Landbrugsministeriet
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Preface

This report is the result of a collaboration between the Danish Institute of Plant and Soil Science and the Danish Land Development Service. Participators from the Danish Institute of Plant and Soil Science were Douglas R. Clark, Jørgen E. Olesen and Harald E. Mikkelsen. Participators from the Danish Land Development Service were Stig Ulf Clausen and Jesper Waagepetersen.

This report makes an evaluation of the effect of changes in climatic conditions on runoff from nine Danish catchments. The effects of changes in drainage, urbanization etc. on runoff in the same catchments is covered by another report (Waagepetersen et al., 1991).

The Danish Meteorological Institute is gratefully acknowledged for providing data on precipitation and sunshine hours. Department of Land Data has provided data on land use and soil types. Hydrological Survey of the Danish Land Development Service has provided data on stream flow.

Foulum, December 1991

Jørgen E. Olesen

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Resumé

Tidsserier for månedlig nedbør, afstrømning og fordampning er estimeret for 1918 til 1987 for 9 afstrømningsoplande i Danmark. Gennemsnitsnedbøren i oplandene er beregnet ved en grid-analyse af data fra nedbørstationer. Data for afstrømning stammer fra stationer med vandføringsmålinger. Estimater for månedlig aktuel fordampning i afstrømningsoplandene er beregnet fra estimater af aktuel fordampning for seks jord-afgrøde kombinationer. Værdierne for oplandene er arealvægtede gennemsnit for de forskellige jord-afgrøde kombinationer, idet der er anvendt oplysninger om fordeling af jordtyper, afgrøder m.v. Estimaterne for månedlig aktuel fordampning for de enkelte jord-afgrøde kombinationer er fremkommet ved anvendelse af regressionsmodeller, der er kalibreret i forhold til estimater med WATCROS modellen for årene 1961-1987, hvor daglige meteorologiske data var til rådighed.

Månedsværdierne og andre afledte variable for oplandene er præsenteret som tidsserier for årlige gennemsnit, månedsgennemsnit og sæsongennemsnit. Den gennemsnitlige årlige variation i variablene er vist i diagrammer. 20 års gennemsnit af de årlige værdier er vist i tabeller for tre 20 års perioder fra 1928 til 1987 sammen med afvigelserne fra 60 års gennemsnittet.

Hovedvariationerne i tidsserierne på både kort og langt sigt er identiske i alle ni afstrømningsoplande. De største forskelle mellem oplandene ses i afstrømningen. Årlig gennemsnitlig nedbør stiger med ca. 10 % over perioden. Det meste af denne stigning forekommer i vinterhalvåret (oktober til marts). Estimaterne for gennemsnitlig årlig aktuel fordampning falder med ca. 6 % over perioden. Dette skyldes hovedsageligt færre soltimer om sommeren. Den gennemsnitlige årlige afstrømning stiger ca. 15 %, hvilket er konsistent med stigende nedbør og reduceret fordampning. Ændringerne i afstrømning varierer dog mellem de forskellige oplande afhængig af individuelle forhold for oplandene, herunder menneskeskabte forandringer.

Det gennemsnitlige årlige forhold mellem afstrømning og nedbør stiger fra ca. 35 % til ca. 37 % fra den første til den sidste 20 års periode. Dette skyldes delvis, at stigningen i nedbøren forekommer i vintermånederne, hvor en forholdsmæssig større del af nedbøren går til afstrømning. Der har gennem perioden også været en sæsonmæssig ændring i nedbørsfordelingen. I den første 20 års perioden var nedbøren størst i sommerperioden, mens den var størst i efterårsmånederne i den seneste periode.

Vandbalanceresidualerne (nedbør - afstrømning - fordampning) viser for alle oplande stigende positive værdier, hvilket kan fortolkes som en stigende opmagasinering af vand i oplandene. I gennemsnit over de 60 år udgør vandbalanceresidualerne ca. 5 % af nedbøren.

