow Regimes from International Experimental and Network Data) project 2, Low flows. The FRIEND research programme is a contributor to the United Nations International Hydrological Programme (IHP) IV.

In order to study both the spatial and temporal variability in the water balance elements of AMOR, a digital terrain model is applied on catchment 1880, Sæternbekken (5.8 km^2), located in eastern Norway. Grid size is 100*100 meters. Several subcatchments are identified within the area. Each subcatchment is homogeneous in terms of vegetation, soil properties, gradient and exposition.

Groundwater level and soil water deficits will be measured at selected points within the subcatchments. Different interpolation routines for the variables temperature, precipitation and global radiation will be tested, and one value assigned to each grid cell.

The water budget for each subcatchment is calculated using AMOR, which accounts for soil moisture variations, but does not model runoff. For the subcatchments discharge is simply estimated from the water balance equation, and the AMOR model evaluated against discharge and soil moisture deficit measurements. The relationships between depth of water table, soil properties, vegetation and evapotranspiration rates will be investigated. Important features of the study are relationships between topography/vegetation and the water balance elements.

For the main catchment, Sæternbekken, the AMOR model will be extended to a complete rainfall-runoff model, by linking the evapotranspiration algorithms of AMOR with the soil moisture routines of the HBV model. The results from the detailed study of subcatchments will guide this work. The linked HBV model will be evaluated against the original HBV in a comparative study. This work is done in cooperation with the Norwegian Water Resources and Energy Adminstration (NVE).

The linked HBV model will also be evaluated for use at a regional scale, by applying it for different physiographic and climatic conditions. Selected catchments from the FRIEND data base will be included in the study. A joint project in the Friend group 2 (low flows) will study the effect of land use and climate change on the low flow regime, and compare low flow indices simulated using different rainfall-runoff models.

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APPENDIX

TABLE OF APPENDIX CONTENTS

A. APPENDIX TEXT

A.1 CATCHMENT DATA

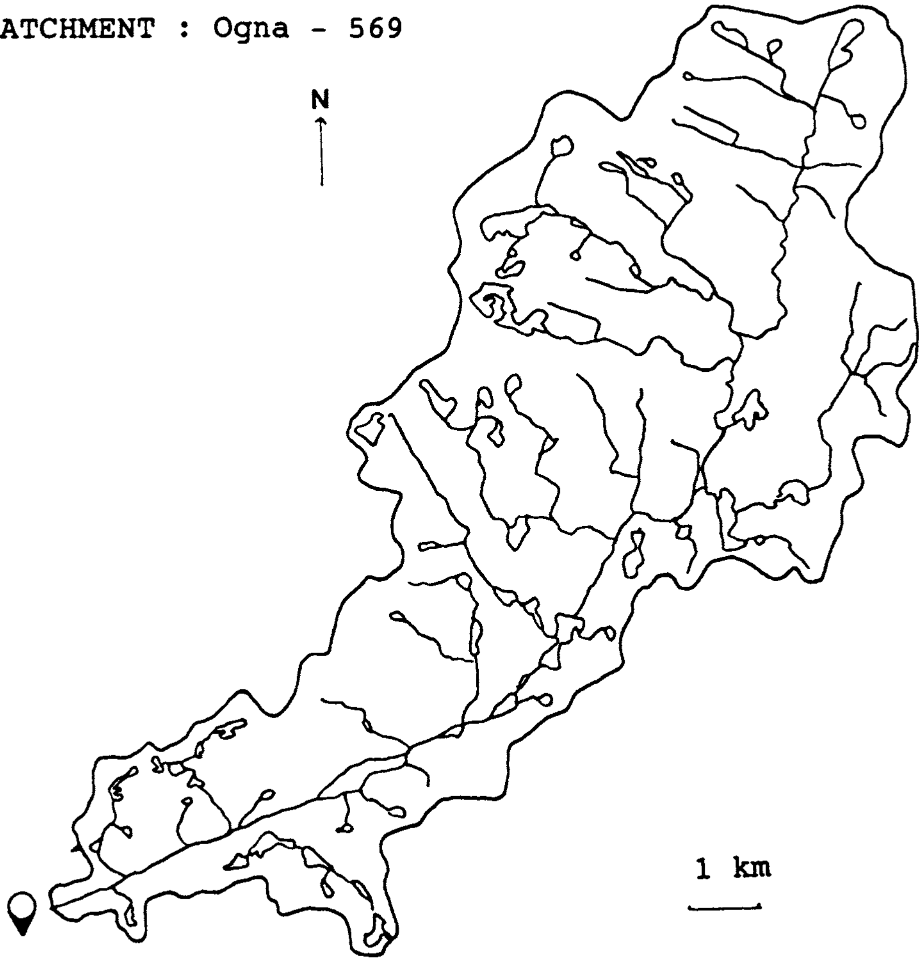
Selected catchment, flow and climatic characteristics are presented for each catchment, along with outline of drainage area and location of related gauging stations. Climatic stations and data are not presented for catchment 569 and 917, due to the lack of representative stations. A summary of chararactericties along with method of calculation and abbrevations is given below. Selected data have been provided by Erichsen (1989), Moltzau (1990) and Bønsnes, pers. comm. (1990).

Characteristics	**Method of calculation**
AREA	Catchment area obtained by planimetering on a 1:50 000 scale map (km^2).
ADF	Average daily flow ($l/s\ km^2$).
ALT	Altitude range, calculated as the maximum range in altitude (m).
BFI	The Base Flow Index - a measure of the proportion of baseflow under the flow hydrograph.
BOG	The proportion of catchment area with bog (%).
CULT	The proportion of catchment area with cultivated land (%).
C-mean,P	Recession constant - calculated as the mean of individual recession segments, precipitation included.
C-mean	Recession constant - calculated as the mean of individual recession segments, precipitation free periods.
FOREST	The proportion of catchment area with forest (%).
LAKE	The proportion of catchment area with lake (%).
RELIEF	Relief ratio: H/L_a, where H is maximum range in altitude and L_a is length of main stream (m/km).
REST	The proportion of the catchment not covered with BOG, CULT, FOREST or LAKE (%).
SAAR	Standard (1930-1960) annual average precipitation (mm).
SOIL CLASS	Equivalent to the soil classes in MORECS where soils of low (3), medium (2) and high (1) water capacity are defined.

Abbrevations

MAP	M711 map number for the location of the gauging station.
mas.	meter above sea level.
Common period	The common period of discharge, precipitation and climate measurements.
Summer period	Months without frost, defined in terms of daynumber.

CATCHMENT : Ogna - 569 MAP : 1212 III

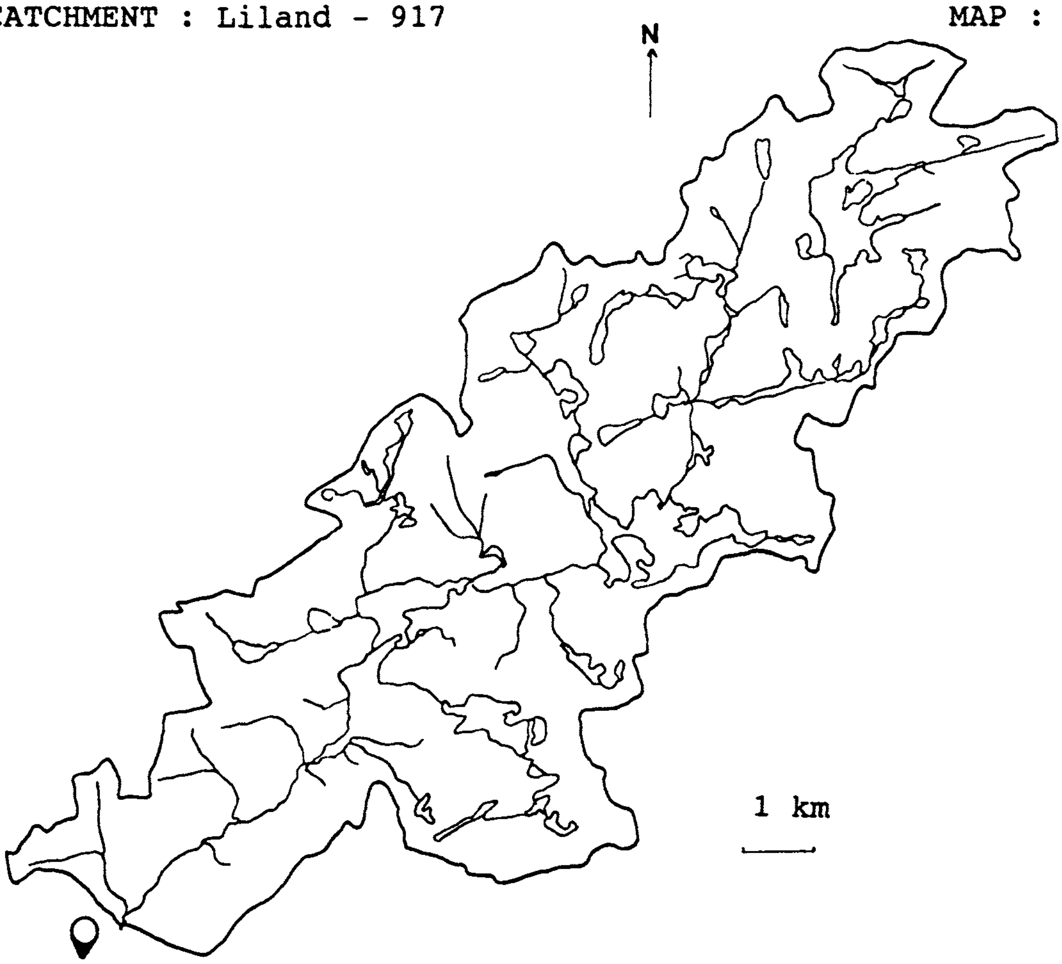


GAUGING STATIONS:	Site no.	mas.	Period
⚲ Discharge station	569-0	10	1940-83
Y Precipitation station			
⌂ Climate station			
Common period			
Summer period			152-305

CATCHMENT CHARACTERISTICS		
AREA	:	70.0 km^2
ALT	:	10-561 mas.
RELIEF	:	30 m/km
LAKE	:	8 %
BOG	:	7 %
CULT	:	-
FOREST	:	2 % ; Conifers
REST	:	83 % ; Includes cultivated land
SOIL CLASS	:	- ; Mainly thin cover of till

FLOW/CLIMATE CHARACTERISTICS		
ADF	:	1743 mm (55.3 l/skm^2)
SAAR	:	
BFI	:	0.29
C-mean,P	:	6.5 (75 %, 7d)
C-mean	:	

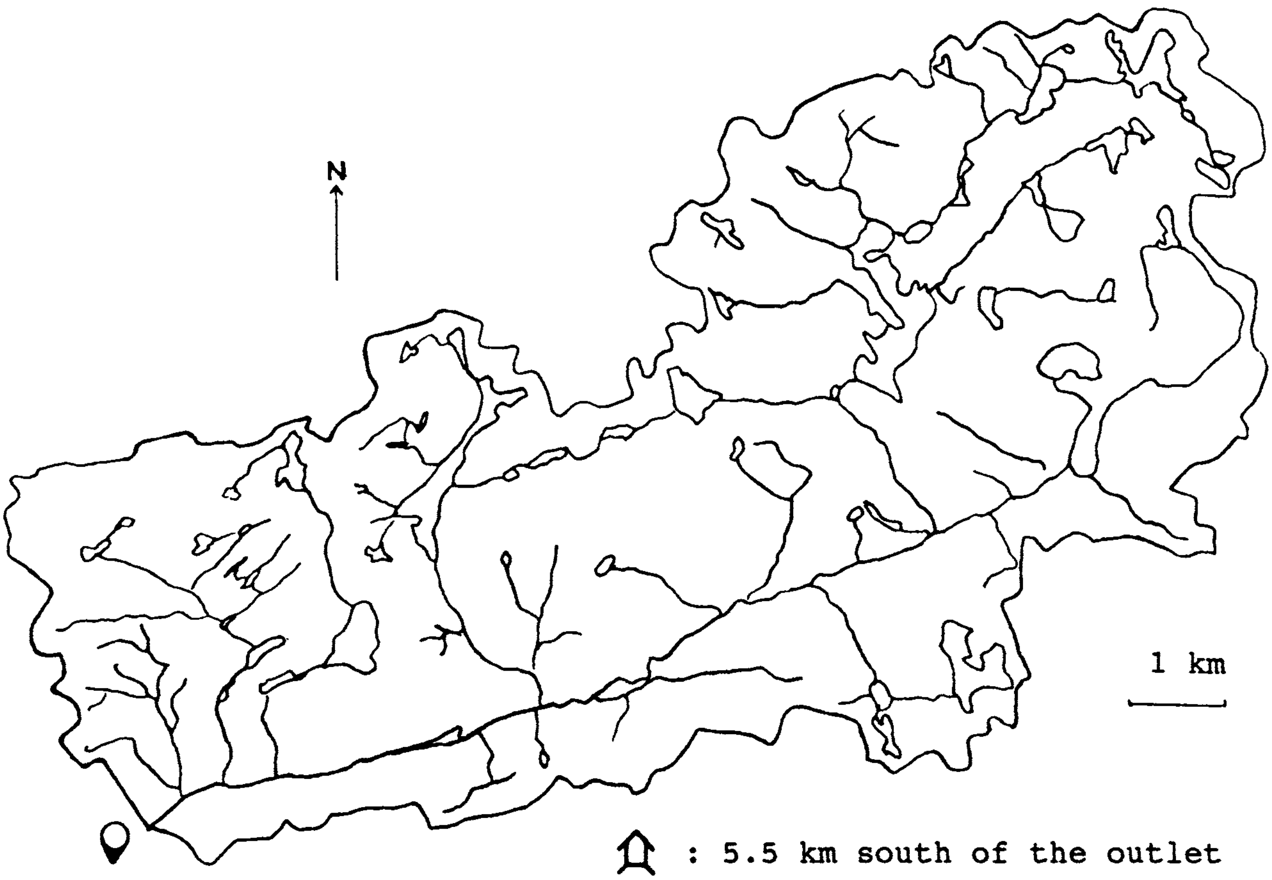
CATCHMENT : Liland - 917 MAP : 1312 II



GAUGING STATIONS:	Site no.	mas.	Period
Discharge station	917-0	330	1940-70
Precipitation station			
Climate station			
Common period			
Summer period			182-305

CATCHMENT CHARACTERISTICS			FLOW/CLIMATE CHARACTERISTICS	
AREA	: 72.0 km^2		ADF	: 1734 mm (55.0 l/skm^2)
ALT	: 330-984 mas.		SAAR	:
RELIEF	: 34 m/km		BFI	: 0.43
LAKE	: 13 %		C-mean,P	: 6.9 (75 %, 7d)
BOG	: 3 %		C-mean	:
CULT	: 0 %			
FOREST	: 10 %	; Deciduous trees		
REST	: 74 %	;		
SOIL CLASS	: -	; Mainly thin cover of till		

CATCHMENT : Hellelandselv - 919 MAP : 1312 III



(climate station symbol) : 5.5 km south of the outlet

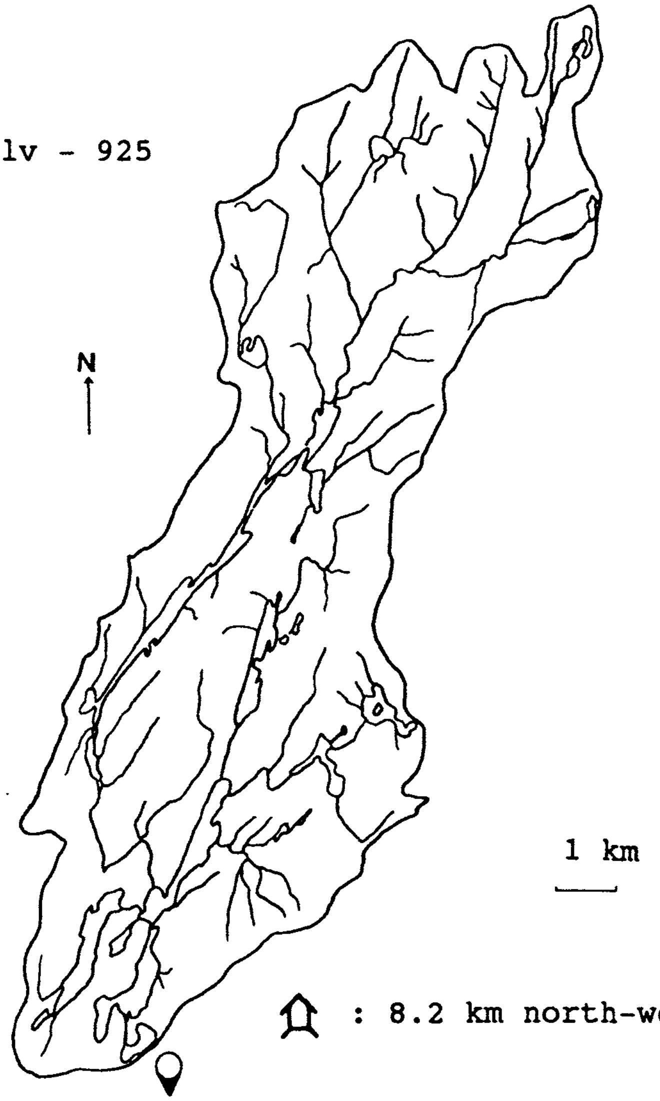
GAUGING STATIONS:	Site no.	mas.	Period
⚲ Discharge station	919-0	200	1940-84
Y Precipitation station	4350	196	1968-84
⌂ Climate station	4350	196	1968-84
Common period			1968-84
Summer period			182-305

CATCHMENT CHARACTERISTICS		
AREA	: 62.0 km^2	
ALT	: 175-906 mas.	
RELIEF	: 53 m/km	
LAKE	: 8 %	
BOG	: 5 %	
CULT	: -	
FOREST	: 32 %	; Deciduous trees
REST	: 55 %	; Includes cultivated land
SOIL CLASS	: -	; Mainly thin cover of till

FLOW/CLIMATE CHARACTERISTICS	
ADF	: 2655 mm (84.2 l/skm^2)
SAAR	: 2136 mm
BFI	: 0.25
C-mean,P	: 4.7 (75 %, 7d)
C-mean	: 4.7 (75 %, 7d)

CATCHMENT : Oselv - 925

MAP : 1115 II



⌂ : 8.2 km north-west of the outlet

GAUGING STATIONS:	Site no.	mas.	Period
♀ Discharge station	925-0	53	1940-86
Y Precipitation station	5046	50	1957-72
⌂ Climate station	5046	50	1957-72
Common period			1957-72
Summer period			152-305

CATCHMENT CHARACTERISTICS

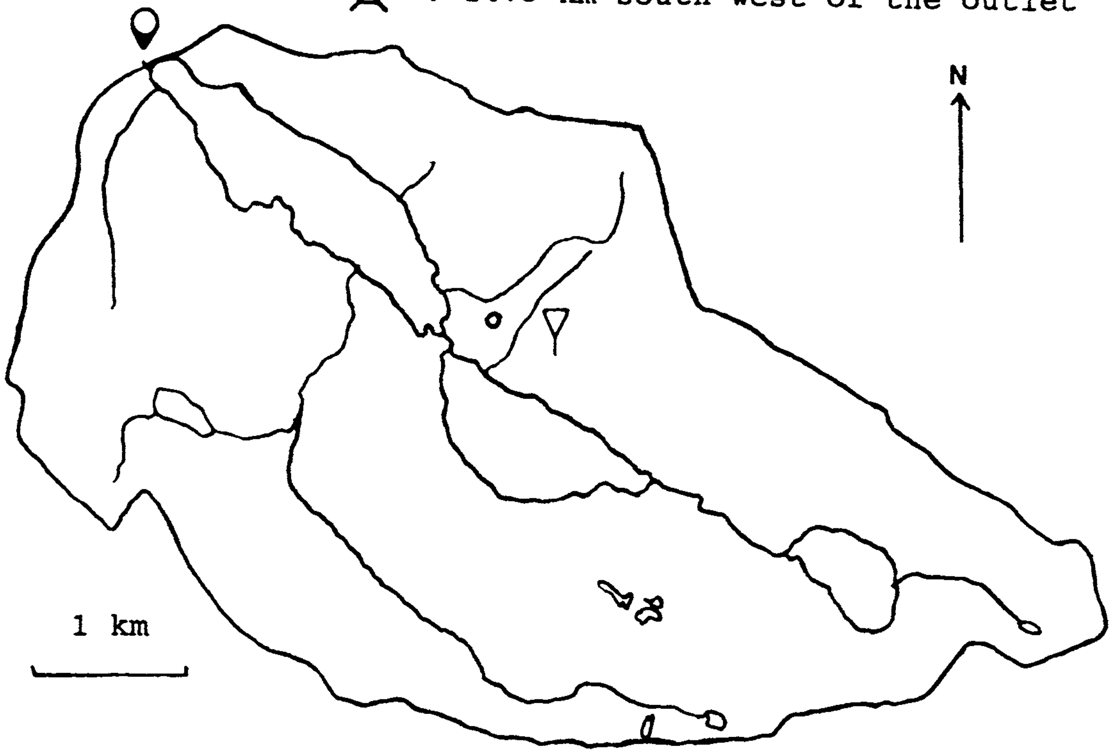
AREA	:	47.0 km^2	
ALT	:	53-962 mas.	
RELIEF	:	55 m/km	
LAKE	:	3 %	
BOG	:	2 %	
CULT	:	6 %	
FOREST	:	53 %	; Mixed forest
REST	:	36 %	;
SOIL CLASS	:	-	; Mainly till and weathering material

FLOW/CLIMATE CHARACTERISTICS

ADF	:	3179 mm (100.8 l/skm^2)
SAAR	:	1975 mm
BFI	:	0.21
C-mean,P	:	5.0 (75 %, 7d)
C-mean	:	4.5 (75 %, 7d)

CATCHMENT : Dalsbøvatn - 955 MAP : 1019 II

Climate station symbol : 14.5 km south-west of the outlet



GAUGING STATIONS:	Site no.	mas.	Period
Discharge station	955-0	47	1940-86
Precipitation station	5945	75	1957-86
Climate station	5910	38	1924-DD
Common period			1957-86
Summer period			152-305

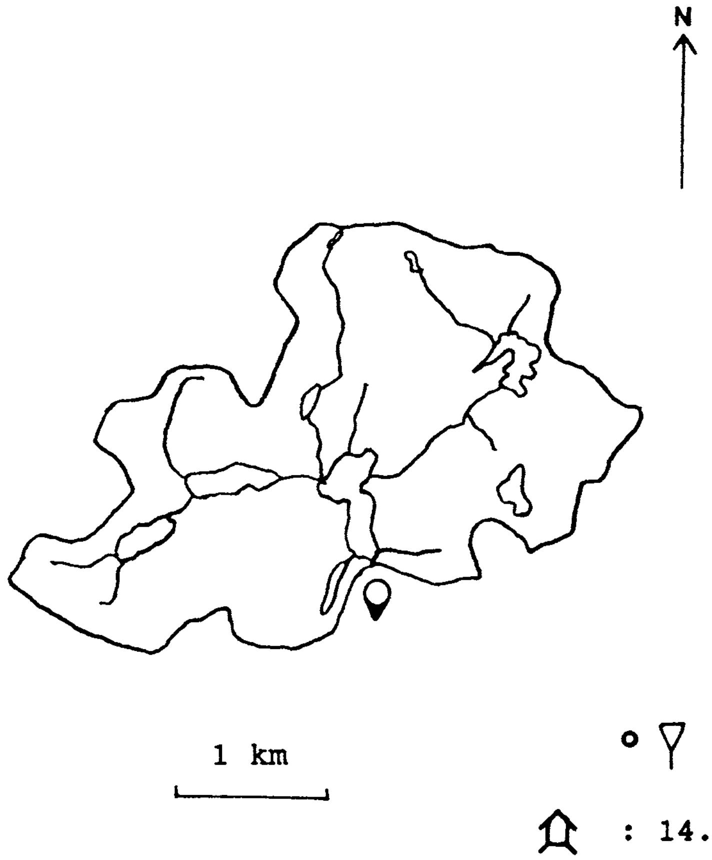
CATCHMENT CHARACTERISTICS

AREA	:	21.0 km^2
ALT	:	47-540 mas.
RELIEF	:	66 m/km
LAKE	:	12 %
BOG	:	1 %
CULT	:	0 %
FOREST	:	4 % ; Conifers
REST	:	83 % ;
SOIL CLASS	:	1 ; Till, debris-slide and organic material

FLOW/CLIMATE CHARACTERISTICS

ADF	:	2438 mm (77.3 l/skm^2)
SAAR	:	1951 mm
BFI	:	0.41
C-mean,P	:	7.4 (75 %, 7d)
C-mean	:	7.1 (75 %, 7d)

CATCHMENT : Grosetbekken - 1128 MAP : 1514 I



: 14.3 km west of the outlet

GAUGING STATIONS:	Site no.	mas.	Period
Discharge station	1128-0	939	1949-84
Precipitation station	3150	870	1957-84
Climate station	3161	948	1963-76
Common period			1963-76
Summer period			182-274

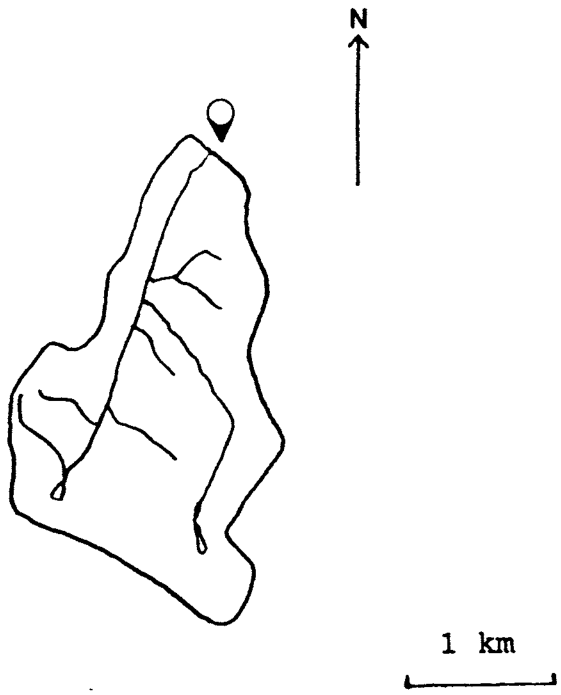
CATCHMENT CHARACTERISTICS

AREA	:	6.4 km^2
ALT	:	939-1121 mas.
RELIEF	:	73 m/km
LAKE	:	9 %
BOG	:	39 %
CULT	:	0 %
FOREST	:	49 % ; Deciduous trees
REST	:	3 % ;
SOIL CLASS	:	- ; Thin (20%) and thick (29%) cover of till

FLOW/CLIMATE CHARACTERISTICS

ADF	:	684 mm (21.7 l/skm^2)
SAAR	:	808 mm
BFI	:	0.49
C-mean,P	:	7.3 (75 %, 7d)
C-mean	:	7.3 (75 %, 7d)

CATCHMENT : Sagstubekken - 1141 MAP : 1914 III

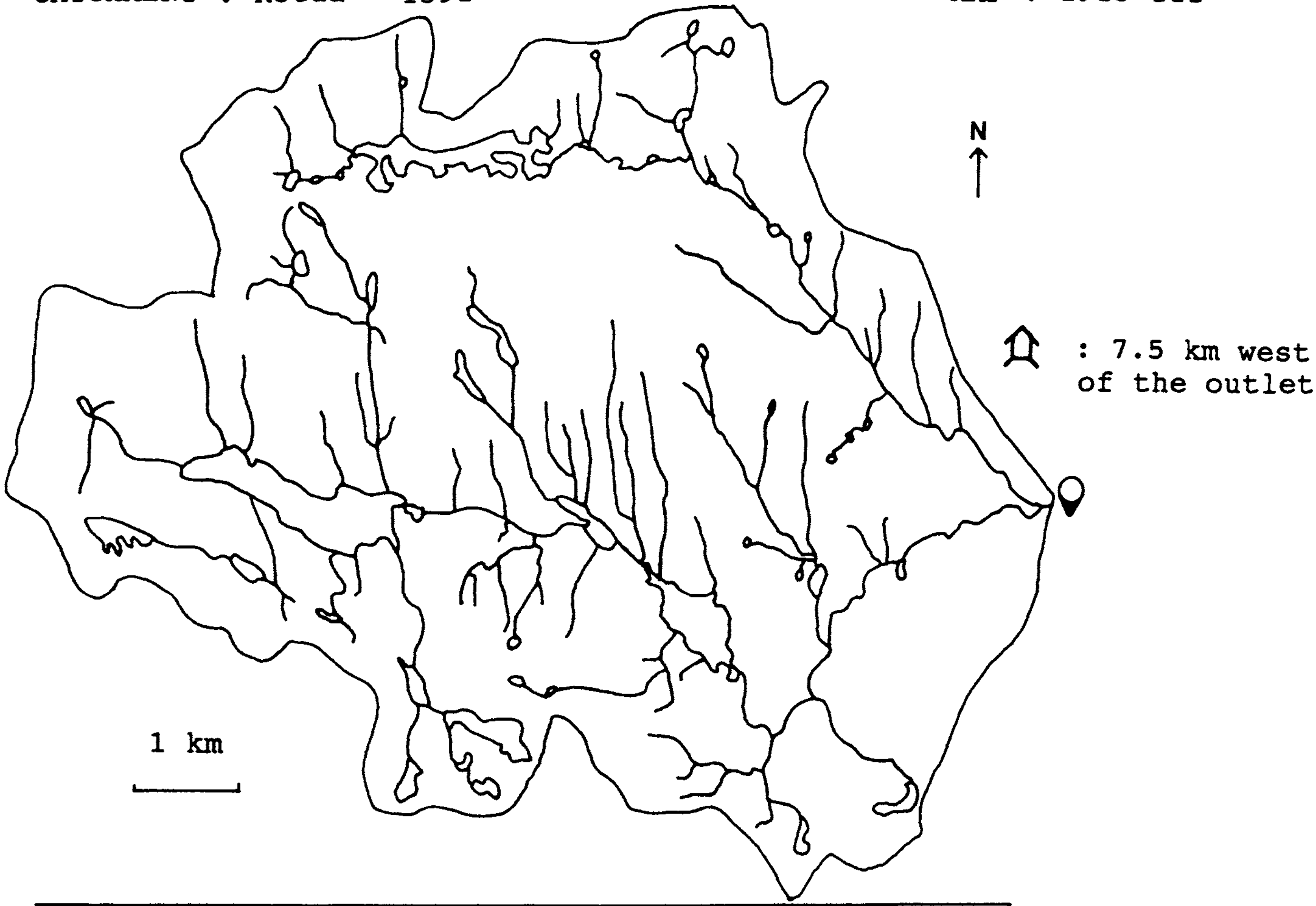


⌂ : 12.1 km south-west of the outlet

GAUGING STATIONS:	Site no.	mas.	Period
Discharge station	1141-0	150	1951-74
Precipitation station	1785	95	1957-84
Climate station	1785	95	1957-84
Common period			1957-74
Summer period			152-305

CATCHMENT CHARACTERISTICS			FLOW/CLIMATE CHARACTERISTICS	
AREA	: 3.2 km^2		ADF	: 508 mm (16.1 l/skm^2)
ALT	: 150-237 mas.		SAAR	: 785 mm
RELIEF	: 28 m/km		BFI	: 0.23
LAKE	: 1 %		C-mean,P	: 4.3 (75 %, 7d)
BOG	: 15 %		C-mean	: 4.2 (75 %, 7d)
CULT	: 2 %			
FOREST	: 82 %	; Conifers		
REST	: 0 %	;		
SOIL CLASS	: -	; Mainly thin cover of till		