Disse residualer er for store til at kunne tillægges stigende opmagasinering i oplandene. Den seneste korttids trend i residualerne har været et fald fra en top i 1980, med negative værdier eller værdier nær nul i alle oplande i 1987.

De store vandbalanceresidualer antyder skævheder i estimeringsprocedurerne. Potentiel og aktuel fordampning kan være underestimeret, eller oplandsarealet med potentiel fordampning kan være underestimeret. Ved beregning af månedsværdier for aktuel fordampning anvendes kun en 2-måneders "hukommelse" i regressionsmodellerne. Dette er tilstrækkeligt til at repræsentere sæsonvariationen, men kan ikke repræsentere effekter af år til år ændringer i jordfugtighed, grundvandshøjde eller udstrækning af vådområder. Dette vil kræve ændringer i både den daglige WATCROS-model og de månedlige regressionsmodeller.

Vandbalanceresidualerne kan også delvis tillægges overestimering af nedbøren på grund af overkorrektion for effekt af vind på opsamlet nedbørmængde. Afstrømningen kan i visse tilfælde være underestimeret fordi dele af det topografiske opland ikke bidrager direkte til afstrømningen. Dette gælder formentlig især oplande med fladt terræn som f.eks. Brede Å. Der kan også være signifikant grundvands afstrømning i visse af oplandene.

I denne undersøgelse er fordampningen i modsætning til de fleste andre hydrologiske undersøgelser estimeret uafhængigt af afstrømningsmålingerne. Fordampningsmålingerne er således ikke justeret under antagelse af, at målingerne af afstrømning og nedbør korrekte. I estimeringsprocedurerne er sæsonskævheder søgt undgået. Der er dog begrænsninger i de anvendte statistiske metoder, som kun kan overkommes gennem anvendelse af mere fysisk baserede simuleringsmodeller med daglige tidsskridt.

I denne undersøgelse er der ikke taget højde for mulige effekter af stigende gødskning på fordampningen. Brug af kunstvanding og effekter af nedbørsintensitet er ligeledes ikke inkluderet. Undersøgelsen inddrager dog de vigtigste klimatiske kilder til variation i afstrømningen. Skønt de absolutte værdier for oplandsvariablene kan indeholde skævheder, er de væsentligste karakteristika i deres variation vist i disse data.

Summary

Time series of monthly precipitation, runoff and evapotranspiration are estimated for 1918 to 1987 for 9 catchments throughout Denmark. Basin-average precipitation values are calculated from a grid analysis of data from stations reporting precipitation. Runoff values are obtained from streamflow measurements. Monthly basin evapotranspiration estimates are calculated from estimates of actual evapotranspiration for six crop-soil combinations. The basin values are area-weighted averages of the individual crop-soil values, using historical data on crop distributions, and other land use data. The crop-soil evapotranspiration estimates are obtained by regression models calibrated using the WATCROS crop water balance model for the 1961-1987 period for which daily meteorological data was available.

The monthly results and other derived catchment variables are presented in time series graphs of annual averages, individual monthly averages, and seasonal averages. Graphs of the average seasonal cycle of monthly values are given. Long-term (20-year) averages of the annual values are tabulated for three consecutive 20-year intervals spanning 1928 to 1987, along with departures of the annual and seasonal values from the 60-year means.

The major long-term (multi-year) and short-term (within year and year-to-year) variations are quite similar among all the nine catchments. The greatest differences among catchments are seen in the runoff data. Average annual precipitation increases about 10 percent over the period of the study, with much of this net increase occurring during the winter half-year (October to March). Estimated average annual basin evapotranspiration declines about 6 percent during the period of study, due primarily to reduced summer sunshine. Average annual runoff increases about 15 percent, consistent with the increased precipitation and reduced evapotranspiration. The runoff response varies among the individual catchments due to basin factors, including man-made changes.