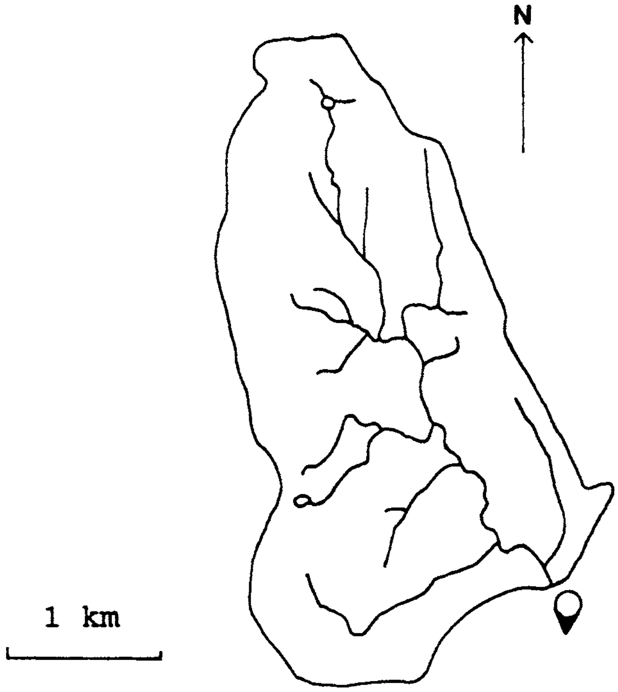
CATCHMENT : Rotua - 1591 MAP : 1915 III



GAUGING STATIONS:	Site no.	mas.	Period
♀ Discharge station	1591-0	195	1966-81
Y Precipitation station	0478	202	1957-81
⌂ Climate station	0478	202	1957-81
Common period			1966-81
Summer period			182-305

CATCHMENT CHARACTERISTICS			FLOW/CLIMATE CHARACTERISTICS	
AREA	: 55.5 km^2		ADF	: 801 mm (25.4 l/skm^2)
ALT	: 195-651 mas		SAAR	: 825 mm
RELIEF	: 43 m/km		BFI	: 0.36
LAKE	: 5 %		C-mean,P	: 6.6 (75 %, 7d)
BOG	: 5 %		C-mean	: 7.3 (75 %, 7d)
CULT	: 0 %			
FOREST	: 90 %	; Conifers		
REST	: 0 %	;		
SOIL CLASS	: 2	; Thin (13%) and thick (77%) cover of till		

CATCHMENT : Sæternbekken - 1880 MAP : 1814 I

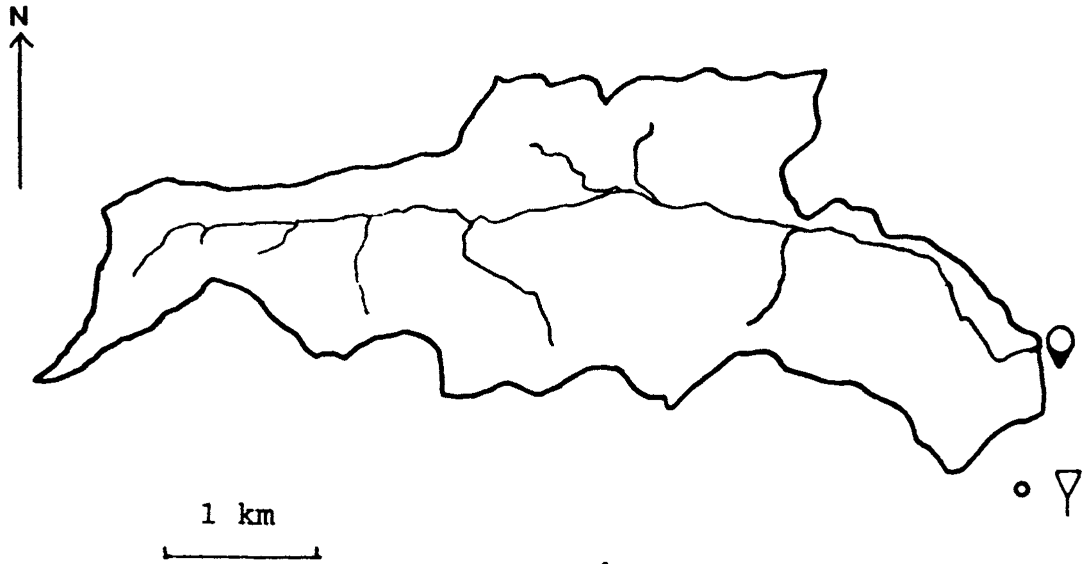


⌂ : 5.3 km south-west of the outlet

GAUGING STATIONS:	Site no.	mas.	Period
Discharge station	1880-0	105	1971-88
Precipitation station	1948	59	1971-88
Climate station	1948	59	1971-88
Common period			1971-88
Summer period			152-305

CATCHMENT CHARACTERISTICS			FLOW/CLIMATE CHARACTERISTICS	
AREA	: 5.8 km^2		ADF	: 492 mm (15.6 l/skm^2)
ALT	: 110-422 mas.		SAAR	: 939 mm
RELIEF	: 77 m/km		BFI	: 0.25
LAKE	: 0 %		C-mean,P	: 6.1 (75 %, 7d)
BOG	: 7 %		C-mean	: 6.8 (75 %, 7d)
CULT	: 6 %			
FOREST	: 87 %	; Conifers		
REST	: 0 %	;		
SOIL CLASS	: 1-2	; Mainly thin cover of till and a small glasifluvial deposit (5%).		

CATCHMENT : Rauåna - 1945 MAP : 1612 IV



: 5.5 km north of the outlet

GAUGING STATIONS:	Site no.	mas.	Period
Discharge station	1945-0	220	1972-87
Precipitation station	3709	164	1919-DD
Climate station	3723	252	1944-DD
Common period			1972-87
Summer period			182-305

CATCHMENT CHARACTERISTICS			FLOW/CLIMATE CHARACTERISTICS	
AREA	: 8.6 km^2		ADF	: 697 mm (22.1 l/skm^2)
ALT	: 220-761 mas		SAAR	: 988 mm
RELIEF	: 82 m/km		BFI	: 0.25
LAKE	: 0 %		C-mean,P	: 7.2 (75 %, 7d)
BOG	: 9 %		C-mean	: 6.4 (75 %, 7d)
CULT	: 0 %			
FOREST	: 88 %	; Conifers		
REST	: 3 %	;		
SOIL CLASS	: -	; Thin (48 %) and thick (40 %) cover of till		

A.2 OUTLINE OF MORECS

The following presentation of MORECS, Meteorological Office (UK) Rainfall and Evaporation Calculation System, is based on Thompson et al. (1981).

Applied at homogeneous subareas MORECS provides a method of estimating evapotranspiration which incorporates vegetational responses. Areal evapotranspiration is calculated by dividing the area into subareas with reasonable homogeneous vegetation, and total evapotranspiration obtained from the area weighted average for each surface.

A.2.1 The Penman-Monteith equation

The calculation of evapotranspiration is in MORECS based on the Penman-Monteith equation, Equation (6.1), which provides a physical based calculation of the rate of water loss from any surface. Direct measurements of net radiation, R_n, were not available for use in MORECS, so R_n is calculated using empirical formulae. R_{NE} is the net radiation adjusted for differences between surface and screen temperatures. These modifications have led to the following equation, which is the combination equation used in MORECS:

$$\lambda E = \frac{\Delta(R_{NE}-G) + \rho c_p(e_s-e)(1+br_a/\rho c_p)/r_a}{\Delta+\gamma(1+r_s/r_a)(1+br_a/\rho c_p)} \qquad (A.2.1)$$

where E = rate of water loss (Kg $m^{-2}s^{-1}$)
R_{NE} = net radiation (Wm^{-2})
Δ = rate of change of saturated vapour pressure with temperature (mb $^oC^{-1}$)
G = soil heat flux (Wm^{-2})
ρ = air density (Kg m^{-3})
c_p = specific heat of air at constant pressure (1005 J Kg^{-1})
e_s = saturation vapour pressure at screen temperature (mb)
e = screen vapour pressure (mb)
λ = latent heat of vapourisation ($\simeq$2465000 J Kg^{-1})
γ = psychrometric constant ($\simeq$0.66 mb $^oC^{-1}$)
r_s = bulk surface resistance (sm^{-1})
r_a = bulk aerodynamic resistance (sm^{-1})
b = $4\epsilon\sigma(273.1 + T_s)^3$, where ϵ = emissivity of surface, σ = Stefan's constant ($5.67*10^{-8}$ Wm^{-2} K^{-4}) and T_s= screen temperature (^oC)

MORECS requires values for global radiation, R_g, which is the sum of shortwave radiation from the sun and atmosphere measured on a horisontal plane. Global radiation is estimated from clear sky shortwave radiation and relative sunshine duration. Clear sky global radiation is given by location and time. Net global radiation, R_{ns}, at the surface is given by:

$$R_{ns} = R_g(1-a) \qquad (A.2.2)$$

where a is the surface albedo.

The incoming longwave radiation is in MORECS estimated using the technique of Brutsaert (1975), which is based on the equations of radiative transfer. The net clear sky longwave radiation is calculated as the difference between incoming and upward radiation, and transformed to actual radiation in MORECS given the number of hours of bright sunshine, n. At night the amount of cloud is typically smaller, and MORECS multiplies the factor n by 1.1.

The average daytime flux density of heat, G_d, into bare soil is calculated as a function of average daytime net all-wave radiation flux density and leaf area index. The average nighttime value of G is calculated from G_d, average monthly values of heat storage in the soil and daylength.

Calculations are made separately for day- and nighttime periods, with mean values of radiation, resistances, temperature and wind speed for each period. Daytime available energy is the calculated average daytime net all-wave radiation flux density minus daytime flux density of heat into bare soil. Nighttime available energy is the net longwave radiation flux density corrected for clouds minus nighttime flux density into bare soil.

Assuming near-neutral atmospheric stability, the variations of wind and temperature with height are logarithmic, and MORECS calculates the neutral forms for aerodynamic resistance r_a, from the equation:

$$r_a = (6.25/U(10+d))\ln(10/z_0)\ln(a/z_0) \qquad (A.2.3)$$

where d = zero-plane displacement height
z_0 = roughness length for momentum transfer
$U(10+d)$ = $U(10m)$ for low vegetation, and
= $0.6\ U(10m)$ for rough/tall vegetation
$U(10m)$ = measured 10 m wind speed
z_0 = 0.1h where h is crop height.
a = constant, which equals 6, except for very rough surfaces as forests, where a=50

Typical crops do not intercept all radiation and evaporation from underlying soil has to be considered. This is done by calculating the surface resistance according to both the surface resistance of crop and bare soil. Surface resistance when soil moisture is not limiting, is given by:

$$1/r_s = (1-A)/r_{sc} + A/r_{ss} \qquad \text{(A.2.4)}$$

where r_{sc} = surface resistance of the crop, freely supplied with water
r_{ss} = surface resistance of bare soil
$A = 0.7^{£}$, where £ is the leaf area index

Equation (A.2.4) was derived for daytime conditions. At night the leaf stomata are closed and the expression used in MORECS is:

$$1/r_s = £/2500 + 1/r_{ss} \qquad \text{(A.2.5)}$$

Values of r_{sc} in Equation (A.2.4) are given for each vegetation type together with corresponding leaf area index. The leaf area index vary through the season according to vegetation type. The dependence of r_{sc} to vapour pressure deficit and temperature is accounted for in case of conifers. r_{sc} equals zero while intercepted water remains. The rate of evaporation of water from a wet canopy is calculated using the formula for free water evaporation. Values of r_{ss} depend on the water content of the soil.

A.2.2 Soil moisture extraction model

MORECS uses the simplifying assumption that the available water is held in two reservoirs X and Y which contains reserves of x and y mm (Figure 6.2). All water in X is freely available, while that in Y becomes increasingly difficult to extract as y decreases. The maximum available water is distributed 40 % in X and 60 % in Y. Water is drawn from X until it is completely exhausted, when extraction from Y begins. Recharge replenishes Y only when X is filled.

For a dense crop intercepting all incident radiation, surface resistance remains at the potential value while X is extracted, but then increases progressively, to very large values following the relation presented by Russell (1980). A similar calculation scheme is applied for surface resistance of bare soil.

The available water capacity depends of the surface cover and the soil type. Available water capacity for a particular surface cover is defined as the value for soils of medium capacity. Values 25 % larger and smaller are used to arbitrarily define soils of high and low capacity. After leaf fall, the surface is assumed to return to bare soil. No account is taken of deep rooting trees which might extract water from potentially much larger reserves in drought conditions.

A.2.3 Calculation of water balance and excess rainfall

The treatment of intercepted water (I) is simplified by assuming that the effective daily rainfall is the sum of condensation during nighttime and rainfall. The interception is given by:

$$I = Rp \le 0.2\,\pounds \qquad \text{(A.2.5)}$$

where R = rainfall
p = proportion of intercepted rainfall
$= 1-(0.5)^{\pounds}$
$\pounds$ = leaf area index

Evaporation of intercepted water is enhanced to allow for more than one rainfall event each day, or for evaporation of intercepted water while rain is still falling. Monthly multiplication factors for I are given, varying between one (winter) and two (summer).

Total water loss from the surface is the sum of intercepted water + (rate of water loss from dry foliage) * number of hours while foliage is dry. Number of dry hours is calculated as a function of evaporation demand and the amount of intercepted water. Day- and nighttime values of evapotranspiration are summed to obtain diurnal values.

The difference between daily evapotranspiration and rainfall, when added to the previous day's soil moisture deficit, yields the current soil moisture deficit. The excess rain after reservoirs X and Y are replenished is assumed to be "hydrologically effective rainfall" (HER). No attempt is made to model or estimate runoff.

A.2.4 Surface types and parameters

This section presents the surface types and related parameters that are available in MORECS.

1. Grass	6. Deciduous	10. Conifers
2. Cereals	7. Upland	11. Urban
3. Potato	8. Riparian	12. Water
4. Beets	9. Rock	13. Bare soil
5. Orchards		

Maximum leaf area index:

1. Grass	
(jan) 2. 2. 2.5 3. 3.5 4.5 5. 5. 5. 4.5 3.5 2. (Dec)	
2. Cereals	5.
3. Potatoes	4.
4. Sugar beet	4.
5. Orchards	Combination of trees and grass
6. Deciduous trees	6.
7. Upland	Combination of trees and grass
8. Riparian	Combination of trees and grass
10. Conifers	6. (constant throughout the year)

Albedo:

1. Grass	.25			
2. Cereals	.25			
3. Potatoes	.25			
4. Sugar beet	.25			
5. Orchards	.25			
6. Deciduous trees	.17			
7. Upland	.25			
8. Riparian	.25			
10. Conifers	.12			
12. Water	.05			
13. Bare soil (dry)	.01	.02	.03	(high,medium,low SMC)
Bare soil (wet)	.05	.01	.15	(high,medium,low SMC)

Effective crop height (m):

1. Grass	.15			
2. Cereals	.08	.80		(Emergence to harvest)
3. Potatoes	.05	.60		(Emergence to harvest)
4. Sugar beet	.05	.35		(Emergence to harvest)
5. Orchards	.15	2.	3.	(Defoliated, leaf emergence, full leaf)
6. Deciduous trees	.15	2.	10.	(Defol., emer., f.leaf)
7. Upland	.15			
9. Bare rock	.05			
10. Conifers	10.			
11. Impervious urban	10.			
12. Water	.005			
13. Bare soil	.05			

Daytime values of surface resistance for dense crops freely supplied with water, r_{sc} (sm^{-1}):

1. Grass (Jan-Dec)		
50 50 50 50 45 40 40 40 40 45 50 50		
2. Cereals	40.	
3. Potatoes	40.	
4. Sugar beet	40.	
5. Orchards	Combination of tree, grass and soil	
6. Deciduous trees	80.	
7. Upland (Jan-Dec)		
120 120 120 100 100 100 100 100 100 120 120 120		
8. Riparian (Jan-Dec)		
50 50 50 50 45 40 40 40 40 45 50 50		
10. Conifers	70.	(at zero vapour pressure deficit and 20 ^{0}C)
12. Water	0.	
13. Bare soil	100.	

Available water capacity (mm):

1. Grass	125.	
2. Cereals	140.	(at maximum rooting depth)
3. Potatoes	90.	(at maximum rooting depth)
4. Sugar beet	140.	(at maximum rooting depth)
5. Orchards	150.	
6. Deciduous trees	175.	(at full foliation)
7. Upland	50.	
8. Riparian	200.	
10. Conifers	175.	
13. Bare soil	20.	

A.3 AMOR MODEL

The AMOR model is a modified version of the MORECS soil water balance model. It has been adjusted to operate on routinely meteorological observations at automatic and climatic station in Norway.

A.3.1 Surface types and parameters

The surface cover types in MORECS are in AMOR given a Norwegian equivalent (Rock and Urban are not available in AMOR yet):

MORECS	AMOR (Norwegian)
1. Grass	Grass (Gress)
2. Cereals	Cereals (Korn)
3. Potato	Potato (Potet)
4. Beets	Beets (Bete)
5. Orchards	Deciduous - Apple (Eple)
6. Deciduous	Deciduous - Birch (Bj¢rk)
7. Upland	Deciduous - Rowan (Rogn)
8. Riparian	Deciduous - Sallow (Selje)
9. Rock	-
10. Conifers	Conifers (Barskog)
11. Urban	-
12. Water	Water (Vann)
13. Bare soil	Bare soil (Bar jord)

Surface cover parameters are given the same values as in MORECS, apart from the parameters listed below. Surface type 5 to 8 are in AMOR modelled as deciduous trees, and the phennological data for each species have been selected in accordance with Lauscher & Printz (1955). For upland and riparian land this implies that some parameter values differs from the values given in MORECS:

Effective crop height (m):

7. Upland	.15	2.	3.	(Defoliated, emergence, full leaf)
8. Riparian	.15	1.	2.	(Defoliated ,emergence, full leaf)

Daytime values of surface resistance for dense crops freely supplied with water, r_{sc} (sm^{-1}):

8. Riparian 50.

A.3.2 Model output

The AMOR model permits evapotranspiration to be calculated by the ten methods listed below. Surface cover parameters are only required by The Penman-Monteith equation.

Potential evapotranspiration (PE):

1. Penman-48 (Penman, 1948)*
2. Penman-Rome (Penman, 1956)
3. Penman-Hansen (Hansen, 1980)
4. Penman-Kj¢benhavn (Kristensen, 1979)
5. Penman-Thom (Thom & Oliver, 1977)*
6. Penman-FAO (FAO, 1977)
7. Penman-Monteith (Monteith, 1965)*
8. Johansson (Johansson, 1974)
9. Makkink (Makkink, 1957)
10. Priestley-Taylor (Priestley-Taylor, 1972)*

Actual evapotranspiration (AE):

11. Penman-Monteith (Penamn-Monteith, 1965)*
12. Brutsaert-Stricker (Brutsaert-Stricker, 1979)

* discussed in Chapter 6.

An excample of model output file is given below. A selection of five evapotranspiration estimates are presented for the climatic station no. 1948, Dønski. The data cover the period 22.06 to 11.07 1983, and corresponds to the plotted data presented in Plate 2.

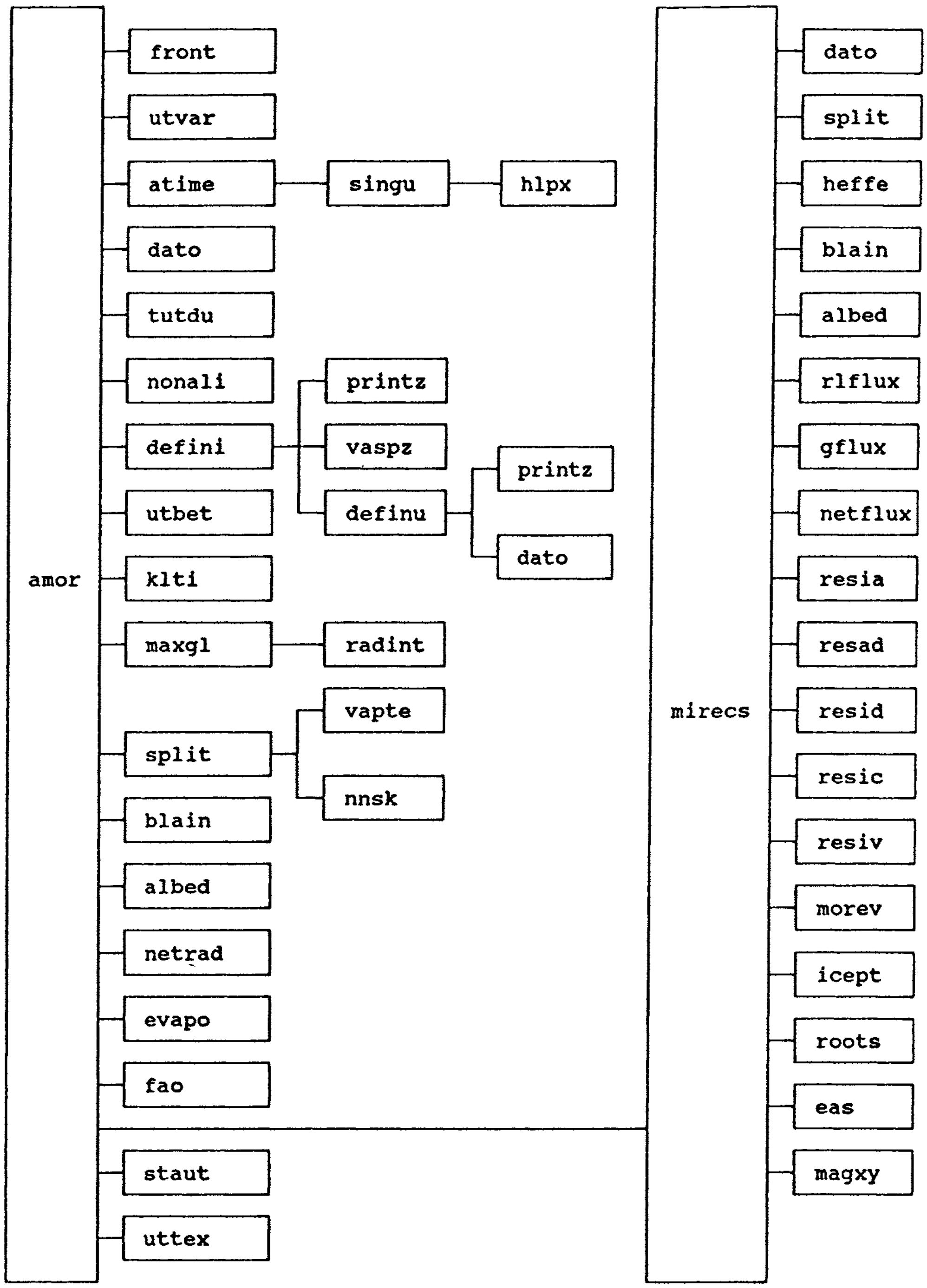
Parameter list:

p1: Penman-48
p2: Penman-Thom
p3: Penman-Monteith PE
p4: Pristley-Taylor
p5: Penman-Monteith AE
p6: Precipitation

Day	p1	p2	p3	p4	p5	p6
22	5.34	5.33	3.72	4.47	3.69	0.00
23	4.37	4.10	3.73	4.01	3.37	0.00
24	2.39	2.41	2.66	1.95	2.11	2.40
25	4.43	4.61	3.65	3.45	2.91	0.00
26	2.73	3.08	2.69	1.83	2.84	0.40
27	2.91	3.10	2.60	2.02	1.93	5.20
28	3.34	4.29	2.62	1.43	1.90	2.80
29	4.31	5.10	2.87	2.49	1.87	0.00
30	1.12	1.29	1.37	0.63	1.78	8.30
1	2.07	2.23	2.03	1.46	1.72	4.60
2	0.78	0.87	1.34	0.49	2.09	11.50
3	1.16	1.32	1.32	0.68	2.32	8.10
4	4.06	4.61	3.11	2.59	1.70	1.30
5	6.08	7.30	3.67	3.64	2.27	0.00
6	5.56	5.77	4.29	4.57	2.85	0.00
7	5.94	6.33	4.33	4.90	2.89	0.00
8	4.72	5.30	3.94	3.60	2.65	0.00
9	6.00	6.37	4.37	5.01	2.89	0.00
10	5.69	6.30	3.94	4.47	2.58	0.00
11	4.99	4.99	4.37	4.52	2.93	0.30

A.3.3 Sub routines in the AMOR model system

The AMOR system is divided into two main parts, amor and mirecs. Amor is the main system for organizing the input and ouput data, and computes daily values of evapotranspiration using the equations listed in A.3.2, apart from the expression by Penman-Monteith. Mirecs is a mini version of the MORECS system, Meteorological Office (Great Britain) Rainfall and Evaporation Calculation System and calculates potensiell and actual evapotranspiration using the Penman-Monteith equation.



AMOR:

Abbrevations	**Purpose**
FRONT	Defines the program at the terminal
UTVAR	Selects the output variables for the main file
ATIME	Defines input filename for automatic weather stations, given station identificantion and start and end of calculation period.
SINGU	Resets NONALI for climatic stations
HLPX	Help file for layout of input file
DATO	Calculates daynumber from dato, and dato from daynumber.
TUTDU	Selects variables for test and graphic files.
NONALI	Return station name, elevation and graphical position from station number.
DEFINI	Defines measurement heights, soil class and surface cover.
PRINTZ	Calculates phenological mean dates from Lauscher & Printz (1955).
VASPZ	Contains possible input to the special routines in AMOR.
DEFINU	Variable list containing default (DEFINI) and selected variables.
PRINTZ	See above.
DATO	See above.
KLTI	Calculates local time after 'mean solar time'.
MAXGL	Calculates maximum global radiation at the surface.
RADINT	Calculates the time integral of radiation between time 1 and 2.
SPLIT	Calculates daytime, nighttime and diurnal averages of hourly variables.
VAPTE	Calculates humidity variables from the formula by Aspiration Psycrometer tafelen (Deutsche Wetterdienst).
NNSK	Calcualtes sunshine hours from cloudiness.
BLAIN	Calculates leaf area indexes after MORECS.
ALBED	Calculates albedo after MORECS.
NETRAD	Calculates net radiation after USDA (US Department of Argiculture) method.
EVAPO	Calculates daily estimates of PE after equation 1,2,3,4,5,8,9 and 10 (Section A.3.2).
FAO	Calculates daily estimates of PE after equation 6 (Section A.3.2).
STAUT	Writes one record of data for each day.
UTTEX	Adds text to the main output file.

MIRECS:

Abbrevations	**Purpose**
DATO	Calculates daynumber from dato, and dato from daynumber.
SPLIT	Calculates daytime, nighttime and diurnal averages of hourly variables.
HEFFE	Calculates effective height of surface cover.
BLAIN	Calculates leaf area index after MORECS.
ALBED	Calculates albedo after MORECS.
RLFLUX	Calculates the longwave radiation flux after MORECS.
GFLUX	Calculates the day- and nighttime soil heat flux after MORECS.
NETFLUX	Calculates the day-, nighttime and diurnal net energy flux after MORECS.
RESIA	Calculates aerodynamic resistance after MORECS.
RESAD	Calculates dynamic aerodynamic resistance.
RESID	Calculates surface resistance after MORECS.
RESIC	Calculates surface resistance after a Jarvis type of model (Jarvis, 1976).
RESIV	Selects aerodynamic and surface resistances.
MOREV	Calculates Penman-Monteith's PE after MORECS.
ICEPT	Accounts for interception after MORECS.
ROOTS	Calculates the increase in SM capacity following the development of roots.
EAS	Calculates Penman-Monteith's AE after MORECS.
MAGXY	Calculates the adjusted SM content of the X and Y reservoirs.

B. APPENDIX TABLES

Table B.4.1 Recession mean and variance values for the complete discharge period.

CATCHMENT (Period)	QUL= % ADF	OBSERVED SERIES no	C-mean	C-var	TRANSFORMED SERIES no	C-mean	C-var
919 (40-84)	100	45	4.4	.14	45	4.4	.14
	75	47	5.0	.17	46	5.1	.17
	50	54	5.9	.23	53	6.0	.23
	30	43	6.7	.27	44	6.8	.29
	20	41	7.7	.28	41	7.7	.28
925 (40-86)	100	85	4.1	.25	82	4.1	.26
	75	85	4.8	.38	80	4.8	.38
	50	97	5.3	.26	94	5.4	.27
	30	91	6.5	.34	88	6.8	.38
	20	66	7.7	.29	66	8.6	.41
955 (40-86)	100	72	7.1	.27	73	7.3	.31
	75	61	7.6	.24	61	7.8	.30
	50	58	9.3	.28	54	9.3	.29
	30	36	10.0	.26	40	11.6	.38
	20	13	9.1	.30	20	13.0	.38
1128 (49-84)	100	27	8.1	.34	27	9.8	.45
	75	26	8.4	.35	29	9.9	.44
	50	16	8.5	.30	26	13.1	.65
	30	8	7.7	.24	19	14.4	.72
	20	2	9.1		12	12.5	.31
1141 (51-74)	100	27	5.1	.40	34	6.4	.48
	75	19	4.3	.30	34	7.8	.62
	50	15	4.4	.21	24	7.2	.79
	30	3	3.9		26	5.7	.49
	20	0			28	5.5	.51
1591 (66-81)	100	11	6.0	.37	13	6.6	.40
	75	13	6.6	.38	14	6.7	.40
	50	12	7.5	.50	13	7.9	.49
	30	10	7.5	.38	11	11.2	.82
	20	11	6.7	.51	10	6.5	.35
1880 (71-88)	100	26	6.2	.41	28	6.4	.40
	75	23	6.1	.38	23	6.4	.38
	50	18	5.9	.27	23	6.7	.40
	30	17	6.4	.28	21	7.9	.42
	20	6	5.9	.09	16	11.0	.68
1945 (72-87)	100	15	6.6	.23	16	6.6	.25
	75	18	7.3	.34	17	7.5	.39
	50	14	7.8	.39	16	9.0	.47
	30	10	8.6	.38	14	11.3	.60
	20	11	8.1	.36	13	8.9	.42
569 (40-83)	100	60	5.7	.19	61	5.9	.27
	75	67	6.5	.24	66	7.0	.51
	50	68	7.5	.34	63	8.0	.51
	30	52	8.4	.33	53	9.2	.51
	20	48	9.6	.31	45	10.3	.38
917 (40-70)	100	37	6.4	.27	37	6.6	.33
	75	31	6.9	.44	32	6.9	.43
	50	32	7.2	.24	32	7.2	.26
	30	24	7.9	.33	27	8.4	.41
	20	17	8.1	.24	18	7.7	.20

Table B.4.2 Recession mean and variance values for the reduced discharge period.

CATCHMENT (Period)	QUL= % ADF	OBSERVED SERIES no	C-mean	C-var	TRANSFORMED SERIES no	C-mean	C-var
919 (68-84)	100	8	4.3	.18	8	4.3	.18
	75	10	4.7	.20	10	4.7	.20
	50	17	5.3	.19	16	5.2	.19
	30	19	6.2	.26	20	6.5	.32
	20	20	7.2	.34	20	7.3	.34
925 (57-72)	100	42	4.2	.31	40	4.2	.31
	75	42	5.0	.48	39	5.1	.48
	50	48	5.5	.28	48	5.6	.29
	30	48	6.7	.41	48	7.0	.44
	20	36	8.1	.30	36	9.1	.37
955 (57-86)	100	36	6.6	.18	35	6.6	.18
	75	37	7.4	.21	36	7.4	.22
	50	38	8.8	.31	37	8.9	.31
	30	26	9.9	.27	26	9.9	.26
	20	13	9.1	.30	14	12.0	.47
1128 (63-76)	100	9	6.7	.17	7	7.0	.17
	75	5	7.3	.22	7	7.9	.22
	50	7	8.4	.30	7	10.5	.35
	30	3	7.3		6	12.4	.52
	20	1	6.9		3	11.6	
1141 (57-74)	100	19	5.2	.39	24	6.3	.47
	75	13	4.4	.29	25	7.6	.61
	50	11	4.6	.22	20	7.6	.80
	30	3	3.9		20	5.5	.51
	20	0			20	5.1	.39
1591 (66-81)	100	11	6.0	.37	13	6.6	.40
	75	13	6.6	.38	14	6.7	.40
	50	12	7.5	.50	13	7.9	.49
	30	10	7.5	.38	11	11.2	.82
	20	11	6.7	.51	10	6.5	.35
1880 (71-88)	100	26	6.2	.41	28	6.4	.40
	75	23	6.1	.38	23	6.4	.38
	50	18	5.9	.27	23	6.7	.40
	30	17	6.4	.28	21	7.9	.42
	20	6	5.9	.09	16	11.0	.68
1945 (72-87)	100	11	6.7	.17	12	6.7	.20
	75	14	7.2	.28	17	7.5	.39
	50	10	7.9	.39	12	9.1	.50
	30	7	7.8	.36	10	10.1	.58
	20	9	7.5	.38	11	8.5	.46

Table B.4.3 Recession mean and variance values for the reduced discharge period. Precipitation limit of 1.0 mm per day.

CATCHMENT (Period)	QUL= * ADF	OBSERVED SERIES no	C-mean	C-var	TRANSFORMED SERIES no	C-mean	C-var
919 (68-84)	1.00	4	4.0	.09	4	4.0	.09
	0.75	3	4.7		3	4.7	
	0.50	10	5.1	.21	9	5.0	.21
	0.30	14	6.4	.25	14	6.3	.25
	0.20	10	6.4	.25	10	6.4	.25
925 (57-72)	1.00	18	4.0	.39	18	4.0	.39
	0.75	15	4.5	.27	15	4.5	.27
	0.50	20	5.0	.21	21	5.0	.21
	0.30	20	6.0	.18	19	6.0	.19
	0.20	19	7.8	.27	19	7.9	.27
955 (57-86)	1.00	15	6.4	.18	15	6.4	.18
	0.75	16	7.1	.22	16	7.1	.22
	0.50	15	8.7	.25	15	8.8	.25
	0.30	14	9.6	.25	14	9.8	.24
	0.20	7	9.0	.29	9	11.5	.44
1128 (63-76)	1.00	5	7.1	.20	5	7.2	.20
	0.75	5	7.3	.22	5	7.3	.22
	0.50	7	8.4	.30	6	9.6	.31
	0.30	2	7.9		4	8.6	.26
	0.20				1	10.6	
1141 (57-74)	1.00	10	5.4	.41	11	6.4	.50
	0.75	6	4.2	.21	10	6.9	.52
	0.50	6	4.6	.16	9	8.5	.99
	0.30	1	3.9		11	6.4	.55
	0.20	0			9	4.9	.43
1591 (66-81)	1.00	7	5.4	.36	7	5.4	.36
	0.75	7	7.3	.43	8	7.2	.43
	0.50	9	6.9	.39	10	7.5	.41
	0.30	8	7.9	.40	7	7.8	.43
	0.20	6	7.7	.58	5	7.5	.38
1880 (71-88)	1.00	9	6.4	.45	9	6.4	.48
	0.75	10	6.8	.44	9	6.5	.44
	0.50	8	5.4	.25	10	7.2	.50
	0.30	12	6.2	.33	14	7.6	.43
	0.20	4	5.6	.07	8	11.3	.67
1945 (72-87)	1.00	8	7.1	.17	8	7.2	.18
	0.75	7	6.4	.24	7	6.4	.24
	0.50	5	6.8	.47	5	6.9	.45
	0.30	6	8.0	.38	7	8.8	.40
	0.20	5	6.4	.23	6	7.3	.34

Table B.4.4 Variable list and statistics.

Variable Label	Mean	Std Dev	Minimum	Maximum	N
CAO75P	39.00	24.62	13	85	10
CMO75P	6.35	1.31	4.3	8.4	10
CVO75P	.32	.08	.17	.44	10
CAO30P	29.40	27.13	3	91	10
CMO30P	7.36	1.64	3.9	10.0	10
CVO30P	.31	.05	.24	.38	9
CAT75P	40.20	22.28	14	80	10
CMT75P	6.99	1.45	4.8	9.9	10
CVT75P	.40	.12	.17	.62	10
CAT30P	34.30	23.21	11	88	10
CMT30P	9.33	2.73	5.7	14.4	10
CVT30P	.50	.17	.29	.82	10
CAO75	8.62	4.69	3	16	8
CMO75	6.04	1.34	4.2	7.3	8
CVO75	.29	.10	.21	.44	7
CAO30	9.63	6.55	1	20	8
CMO30	7.01	1.78	3.9	9.8	8
CVO30	.29	.10	.18	.40	6
CAT75	9.13	4.52	3	16	8
CMT75	6.33	1.11	4.5	7.3	8
CVT75	.33	.13	.22	.52	7
CAT30	11.25	4.95	4	19	8
CMT30	7.66	1.36	6.0	9.8	8
CVT30	.36	.13	.19	.55	7
BFI	.32	.10	.21	.49	10
SAAR	1300.88	602.25	785	2136	8
ADF	47.35	31.61	15.6	100.8	10
AREA	35.15	28.79	3.2	72.0	10
RELIEF	54.10	19.98	28	82	10
LAKE	5.90	4.82	0	13	10
BOG	9.30	11.18	1	39	10
CULT	1.75	2.71	0	6	8
FOR	49.70	36.19	2	90	10
REST	33.70	36.87	0	83	10
ALT	494.10	249.55	87.00	909.00	10

Table B.4.5 Correlation coefficients.

Correlation matrix A: Precipitation included (10 cases).

	CAO75P	CMO75P	CVO75P	CAO30P	CMO30P	CAT75P
CAO75P	1.0000	-.2160	-.3438	.9450**	.2442	.9797**
CMO75P	-.2160	1.0000	.1882	-.3587	.7866*	-.2986
CVO75P	-.3438	.1882	1.0000	-.1842	-.1040	-.3885
CAO30P	.9450**	-.3587	-.1842	1.0000	.1133	.8952**
CMO30P	.2442	.7866*	-.1040	.1133	1.0000	.1249
CAT75P	.9797**	-.2986	-.3885	.8952**	.1249	1.0000
CMT75P	-.4516	.6879	.0963	-.6655	.2148	-.3859
CVT75P	-.2476	-.0883	.3544	-.3078	-.4036	-.1199
CAT30P	.9461**	-.4610	-.2279	.9700**	-.0415	.9427**
CMT30P	-.2368	.9340**	.1152	-.3638	.6854	-.3072
CVT30P	-.5608	.4774	.3659	-.5406	.0989	-.5771
BFI	-.1944	.8003*	.2191	-.3435	.5281	-.2114
ADF	.8768**	-.2669	-.3513	.8826**	.2507	.8352*
AREA	.4139	-.1557	-.0857	.5026	.2117	.3529
ALTLOW	-.4054	.5569	.2754	-.4428	.0370	-.4062
ALTHIGH	.2091	.3578	.2104	.2962	.3238	.1041
RELIEF	-.1371	.4678	.0761	-.1317	.3510	-.2447
LAKE	.2989	.4484	-.1743	.1423	.5563	.2869
BOG	-.3683	.3885	.0806	-.4578	-.1640	-.3144
FOR	-.6359	-.2286	.3811	-.4558	-.5208	-.6346
REST	.6796	.0822	-.3994	.5406	.5211	.6640
ALT	.6708	-.1995	-.0611	.8086*	.3227	.5541

	CMT75P	CVT75P	CAT30P	CMT30P	CVT30P	BFI
CAO75P	-.4516	-.2476	.9461**	-.2368	-.5608	-.1944
CMO75P	.6879	-.0883	-.4610	.9340**	.4774	.8003*
CVO75P	.0963	.3544	-.2279	.1152	.3659	.2191
CAO30P	-.6655	-.3078	.9700**	-.3638	-.5406	-.3435
CMO30P	.2148	-.4036	-.0415	.6854	.0989	.5281
CAT75P	-.3859	-.1199	.9427**	-.3072	-.5771	-.2114
CMT75P	1.0000	.4510	-.5871	.7130	.5584	.6674
CVT75P	.4510	1.0000	-.1616	-.0766	.3847	-.0147
CAT30P	-.5871	-.1616	1.0000	-.4471	-.5771	-.3846
CMT30P	.7130	-.0766	-.4471	1.0000	.6628	.7419*
CVT30P	.5584	.3847	-.5771	.6628	1.0000	.3868
BFI	.6674	-.0147	-.3846	.7419*	.3868	1.0000
ADF	-.6090	-.5463	.8464*	-.2967	-.6494	-.1290
AREA	-.5407	-.2401	.3922	-.2414	-.1889	.0499
ALTLOW	.6872	.0930	-.4184	.6171	.4923	.6734
ALTHIGH	-.0165	-.4057	.2048	.3560	.0655	.4221
RELIEF	.1887	-.4654	-.2116	.4914	.0699	.0637
LAKE	.1990	-.2658	.0987	.3177	-.1552	.7525*
BOG	.7655*	.3363	-.3611	.5140	.5131	.4342
FOR	.0048	.2092	-.4401	-.0534	.4651	-.4035
REST	-.2314	-.2769	.4992	-.1107	-.5691	.2036
ALT	-.7588*	-.5543	.6800	-.2664	-.4570	-.2529

Correlation matrix A: cont.

	ADF	AREA	ALTLOW	ALTHIGH	RELIEF	LAKE
CAO75P	.8768**	.4139	-.4054	.2091	-.1371	.2989
CMO75P	-.2669	-.1557	.5569	.3578	.4678	.4484
CVO75P	-.3513	-.0857	.2754	.2104	.0761	-.1743
CAO30P	.8826**	.5026	-.4428	.2962	-.1317	.1423
CMO30P	.2507	.2117	.0370	.3238	.3510	.5563
CAT75P	.8352*	.3529	-.4062	.1041	-.2447	.2869
CMT75P	-.6090	-.5407	.6872	-.0165	.1887	.1990
CVT75P	-.5463	-.2401	.0930	-.4057	-.4654	-.2658
CAT30P	.8464*	.3922	-.4184	.2048	-.2116	.0987
CMT30P	-.2967	-.2414	.6171	.3560	.4914	.3177
CVT30P	-.6494	-.1889	.4923	.0655	.0699	-.1552
BFI	-.1290	.0499	.6734	.4221	.0637	.7525*
ADF	1.0000	.5675	-.3766	.3787	-.1475	.4419
AREA	.5675	1.0000	-.2830	.3539	-.6018	.5202
ALTLOW	-.3766	-.2830	1.0000	.5862	.2868	.2503
ALTHIGH	.3787	.3539	.5862	1.0000	.2203	.4435
RELIEF	-.1475	-.6018	.2868	.2203	1.0000	-.2642
LAKE	.4419	.5202	.2503	.4435	-.2642	1.0000
BOG	-.5122	-.4989	.8858**	.2740	.2392	-.0097
FOR	-.6365	-.5563	.0677	-.2919	.3143	-.8604**
REST	.7158*	.6470	-.3470	.1591	-.3601	.7560*
ALT	.8296*	.7011	-.4211	.4880	-.0624	.2268

	BOG	FOR	REST	ALT
CAO75P	-.3683	-.6359	.6796	.6708
CMO75P	.3885	-.2286	.0822	-.1995
CVO75P	.0806	.3811	-.3994	-.0611
CAO30P	-.4578	-.4558	.5406	.8086*
CMO30P	-.1640	-.5208	.5211	.3227
CAT75P	-.3144	-.6346	.6640	.5541
CMT75P	.7655*	.0048	-.2314	-.7588*
CVT75P	.3363	.2092	-.2769	-.5543
CAT30P	-.3611	-.4401	.4992	.6800
CMT30P	.5140	-.0534	-.1107	-.2664
CVT30P	.5131	.4651	-.5691	-.4570
BFI	.4342	-.4035	.2036	-.2529
ADF	-.5122	-.6365	.7158*	.8296*
AREA	-.4989	-.5563	.6470	.7011
ALTLOW	.8858**	.0677	-.3470	-.4211
ALTHIGH	.2740	-.2919	.1591	.4880
RELIEF	.2392	.3143	-.3601	-.0624
LAKE	-.0097	-.8604**	.7560*	.2268
BOG	1.0000	.1879	-.4738	-.6476
FOR	.1879	1.0000	-.9518**	-.3997
REST	-.4738	-.9518**	1.0000	.5519
ALT	-.6476	-.3997	.5519	1.0000

N of cases: 10 1-tailed Signif: * - .01 ** - .001

Correlation matrix B: Precipitation not included (8 cases).

	CMO75P	CMO30P	CMO75	CMO30	CMT75P	CMT30P
CMO75P	1.0000	.7939*	.8944*	.8444*	.7000	.9728**
CMO30P	.7939*	1.0000	.6971	.9820**	.2254	.7382
CMO75	.8944*	.6971	1.0000	.7831	.5402	.8586*
CMO30	.8444*	.9820**	.7831	1.0000	.3149	.8116*
CMT75P	.7000	.2254	.5402	.3149	1.0000	.7160
CMT30P	.9728**	.7382	.8586*	.8116*	.7160	1.0000
CMT75	.6161	.2210	.6947	.3464	.8364*	.6219
CMT30	.9075**	.8298*	.8374*	.8588*	.6542	.8339*
BFI	.8251*	.5606	.7468	.6818	.7410	.8708*
SAAR	-.2641	.2779	-.3767	.1802	-.6056	-.3055
ADF	-.2911	.2274	-.4071	.1419	-.6125	-.2882
AREA	-.3343	.0631	-.2298	.0710	-.7039	-.2314
ALTLOW	.5851	.0908	.3865	.1763	.7235	.6610
ALTHIGH	.3426	.3504	.1018	.3320	-.0098	.4236
RELIEF	.6819	.6427	.5694	.5693	.2232	.5405
LAKE	.4401	.5578	.3127	.6188	.2539	.4694
BOG	.4390	-.1259	.2406	-.0438	.7804	.5035
FOR	-.1881	-.4784	.0102	-.4528	-.0047	-.1504
REST	-.0047	.4792	-.1194	.4192	-.2912	-.0647
ALT	-.2527	.2829	-.3018	.1717	-.7822	-.2458

	CMT75	CMT30	BFI	SAAR	ADF	AREA
CMO75P	.6161	.9075**	.8251*	-.2641	-.2911	-.3343
CMO30P	.2210	.8298*	.5606	.2779	.2274	.0631
CMO75	.6947	.8374*	.7468	-.3767	-.4071	-.2298
CMO30	.3464	.8588*	.6818	.1802	.1419	.0710
CMT75P	.8364*	.6542	.7410	-.6056	-.6125	-.7039
CMT30P	.6219	.8339*	.8708*	-.3055	-.2882	-.2314
CMT75	1.0000	.6876	.6534	-.7176	-.7368	-.5839
CMT30	.6876	1.0000	.6972	-.1879	-.2639	-.4205
BFI	.6534	.6972	1.0000	-.1948	-.1749	-.1560
SAAR	-.7176	-.1879	-.1948	1.0000	.9669**	.5885
ADF	-.7368	-.2639	-.1749	.9669**	1.0000	.6447
AREA	-.5839	-.4205	-.1560	.5885	.6447	1.0000
ALTLOW	.3814	.2651	.6923	-.4315	-.3831	-.3050
ALTHIGH	-.3823	.0004	.3280	.3056	.3921	.3754
RELIEF	.0641	.5988	.2467	-.0021	-.0890	-.3596
LAKE	.1291	.4084	.7319	.4806	.4588	.2974
BOG	.4357	.1707	.5722	-.5471	-.5024	-.4952
FOR	.2029	-.2448	-.3898	-.7753	-.7255	-.2405
REST	-.3515	.1600	.1071	.9018*	.8328*	.3942
ALT	-.8209*	-.2823	-.3828	.7913*	.8334*	.7320

Correlation matrix B: cont.

	ALTLOW	ALTHIGH	RELIEF	LAKE	BOG	FOR
CMO75P	.5851	.3426	.6819	.4401	.4390	-.1881
CMO30P	.0908	.3504	.6427	.5578	-.1259	-.4784
CMO75	.3865	.1018	.5694	.3127	.2406	.0102
CMO30	.1763	.3320	.5693	.6188	-.0438	-.4528
CMT75P	.7235	-.0098	.2232	.2539	.7804	-.0047
CMT30P	.6610	.4236	.5405	.4694	.5035	-.1504
CMT75	.3814	-.3823	.0641	.1291	.4357	.2029
CMT30	.2651	.0004	.5988	.4084	.1707	-.2448
BFI	.6923	.3280	.2467	.7319	.5722	-.3898
SAAR	-.4315	.3056	-.0021	.4806	-.5471	-.7753
ADF	-.3831	.3921	-.0890	.4588	-.5024	-.7255
AREA	-.3050	.3754	-.3596	.2974	-.4952	-.2405
ALTLOW	1.0000	.5674	.2753	.2957	.9544**	-.0176
ALTHIGH	.5674	1.0000	.3689	.3837	.3606	-.3171
RELIEF	.2753	.3689	1.0000	.0262	.1579	-.0948
LAKE	.2957	.3837	.0262	1.0000	.1397	-.8668*
BOG	.9544**	.3606	.1579	.1397	1.0000	.0842
FOR	-.0176	-.3171	-.0948	-.8668*	.0842	1.0000
REST	-.3618	.1347	.0256	.7055	-.4668	-.9183**
ALT	-.4515	.4785	.1061	.1005	-.6269	-.3249

	REST	ALT
CMO75P	-.0047	-.2527
CMO30P	.4792	.2829
CMO75	-.1194	-.3018
CMO30	.4192	.1717
CMT75P	-.2912	-.7822
CMT30P	-.0647	-.2458
CMT75	-.3515	-.8209*
CMT30	.1600	-.2823
BFI	.1071	-.3828
SAAR	.9018*	.7913*
ADF	.8328*	.8334*
AREA	.3942	.7320
ALTLOW	-.3618	-.4515
ALTHIGH	.1347	.4785
RELIEF	.0256	.1061
LAKE	.7055	.1005
BOG	-.4668	-.6269
FOR	-.9183**	-.3249
REST	1.0000	.5318
ALT	.5318	1.0000

N of cases: 8 1-tailed Signif: * - .01 ** - .001

Table B.5.1 Recession mean and variance values.

CATCHM.	QUL=	OBSERVED SERIES			TRANSFOR.SERIES			HBV SIM. SERIES		
(period)	%ADF	no	C-mean	C-var	no	C-mean	C-var	no	C-mean	C-var
917 (57-70)	100	17	6.7	.29	18	7.2	.37	19	8.6	.43
	75	12	6.6	.34	13	6.5	.33	19	7.7	.22
	50	15	7.4	.28	14	7.5	.31	13	7.0	.16
	30	11	8.0	.35	14	9.1	.47	8	7.9	.07
	20	9	8.1	.18	10	7.8	.14	6	20.0	.35
1128 (64-75)	100	9	6.7	.17	7	7.0	.17	11	7.3	.22
	75	5	7.3	.22	7	7.9	.22	10	8.0	.04
	50	7	8.4	.30	7	10.5	.35	12	7.3	.08
	30	3	7.3		6	12.4	.52	7	10.8	.23
	20	1	6.9		3	11.6	.08	3	58.9	
1591 (66-81)	100	11	6.0	.37	13	6.6	.40	14	6.5	.25
	75	13	6.6	.38	14	6.7	.40	20	5.9	.16
	50	12	7.5	.50	13	7.9	.49	19	7.5	.20
	30	10	7.5	.38	11	11.2	.82	28	34.7	.63
	20	11	6.7	.51	10	6.5	.35	18	80.5	.32
1945 (72-86)	100	11	6.7	.17	12	6.7	.20	15	4.9	.12
	75	14	7.2	.28	17	7.5	.39	14	7.3	.23
	50	10	7.9	.39	12	9.1	.50	17	20.4	.50
	30	7	7.8	.36	10	10.1	.58	19	52.4	.16
	20	9	7.5	.38	11	8.5	.46	3	47.6	.00
1945* (72-86)	100							12	5.3	.06
	75							17	5.8	.22
	50							12	5.3	.12
	30							17	5.5	.16
	20							12	7.4	.29

Table B.5.2 Recession mean and variance values. Precipitation limit of 1.0 mm per day.

CATCHM.	QUL=	OBSERVED SERIES			TRANSFOR.SERIES			HBV SIM. SERIES		
(period)	%ADF	no	C-mean	C-var	no	C-mean	C-var	no	C-mean	C-var
1128 (64-75)	100	5	7.1	.20	5	7.2	.20	6	7.5	.21
	75	5	7.3	.22	5	7.3	.22	9	8.0	.04
	50	7	8.4	.30	6	9.6	.31	12	7.3	.08
	30	2	7.9		4	8.6	.26	7	10.8	.23
	20				1	10.6		3	58.9	
1591 (66-81)	100	7	5.4	.36	7	5.4	.36	6	5.3	.06
	75	7	7.3	.43	8	7.2	.43	7	4.9	.09
	50	9	6.9	.39	10	7.5	.41	10	7.6	.25
	30	8	7.9	.40	7	7.8	.43	18	36.7	.67
	20	6	7.7	.58	5	7.5	.38	15	80.1	.35
1945 (72-86)	100	8	7.1	.17	8	7.2	.18	5	4.8	.20
	75	7	6.4	.24	7	6.4	.24	7	7.3	.22
	50	5	6.8	.47	5	6.9	.45	9	19.1	.65
	30	6	8.0	.38	7	8.8	.40	10	50.5	.18
	20	5	6.4	.23	6	7.3	.34	2	47.6	.00
1945* (72-86)	100							5	5.2	.06
	75							8	5.1	.03
	50							7	5.0	.04
	30							11	5.2	.06
	20							8	6.7	.29

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PART II

Analaysis of summer low flows in Norway

Moltzau, B.E. & Tallaksen, L.M. 1988. Analysis of summer low flows in Norway.
Nord. Hydr. Conf. Rovaniemi, NHP-Rap., 22(1), 109-118.

ANALYSIS OF SUMMER LOW FLOWS IN NORWAY

BJØRN EDVARD MOLTZAU & LENA MERETE TALLAKSEN

Department of Geography, University of Oslo, P.O. Box 1042,
Blindern, 0316 OSLO 3, NORWAY.

Abstract

The main goals of these studies are to understand the dependence of minimum runoff from climatological and physiographical factors. The low flow indices used are mean 7 and 30 day minimum runoff standardised by both area and mean annual runoff. Data from the summer period, 1.June - 30.September, for 75 discharge and precipitation stations were used, restricted to a uniform length of record. The catchments involved are glacier free, their area are less than 1000 km^2, and they are without severe human impacts.

The analysis have included:

1. selecting watershed and climatic parameters related to low flow characteristics,
2. deriving a statistical model for low flow prediction at ungauged locations, and
3. investigating the possibility to improve the accuracy of the regression equations by including a general index of hydrograph behavior, the Base Flow Index (BFI), developed during a low flow study of U.K. catchments.

LIST OF SYMBOLS AND ABBREVIATIONS

AREA	Catchment area in km^2 obtained by planimetering on 1:50 000 scale maps.
FORM	Form factor: $\frac{Areal}{La^2}$, where La is length of catchment axis from outlet to most remote point on the water divide.
RELIEF	Relief-ratio: $\frac{H}{La}$ (m/km) where H is maximum range in altitude.
ROCK	Area above tree limit in % .
ASE	Weighted percentual lake area index (%). $100 \cdot \sum \frac{Ai \cdot ai}{Area^2}$, where ai is surface area of lake i, and Ai is catchment area of lake i.
AS	Lake area in % .
S1085	Stream channel slope (m/km) measured between two points 10% and 85% upstream the gauging station on a 1:50 000 scale map.
BFI	The Base Flow Index - a measure of the proportion of baseflow under the flow hydrograph.
ADF	Standard (1940/50-1970/86) mean annual runoff in $\frac{l}{s \cdot km^2}$ (average daily flow).
SAAR	Standard (1930-1960) annual average precipitation in mm.
MAM(7)	Mean 7 day minimum ($\frac{l}{s \cdot km^2}$) from the summer period 1.June to 30.September.
MAM(30)	Mean 30 day minimum ($\frac{l}{s \cdot km^2}$) from the summer period 1.June to 30.September.
STD(7)	Ratio between mean 7 day minimum and mean annual runoff (STD(7) = MAM(7)/ADF)
STD(30)	Ratio between mean 30 day minimum and mean annual runoff (STD(30) = MAM(30)/ADF)

1 INTRODUCTION

As the demand for water increases, it is important to consider the most effective or optimal management of our water resources. The low flow characteristics of rivers often provide treshold values for different water-based activities. This has made it increasingly necessary to achieve a better understanding and prediction of low streamflow.

Variations in low flow characteristics are caused by differences in climatic and physiographic characteristics of the watersheds. Low flows of ungauged catchments may be estimated by relating flow characteristics to catchment and climatic characteristics. In this study a low flow regression model is developed for Norwegian catchments using multiple regression techniques. It provides a set of equations that permits estimation of selected low flow indices. The model is evaluated both as an explanatory and a predictive model.

The ability of a catchment to maintain high flows during dry weather depends upon its ability to both store and release water. It is generally accepted that it is necessary to include a numerical expression for the influence of soil characteristics and geology on the low flow behaviour of rivers. If this expression is not included in the model, the result may show partial correlation phenomena rather than direct causuality.

Browne (1981) has summarized a number of ways in which this effect might be numerically defined. The Institute of Hydrology in Wallingford (NERC, 1980) has developed the Base Flow Index, for the purpose of incorporating the influence of soil and geology.

2 LOW FLOW-, CLIMATIC-, AND CATCHMENT CARACTERISTICS

Catchment and climatic characteristics are selected based on the results of a previous study (Moltzau, 1987). The following 7 catchment characteristics are included as independent variables: catchment area (AREA), form factor (FORM), relief-ratio (RELIEF), area above tree limit (ROCK), stream channel slope (S1085), weighted percentual lake area index (ASE) and the Base Flow Index (BFI). The catchment area ranged from 5.9 km^2 to 918 km^2, with an average of 317 km^2. The weighted percentual lake area index (ASE) was selected in preference to the ordinary lake percentage index (AS) because ASE has in a previous study (Moltzau & Nordseth, 1988) shown to be more significant for low flow than AS. Bog is not included as a result of low significanse in preliminary analysis.

Two climatic indices are included, i.e. mean annual runoff (ADF) and mean annual precipitation (SAAR). Mean annual precipitation is a measure of both the amount of water supplied to the catchment and the potential runoff. For each sample catchment, a point estimate of mean annual precipitation was supplied by Norwegian Meteorological Institute. SAAR ranges from 3071 mm in the west (Hovlandsdal) to 350 mm in the north of Norway (Alta-Lufthavn). The mean for all 75 stations was 1233 mm.

The low flow characteristics selected are mean 7 and 30-day minimum standardised with both area MAM7 & MAM30, and mean annual runoff, STD7 & STD30. These are defined as the lowest average flow in the summer period for 7 and 30 number of consecutive days each year.

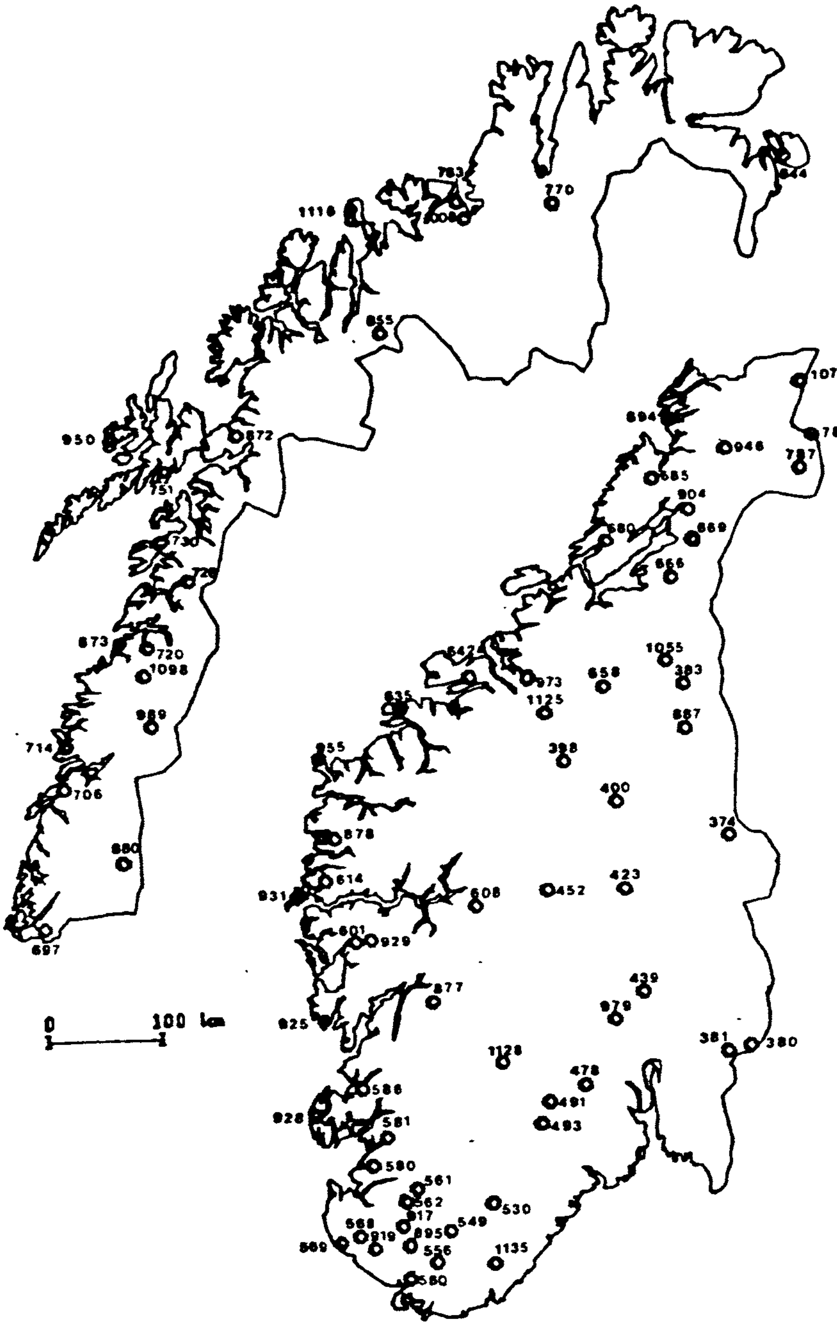

Figure 1. Geographical distribution of the 75 catchments.

The best way to determine the summer period would be to examine individual years for each catchment and thereby establish the longest snowfree period each year. As this would be a very timeconsuming process when working on a large database, the procedure was abandoned in favour of a fixed summer period for all catchments (1.June to 30.September).

The total sample of low flow data contains 3170 station- years of record. The average length of records is 42 years. Only 2 records are shorter than 30 years, 57 records are longer than 40 years. The daily flow records used for each station are taken from the period 1940-50 to 1970-86. The runoff data are given by the Norwegian Water Resources and Energy Administration. The selected catchments are evenly distributed geographically, fig.1. The critera used for accepting a catchment in the database are:

- a uniform period of record, minimum 20 years
- catchment without glaciers
- catchment without severe human impacts
- catchment area less than 1000 km^2

The Base Flow Index (BFI) was developed during a low flow study (Low Flow Studies IH, 1980) of U.K. catchments. The index is the ratio of base flow to total flow calculated from a hydrograph separation procedure using daily discharge.

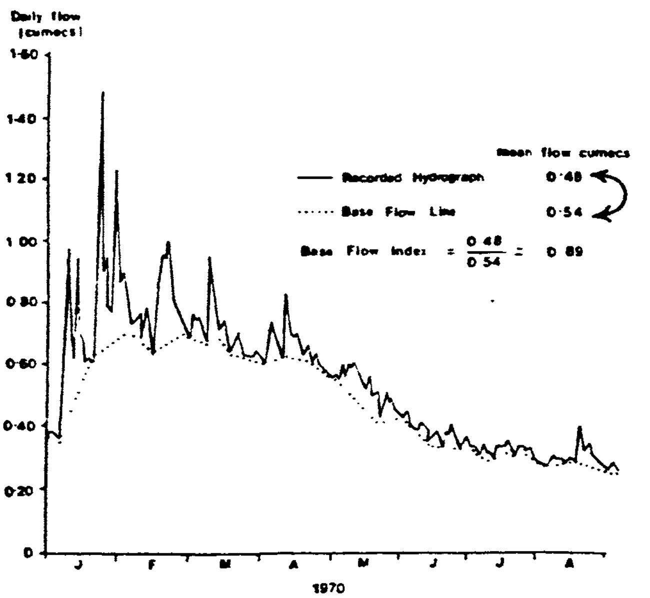

Figure 2. Base flow separation for Pang (from Gustard, 1983).

A computer program calculates the minima of five day non-overlapping periods and subsequently searches for turning points in this sequence of minima. The turning points are then connected to obtain the separated hydrograph, fig.2. A high BFI indicates a stable flow regime with high storage, and a low BFI results from a flashy regime with low storage. Values of the index which are nearly normally distributed for the sample, range from 0.21 to 0.83 with an average of 0.56.

The index is supposed to be a parameter representing the proportion of the river's runoff that derives from stored sources. Accordingly, it may characterize the catchment's ability to store and release water during dry weather. The index is incorporated in the Low Flow Study as a catchment characteristic representing the influence of soil and geology. On the same background the index has been included in this study.

The estimation technique for the Base Flow Index has been tested on 14 catchments with area less then 50 km^2 (Tallaksen, 1987), which shows that the method applied on river regimes with a distinct snowmelt period is not recommandable. The method fails to separate the larger snowmelt floods. In order to avoid this problem the BFI is calculated using data only from the summer period.

The calculation of the BFI used in this study is based on recommandations given by the Institute of Hydrology (Gustard et al, 1987). Here modifications of the original BFI calculation procedure are presented. These include using the whole data period to obtain one value of the BFI, not averaging separate years.

3 REGRESSION ANALYSIS

Given the present knowledge of the physical environment, it is not possible to model the multitude of processes and interactions which give rise to the low flow characteristics. The model described attempts to counter this problem by indexing some of the physical characteristics which affect the hydrological processes.

Regression is a statistical technique and does not provide proof of causal relationships between any variables. It may, however, be used to evaluate correlations inferred from a knowledge of the physical environment.

The objective of a multiple regression analysis is to select an optimal equation combining independent variables and coefficient from which a response may be estimated. The information obtained may be used in a physical approach to select the independent variables significant for low flow, and in a statistical approach to estimate the dependent variables. The primary structural difference between these two approaches is that the statistical model tolerates correlation between the independent variables, whereas the physical approach does not.

Stepwise multiple linear regression is used to analyse the relationship between runoff variables (dependent variables) and the selected set of catchment and climatic characteristics (independent variables). Coefficients are estimated for each variable so as to minimize the total sum of squares between observed and predicted values of the dependent variable. This was achieved using standard statistical packages including SPSSPC+ on a microcomputer.

4 RESULTS AND DISCUSSION

Table I shows the correlation coefficients of all pairs of dependent and independent variables. The best single predictor for the mean annual 7 and 30 day low water index (MAM) is ADF - average daily flow, followed by RELIEF. However, ADF and RELIEF are mutually correlated (r=0.47), probably because catchments with high relief often are located in areas with high runoff values. The high correlation between RELIEF and S1085 (r=0.72) suggest that there is no need to include both these variables. Thus S1085 has been left out in futher regression analysis. The positive correlation between ROCK and the low flow indices may partly be explained by the same argument as for RELIEF.

TABLE I. Pearson Correlation coefficient matrix for the regression variables (N=75).

	MAM(7)	MAM(30)	SDT(7)	SDT(30)	ADF	SAAR	AREA	FORM	RELIEF	ROCK	ASE	S1085	BFI
MAM(7)	-												
MAM(30)	.914	-											
SDT(7)	.449	.185	-										
STD(30)	.607	.463	.910	-									
ADF	.632	.816	-.291	-.051	-								
SAAR	.286	.516	-.514	-.306	.820	-							
AREA	-.133	-.197	.240	.210	-.354	-.238	-						
FORM	.089	.043	.197	.223	-.104	-.105	.023	-					
RELIEF	.638	.590	.170	.272	.471	.206	-.471	.313	-				
ROCK	.466	.497	.251	.438	.388	.209	-.009	.126	.179	-			
ASE	.199	.165	-.101	-.162	.267	.196	-.389	-.068	.283	-.121	-		
S1085	.445	.488	-.040	.062	.479	.320	-.474	.151	.720	.156	.542	-	
BFI	.338	.064	.733	.586	-.334	-.437	.163	.103	.074	.059	.230	-.027	-

When looking at the low flow indices standardised by ADF in order to reduce the climatic influence (STD), the best predictor is BFI - the Base Flow Index. Recalling that BFI is a measure of storage properties, it is reasonable that it also forces out to be the most important factor. The influence of RELIEF is negligible, and this agrees with the fact that RELIEF is intercorrelated with the climatic variable ADF.

Different combinations of independent variables are tried in the regression analysis, and a summary of the results from the analysis is given in Table II. Here the estimation equations are presented for the 4 different low flow indices defined in section 2, together with the multiple correlation coefficient R^2, and the standard error of estimate SE. The magnitude of R^2 is considered satisfactory, and is particulary encouraging for the MAM(7) and MAM(30) values when the climatic variable is ADF, respective 0.83 and 0.86.

Generally, the coefficient of determination is highest when the climatic variable is ADF and not SAAR. This may be a result of regarding ADF as areal values, while SAAR is estimated as point values. Because of the large variation in topography it is also difficult to obtain representative point values.

Mainly due to the lack of relevant soil maps in Norway the influence of soils and geology upon flow characteristics has not yet been incorporated in regional studies. However, other catchment characteristics have been considered superior. This is due to the relative impermeable solid geology and a generally scarce cover of loose deposits. Further, the numerous lakes in almost every catchment has been regarded as more important in controlling both flood and low water on a regional scale.

TABLE II. Regressions on catchment and climatic characteristics.

Dependent variable	Regression coefficients							Intercept	R^2 (%)	SE
	RELIEF	ROCK	BFI	ASE	AREA	SAAR	ADF			
MAM(7)	0.137(1)	0.113(2)	X	0	X	0	X	- 1.360	53.50	5.91
MAM(30)	0.207(1)	0.201(3)	X	0	X	0.009(2)	X	-11.537	62.08	10.15
MAM(7)	0.105(1)	0.081(3)	X	0	X	X	0.103(2)	- 2.815	60.68	5.47
MAM(30)	0.120(2)	0.126(3)	X	0	X	X	0.366(1)	- 9.098	75.94	8.09
STD(7)	0.002(3)	0.002(2)	X	0	0.0002(4)	-0.0002(1)	X	0.224	50.81	0.12
STD(30)	0.002(3)	0.003(1)	X	0	0.0002(4)	-0.0001(2)	X	0.245	50.45	0.14
MAM(7)	0.118(1)	0.090(2)	25.179(3)	0	X	0.004(4)	X	-18.211	67.82	4.98
MAM(30)	0.192(1)	0.184(3)	24.298(4)	0	X	0.012(2)	X	-26.702	65.58	9.74
MAM(7)	0.072(1)	0	37.442(3)	-0.563(4)	X	X	0.243(2)	-22.030	83.68	3.55
MAM(30)	0.085(4)	0	46.787(2)	-1.059(3)	X	X	0.558(1)	-31.744	85.60	6.30
STD(7)	0.001(3)	0.001(5)	0.723(1)	-0.010(2)	0	-0.0001(4)	X	- 0.123	71.86	0.09
STD(30)	0.001(4)	0.002(2)	0.843(1)	-0.019(3)	0	0	X	- 0.153	63.26	0.12

Notes: X - the variable is not included in the analysis.
0 - the variable is not significant for the regression.
Regressions are of the linear form:
MAM(7)=-1.360 + 0.137 RELIEF + 0.113 ROCK

As the BFI has the effect of lake incorporated, one might expect to find a high correlation between the index and the ASE based on the above assumptions. This is not so, r=0.23, which might be explained in two ways. First, the sample of catchments is perhaps not representative, i.e. the lake percentage is less than average. The mean ASE is 2.96 which corresponds with a previous study (Moltzau, 1987) including 220 catchments with a mean of 2.79.

Secondly, several important properties of a catchment are obviously left out when storage properties are represented only by the ASE, and indirectly by the other catchment characteristics (relief, rock, etc.). The importance of these properties can be seen from the regression analysis, where the accuracy of all the equations increased when including the BFI. The effect is larger for the 7 day than the 30 day low water index. This might just be a result of the lower starting values of R^2, before the BFI is included, for the 7 day index.

The fact that BFI has a low correlation with ASE suggest that ASE has little effect upon low water, a statement that is confirmed in the low correlation between the low flow indices and ASE. This statment is not the same as to say that a lake has little or no effect on low water. Instead, it points to the importance of other storage possibilities in the catchment, as well as one bare in mind that ASE may not be the best way of indexing the effect of lake on low flow. The Base Flow Index represents an integrated effect of catchment characteristics, i.e. a natural integration almost impossible to desintegrate. Still, it is reasonable to believe that cover properties do play an important part.

The question remains as to what method to use when estimating the BFI at an ungauged location. The success of incorporating the BFI or similar indices, in the analysis depends upon the estimation procedure developed for the BFI at the ungauged site. The index should be related in some way to catchment characteristics. When looking at the physical meaning of the index, as a measure of the discharge that derives from stored sources, the relevant characteristics are those that in one way or another express storage properties. In Great Britain estimation procedures for ungauged sites have mainly been based on relationships between BFI and catchment geology, regression equations using catchment geology and soil classes and transference of gauged BFIs from nearby catchments with similar geology, soils and topography. However, these methods are not directly applicable for our study area due to insufficient information of cover properties.

5 CONCLUSION

The regression analysis conclude that the most important characteristics in explaining the regional variation in spesific low flow variables is the climatic parameter. When low flow runoff is standardised by mean annual runoff the Base Flow Index which represents storage properties, is the dominant independent variable in the results. Mean annual runoff is prefered to annual average precipitation as a climatic parameter.

Including the Base Flow Index in the low flow models increases the estimation accuracy of all the regression equations. The results demonstrate the need for incorporating an index in low flow analysis that represents the storage properties of the catchment. Other methods to express this effect numerically might be prefered. This could be a recession constant or a soil index derived from relevant soil maps. What type of index to include depends upon the availability of the additional information needed for its computation.

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PART III

Analysis of time variability in recessions

In: FRIENDS in Hydrology (Proc. Bolkesjø Symp., April 1989), 85-96. IAHS Publ. no. 187.

ANALYSIS OF TIME VARIABILITY IN RECESSIONS

Lena Tallaksen
Department of Geography, University of Oslo, P.O. Box 1042,
Blindern, 0316 OSLO 3, NORWAY.

ABSTRACT It is generally accepted that it is necessary to include a numerical expression for the storage properties of a catchment in a low flow study. In Norway the recession constant has commonly been used for this purpose. When looking at individual recession segments, they show great time variability within a catchment. This study looks at natural causes for this variation, by incorporating data on precipitation and temperature during the recession period. The recession constant is included in a low flow regression model in order to investigate the possibilities of improving the accuracy of the estimation equations. These results are compared with an earlier study where another expression for storage properties, the Base Flow Index, was included in the same type of low flow regression model.

INTRODUCTION

During low flow periods, the regime is characterized by a gradual depletion of moisture stored in the catchment. The drainage rate can be analysed using the recession curve. The recession constant derived from the recession curve has often been incorporated in analyses as a quantitative expression for a catchment's storage capacity.

The recession characteristics of each catchment are analysed by looking at the mean value and variance of n estimates of the recession constant calculated from individual segments. The segments are selected automatically from the hydrograph, the criteria are set interactively, and the recession constant for each segment determined by a least squares method. This produces for each catchment a distribution of the recession constant, rather than one value derived from a master recession. The distribution itself contains valuable information concerning the physical properties of the catchment, and parameters from the recession sample might be looked upon as selected from a population.

The first part of this analysis is consentrated on methods and difficulties arising when trying to isolate the effect of climate on the recession variability. Preliminary conclusions are discussed concerning this influence. The second part incorporates a recession constant in a low flow regression model. The choice of recession constant is discussed and its effect on the accuracy of the regression equation investigated. Similar analysis has previously been done for the Base Flow Index (Moltzau & Tallaksen, 1988) and the results are compared. In addition a regional analysis of recessions is performed. Both the recession constant and coeffecient of variation are plotted on a map to detect, if possible, any regional pattern in the data.

DATA QUALITY

Data quality is of special importance when analysing low flows. Time sequences from the hydrograph exhibit a random element due to errors in the data. It is possible to smooth out the data by use of e.g. moving averages. This has not been done here because the variability itself is the object of the study.

However, one particulary feature of the low flow data is modified. These data are for many catchments presented in a staircase manner, which means that several equal values follow before a lower value is recorded. The most obvious reason for this is the lack of accuracy in the low flow measurements. It is of course possible that it sometimes could be a result of natural causes, like precipitation offsetting the recession rate, but the frequency of occurance indicates a more regular source.

Runoff data were supplied by the Norwegian Water Resources and Energy Administration and precipitation and temperature data by the Norwegian Meteorological Institute.

RECESSION ANALYSIS

The most widely used approach to decribe the recession prosess is to fit an equation of the simple exponential form :

$$Q_t = Q_0 exp(-t/C) \tag{1}$$

to the recession limb, where Q_t is the flow at time t, Q_0 is the flow when t=0, and C is the recession constant.

Various equations and methods of constructing a master recession curve are discussed in Hall (1968) and Toebes and Strang (1964). In more resent works subjective methods, e.g. the matching strip method, are abandoned in favour of more objective and computerized solutions.

In this study equation (1) is fitted to individual recession segments by a least-squares method. As to the problem of equal values in the time series, these are left out and the calculation based on decreasing values only. The curve-fitting equations are derived with respect to the original nonlinearized exponential equation. The sum of residuals squared are calculated using a relative residual, R :

$$\mathrm{R} = [Q_0 exp(-t/C) - Q_t]/Q_t \tag{2}$$

Newtons method is then used in the solution of the nonlinear equations.

A comparision made between this approach and a least-squares fit made to a linearized form achieved by taking the logarithm of the equation revealed small differences.

In case of a steep start of recession the direct fit produces a flatter curve, i.e. a lower C-value than results from a loglinear fit (Tallaksen,1987).
The segments are automatically selected from the time series on the following criteria :

a) A defined upper limit (QUL) for start of recession, however, at least two days from peak of discharge.
b) A defined lower limit for length of recession, however, at least N decreasing values in the sequence.
c) The sequence continues as long as the next runoff value is less than or equal to the last value, and does not reach zero.
d) A defined limit for the goodness of fit of theoretical curve.
e) A defined threshold value for precipitation can be incorporated.

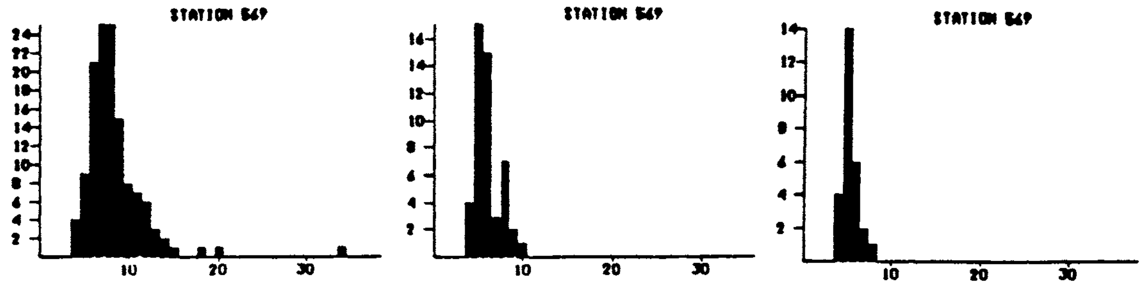
As a measure of goodness of fit of the model, the correlation coeffecient, based on observed and predicted values of the runoff is calculated. The acceptable minimum limit is 0.90, however, a higher value is set when N $<$ seven ensuring that the significant level is maksimum 1 %. Minimum number of decreasing values, N, is set to five.

The least squares approach to estimate recession constants is applied to 20 Norwegian catchments with area less than 100 km^2. Initially, the number of recessions at each catchment was large, but due to non-overlapping discharge, precipitation and temperature data series there was a marked reduction in numbers. Catchments with less than 10 individual recessions are disregarded.

A problem in humid areas is that recharge may occur frequently and thereby influence the recession pattern. In order to detect the way in which natural factors contribute to the recession variance, it is essensial to eliminate variation due to the particulary segment sample.

If all recessions below a given treshold are used, there is a significant correlation between C-value and both starting value (Q_0) and length of recession (LENGTH). This implies limitations in the generality of the two parameter recession model (1). A decrease in Q_0 and an increase in LENGTH involve an increase in C-value, as also reported by e.g. Federer (1973) and Peiera & Keller (1982). In order to remove this influence, a standard recession is defined. Q_0 is limited to be the first value below an upper limit (QUL), and the recession segments are given equal lengths.

Fig. 1 presents the distribution of C-values together with the mean value (C-mean) and coeffecient of variation (Cv) for catchment 569 given different segment selection criteria. QUL is for all cases set to $0.75 * ADF$ (mean annual runoff). In a) no standard recession is defined, and the minimum length is seven days. The correlation with Q_0 and LENGTH is -0.28 and 0.33 respectively. In b) the standard recession is presented, LENGTH equals seven for all segments. In c) a precipitation limit of 1.0 mm is introduced.
As can be seen from C-mean and Cv values there is a reduction in C-mean and in variance moving from a) to c).



a) C-mean=8.3, Cv=0.42, No of rec=129

b) C-mean=6.1, Cv=0.22, No of rec=49

c) C-mean=5.4, Cv=0.16, No of rec=27

Fig. 1 Distribution of C-values for catchment 569

CLIMATIC INFLUENCES ON RECESSION

Many studies have been concerned with the effect of evapotranspiration on the streamflow recession (Federer, 1973; Langbein,1942; Singh, 1968; Tschinkel, 1963; Weisman, 1977). A seasonal variation in the recession rate has been found (Brandesten, 1988; Demuth, 1988; Grip, 1977; Singh and Stall, 1971). Jones & McGilchrist (1977) also found seasonal effects in recession, but in some cases there was no readily recognizable trend.

In this paper the interest is to detect if possible the influence on recession variability caused by recharge from precipitation and losses through evapotranspiration. Evapotranspiration (ET) is at this stage roughly represented by temperature (TEMP). The effect of ET on the recession curve depends upon type and extend of vegetation cover, lake percentage, physical characteristics of soil and geology and depth to groundwater table. The effect of precipitation (PREC) depends upon catchment responsetime reflected in its ability to produce a reduction in recession rate rather than a rise in streamflow.

Method 1

Standard recessions are computed with parameters $QUL = 0.75 * ADF$ (mean annual runoff) and LENGTH=7. For each segment the average temperature and precipitation values are calculated. Correlation with precipitation and temperature is tested for C-value and the results are presented in Table 1.

The correlation analysis is then repeated when recessions influenced by precipitation are removed. The threshold value for precipitation is set to 1.0 mm per day. The new values are presented below the line in Table 1.

The missing values on precipitation correlations for four catchments are due to the lack of explicit values for these stations, only 'precipitation-free' periods have been available.

Table 1 Correlations with C-value

Catchment	Day No.	TEMP	PREC	C-mean	Cv	No of rec
569	.33	-.38	-	5.9	.22	15
706	-.12	-.04	-	7.8	.35	15
873	-.63*	.06	.27	11.8	.39	15
895	-.11	-.10	-	5.0	.28	32
919	-.08	-.33	.18	4.9	.20	17
925	-.45*	.01	.29	4.6	.26	41
955	-.11	-.25	-	7.2	.21	35
1098	.04	.02	.67	11.3	.58	10
1591	-.15	.19	-.13	6.4	.67	14
2205	-.18	-.23	.59	4.2	.38	11
569	.62	-.49	-	5.2	.13	12
895	.48	-.48	-	4.3	.30	11
925	-.41	-.03	-	4.3	.26	24
955	-.28	-.78**	-	7.0	.20	19
1591	-.21	.15	-	6.6	.67	13

1-tailed Signif: * .01 ** .001

Because of the small number of recessions for most of the catchments it is hard to discuss the significance in the altered figures. However, there is a trend towards higher correlation with temperature when precipitation is removed. Introducing the threshold value for precipitation, leeds to a marked reduction in number of recessions, particulary for those catchments with high storage capacity. Generally, limitations on the precipitation value leed to a lower C-mean and a reduction in variance Cv, Fig.1. This effect on Cv might be lost because of the reduction in sample size.

Catchment 955 is the only catchment where C-value has a significant correlation with temperature (r=0.78, N=19). The catchment is situated on the northwestern coast, 97 % of the land is bare rock and the ordinary lake percentage is 11. The lack of vegetation might link temperature more directly to water losses.

Two catchments have significant correlation with daynumber, i.e. time of year. Both catchments are located on the coast, in western and northern Norway respectively, and have similar cover and vegetation properties. The negative sign relates rapid recession rates with high daynumbers. This is difficult to explain, perhaps influence of climate, not only during the recession, but also as reflected in antecedent moisture conditions might be important? Jones & McGilchrist (1978) were unable to relate indicators of catchment wetness to recession parameters.

Method 2

In work by Brandesten (1988), Federer (1973) and Grip (1980) streamflow recessions of the form $k = Q_{t+1}/Q_t$ are found to vary with seasonal changes in evapotranspiration.

All real data exhibit variability and one might discuss the use of quotients with a time period of only one day, because random errors influence the data too much. However, given sufficient time periods one might expect an existing pattern to be reflected in mean values. This work analyses the quotient for 9 catchments with corresponding climatic stations (precipitation and temperature data).

The original flow series are modified so that equal values are replaced with a loglinear interpolation. The resultant increase in number of recessions for group 3 (defined below) ranged from 5 to 167 %.

The k-values are subdivided into five groups according to the starting value, Q_t :

1) All k-values less than unity
2) Q_t < ADF (mean annual runoff)
3) Q_t < ADF and PREC <= 1.0 mm
4) ADF/2 < Q_t < ADF and PREC <= 1.0 mm
5) Q_t < ADF/2 and PREC <= 1.0 mm

Correlation analyses of k-value against Qt, daynumber, temperature (TEMP) and precipitation (PREC) are performed for all groups. TEMP is taken as the mean of day t and t+1, while PREC is given the value of day t+1. Neither group give any indication of correlation between k-value and TEMP or PREC. The only significant correlation in all groups is (not surprisingly) with Q_t. Mean k-value is lowest for group 1 and 4, and highest in group 5. Catchment 925 in Table 2 represents typically values for the analysis.

Table 2 Correlation with k-value

Catchm	Year	Day no	Q_0	TEMP	PREC	k-mean	Cv	No of rec
925	.07*	-.20**	-.57**	.16**	-.09**	.78	.15	2315
	.09**	-.16**	-.56**	.02	.03	.84	.10	1520
	.08*	-.20**	-.61**	.02	.02	.83	.10	1191
	.11	-.35**	-.31**	.10	.04	.74	.11	267
	.11**	-.19**	-.49**	.03	.06	.86	.08	923

1-tailed Signif: * .01 ** .001

It is likely that this is not a suitable method for detailed study of the influence by TEMP and PREC, because the recession periods are devided into small intervals. A prolonged warm period would probably result in an overall increase in the recession rate. However, due to the fact that the recessions tend to flatten as t increases, linking high k-values to high TEMP values, the effect is difficult to detect. An overall effect of PREC and starting value Q_t, can be seen in the mean k-values.

Monthly recession coeffecients are calculated on mean values of Q_{t+1}/Q_t for Q_t < ADF and PREC <= 1.0 mm (group 3), in order to detect any seasonal fluctuations in the recession rate, Table 3.

Only two catchments (1591 and 1892) show an indication of the expected seasonal pattern, with the steepest recessions to be found during the warmest months. Both catchments are situated in the lower eastern parts of Norway, and are the only catchments which are primary forested. Otherwise, the steepest recessions are found in September.

Table 3 Mean monthly recession rates k $=Q_{t+1}/Q_t$

Catchm		June	July	Aug	Sept
873	no of rec.	95	167	165	84
	k-mean	.92	.93	.93	.89
919	no of rec.	260	301	283	146
	k-mean	.85	.85	.84	.83
925	no of rec.	342	365	294	218
	k-mean	.86	.83	.81	.81
1098	no of rec.	0	78	211	129
	k-mean	-	.91	.93	.93
1116	no of rec.	10	127	270	138
	k-mean	.95	.95	.96	.93
1245	no of rec.	2	132	217	176
	k-mean	.96	.97	.98	.98
1591	no of rec.	202	188	238	178
	k-mean	.83	.80	.83	.84
1892	no of rec.	211	214	171	127
	k-mean	.85	.82	.82	.86
2205	no of rec.	94	98	80	42
	k-mean	.81	.76	.75	.72

This might be a result of more frequent storms interrupting the recessions, and a generally reduction in number of recessions support this. However, two of these catchments (873 and 925) also show a significant correlation with daynumber applying method 1.

This section demonstrates some of the uncertainties in interpreting the results from analyses using quotients of the type k-value. The method is not recommendable, unless studying an overall trend in mean values.

Further research

Generally, the correlation between C-value and temperature is low. It is probably necessary to introduce a more complex index of evapotranspiration (ET) in order to determine its influence. When estimating ET it is important to take into account different types of vegetation cover and their effect on the waterbudget. The catchments in this study cover a wide range in vegetation types and this might be one of the reasons why there is no clear pattern in the data. It is also important to distinguish between water lost by ET that would otherwise become streamflow and water that would not. Expressed in another way we need to obtain a better understanding of water movement at the field scale. This might lead to the recognition of a more detailed physical approach where the vertical waterbalance of a soil column is modeled, and thereby enables an estimate of water passing to and from the groundwater zone to be computed. Such a model could also assess the reduction in the recession rate due to slight precipitation.

There will be a continuation of the work presented here, as the results so far have not given sufficient understanding of the time variability in recessions. The aim is to understand the principles governing the recession curve and thereby be able to predict the recession rate given sufficient information about the factors affecting it. The work will concentrate on the ideas mentioned in this article, and hopefully new results presented at Bolkesjø in April, 1989.

REGIONAL REGRESSION ANALYSIS

The ability of a catchment to maintain high flows during dry weather depends upon its ability to both store and release water. It is generally accepted that it is necessary to include a numerical expression for the influence of soil characteristics and geology on the low flow behaviour of rivers. Browne (1981) has summarized a number of ways in which this effect might be numerically defined. Studies of the hydrogeology of drainage basins by use of recessions have been made by Farvolden (1963) & Knisel (1963).

The Institute of Hydrology in Wallingford (NERC, 1980) has developed the Base Flow Index (BFI) for the purpose of incorporating the influence of soil and geology. A previous study (Moltzau & Tallaksen, 1988) demonstrated that including the BFI in a low flow model for Norwegian catchments, increased the estimation accuracy of the regression equations. In this section BFI is replaced in an identical model by the recession constant. Vogel & Kroll (1988) found considerable improvements in regional regression relationships for low flow indices when including a base flow recession constant.

The low flow indices used are mean 7 and 30 day minimum runoff standardized by both area (MAM) and mean annual runoff (STD). Catchment characteristics selected are catchment area (AREA), relief-ratio (RELIEF), area above tree limit (ROCK) and weighted percentual lake area index (ASE). Two climatic indices are included, i.e. mean annual runoff (ADF) and mean annual precipitation (SAAR). Data from the summer period, 1.June to 30.September, for 68 discharge and precipitation stations are used, restricted to a uniform length of record. The average record length is 43 years. The selected catchments are evenly distributed geographically in Norway, ant the criteria used for accepting a catchment are :

a) a uniform period of record, minimum 20 years
b) catchment without glaciers
c) catchment without severe human impacts
d) catchment area less than 1000 km^2
e) a minimum of 10 recessions

The recession constants are calculated using standard recessions where QUL=ADF and LENGTH=8 days, chosen as a compromise between length of recession and number of segments. The number of recessions ranged from 11 to 65, with a mean value of 34. Data on precipitation is not included.

The values of the recession index are expected to be related to the nature of the catchment, quantified through geomorphological and climatic parameters. The question is whether it is possible to predict the streamflow recession curve (mean value) and variance from these parameters. This could be valuable in areas of insufficient or inexisting data. Rodriguez-Iturbe & Valdes (1979) linked the IUH with geomorphological parameters of a basin. Looking at the correlation matrix in Table 4, C-mean is not significant correlated to any of the geomorphological parameters represented here. However, drainage density, available at only 28 catchments, and the climatic parameter SAAR show a significant correlation at the 1 % level (-0.48 and -0.51). Further research should incorporate precipitation data, and thereby reduce the influence of climate. Hopefully, the relation to geomorphological parameters would improve. The recession constant is highly correlated with the low flow indices, particulary the STD values, as also reported by Bingham (1986).

Table 4 Correlation matrix

	MAM(7)	MAM(30)	STD(7)	STD(30)	ADF	SAAR	AREA	RELIEF	ROCK	ASE	BFI	C-MEAN
MAM(7)	-											
MAM(30)	.929**	-										
STD(7)	.562*	.332	-									
STD(30)	.575*	.415	.961**	-								
ADF	.399	.637**	-.382	-.337	-							
SAAR	-.073	.176	-.623**	-.614**	.806**	-						
AREA	-.121	-.229	.289	.296	-.468*	-.400	-					
RELIEF	.793**	.772**	.243	.255	.460*	.065	-.507*	-				
ROCK	.417	.581**	.187	.324	.438	.089	-.243	.315	-			
ASE	.111	.121	-.108	-.183	.336	.495*	-.163	.085	-.198	-		
BFI	.471*	.234	.735**	.651*	-.362	-.476*	.173	.269	-.052	.197	-	
C-MEAN	.420	.176	.914**	.830**	-.425	-.512*	.368	.107	-.045	.014	.770**	-
Cv	-.064	-.047	-.056	-.052	.012	.216	.150	-.142	-.151	.297	.113	.072

1-tailed Signif: * .01 ** .001

The coefficient of variation of the recession constant (Cv) is neither related to any of the geomorphological and climatic parameters nor to the low flow indices. This suggests that the variance of C-value is independent of the type of low flow regime, a fact also indicated in the lack of correlation with C-mean.

Stepwise multiple linear regression is used to develope the low flow model, and in Table 5 the coefficient of determination R^2 and the standard error of estimate are summarized. The recession constant (and BFI) are included in the regressions presented below the line in Table 5.

Numbers in bracket give the values from the corresponding analysis of 75 catchments (Moltzau & Tallaksen, 1988) where the Base Flow Index (BFI) represented storage properties.

Table 5 Regressions on catchment and climatic characteristics

Low flow indices	Catchment and climatic characteristics	R^2 values	Standard errors
MAM(7)	RELIEF, ADF, ROCK	60.2 (60.7)	5.47 (5.47)
MAM(30)	ADF, RELIEF, ROCK	75.8 (75.9)	8.16 (8.09)
STD(7)	SAAR, ROCK, RELIEF, AREAL	50.1 (50.8)	0.12 (0.12)
STD(30)	ROCK, SAAR, RELIEF, AREAL	50.0 (50.5)	0.14 (0.14)
MAM(7)	RELIEF, SAAR, C-MEAN, ROCK	75.3 (83.7)	4.34 (3.55)
MAM(30)	ADF, C-MEAN, ROCK, RELIEF, ASE	81.2 (85.6)	7.30 (6.30)
STD(7)	C-MEAN, ROCK, SAAR, RELIEF, ASE	82.5 (71.9)	0.07 (0.09)
STD(30)	C-MEAN, ROCK, ASE, RELIEF, AREAL	68.8 (63.3)	0.11 (0.12)

When low flow runoff is standardized by area (MAM), including the BFI leads to the highest increase in the estimation accuracy. However, when standardized by mean annual runoff (STD) the recession constant (C-mean) is preferred. This result might be influenced by the fact that mean annual runoff (ADF) is slightly correlated with C-mean (-0.42), although there also exists a correlation between BFI and C-mean (-0.36). Whether C-mean or BFI is preffered, they both demonstrate the importance of including a quantitative expression for storage capacity in a low flow model. The question remains as to what method to use when estimating the indexes at ungauged locations. The previous section shows that the recession constant is incompletely represented by the geomorphological and climatic parameters mentioned here. In UK the BFI has shown to be well correlated to soil type, while relatively independent of other characteristics. In mainland Europe relating the variability of BFI to soil properties have been less successful (Gustard & Gross, 1988).

Regional variation in the recessions

The recession values and coefficient of variation for 68 catchments were plotted on a map in order to study any regional pattern. C-mean shows little diversity in southeastern parts of Norway, while it elsewhere has a wider range. However, it is not possible to detect any regularity in this pattern. The middle range of coefficient of variation (Cv=0.2-0.6) are scattered all over the country, while the extreme values (low and high) are located closer to the coast, particulary in western Norway.

CONCLUSIONS

The objective of the first part of this study was to assess to what degree climatic data (precipitation and temperature) influenced the recession rate during the recession period. The recession characteristics were analysed by looking at mean value and variance of n estimates of the recession constant calculated from individual segments. The analysis is concentrated on methods and difficulties arising when trying to isolate the effect of climate on the recession variability. It is concluded that influence of precipitation is dependent on the catchment's storage capacity.

It has not been possible to find a significant relationship between temperature and recession values through these statistical analyses. Neither has there been any success relating the recession values to geomorphological characteristics. A further approach is to model the catchment system in order to assess a vertical water budget. In that way a more realistic estimate for waterlosses during recession periods could be obtained.

The second part demonstrates that including a recession constant in a low flow model increases the estimation accuracy of all the regression equations. The same effect is achieved incorporating the Base Flow Index. The recession constant is preffered when the low flow indices are standardized by mean annual runoff and the Base Flow Index preffered when they are standardized by area. Both analyses demonstrate the need for incorporating an expression for storage properties.

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