The average annual runoff ratio increases from a value of about 35 percent to about 37 percent from the first 20-year interval to the most recent one. This can be attributed in part to the increase of precipitation in the winter months when evapotranspiration cannot extract a proportionate share of the increase. During the period there has also been a shift in the seasonal distribution of precipitation. In the first 20-year period precipitation peaked during summer, while peaking during autumn in the most recent period.

The basin water balance residuals (precipitation - runoff - evapotranspiration) all show increasingly positive values, meaning a rising rate of recharge of water storage in the catchments. On average over the 60 years the water balance residual is about 5 percent of the precipitation. These residuals are too large to be attributed to increased water storage in the catchments. The recent short-term trend in the residuals has been a decline from

a peak in 1980, with all of the catchments showing a near-zero or negative value (net annual decline in water storage) by 1987.

The large long-term water balance residuals that result from these estimates may indicate biases in the estimation procedures. Potential evapotranspiration could be underestimated, the actual evapotranspiration estimates could be underestimated, or the area of the basins that are assumed to evaporate at the potential rate may be underestimated. The monthly actual evapotranspiration model uses only a 2-month lag in calculations. This is sufficient for the seasonal variations, but can not represent the effect of persistent (year-to-year) changes in soil moisture, ground water levels, or the fluctuating extent and wetness of marshes, small ponds and other groundwater-dependent wetlands. Both the daily WATCROS model and the monthly statistical models would have to include long-term groundwater components to account for these additional sources of variation on evapotranspiration.

The water balance residuals may also be due, in part, to overestimation of precipitation, due to overcorrection for the effect of wind on the catch of the raingages. Runoff could be underestimated because parts of the topographically-defined surface drainage area may not contribute directly to the streamflow, especially in the flatter catchments like Brede Å. There could also be a significant, unmeasured groundwater discharge in some of these catchments, which could account for some of the residual excess.

An advantage of this study's estimation procedures, unlike most other hydrologic studies, is that the evapotranspiration has been estimated completely independent from the streamflow measurements. We do not "adjust" the evapotranspiration estimates under the assumption that the runoff and precipitation measurements are correct. Particular attention has been paid to avoidance of seasonal biases in the statistical estimation procedures. There are limitations to the regression approach which can only be rectified through the use of a more physically-based catchment and evapotranspiration model, using a daily time-step.

Factors not taken into account in this study include possible effects of increased fertilization on evapotranspiration, the use of irrigation, and the effects of changes in the frequency of high-intensity precipitation events which would not be reflected in monthly totals. The results do take the largest sources of climatic variation into account, however. While the absolute values of the catchment terms may contain biases, the major characteristics of their variability are clearly shown by these data.

1 Introduction

Public awareness of possible future climate changes – both natural and man-induced – has raised concerns about the sensitivity of Denmarks water resources to climate variations and land use changes. These concerns have created a need to assess the impacts of these variations and changes on ecosystems, agriculture, economics and society.

In recent years, both high and low water levels in streams have received public attention. The water flow in streams is of great importance, partly because the flow determines the ecosystem in the stream and surrounding areas, and partly because excessive precipitation may cause flooding of surrounding agricultural areas.

The variables involved in the hydrological cycle are interrelated by the water balance equation for a catchment:

$$P - E_a - Q = \Delta S \tag{1.1}$$

where P is the precipitation, E_a is loss of water by evapotranspiration, Q is the runoff and ΔS is the change in water storage in the basin. The storage term comprises changes in the water content in the root zone, the intermediate unsaturated zone and the saturated zone (ground water) and lakes or other surface water reservoirs. Runoff is runoff in streams and import or export of water in the ground water zone across the catchment boundaries.

Measurements of precipitation and streamflow have been made for many years in Denmark. These data enable numerical simulations of catchment water balances to be calibrated so that the unknown evapotranspiration and water storage terms can be estimated.

Various models have been used to describe the water balance of catchments in Denmark. Most models describe processes on a daily basis and have only been used for a limited number of years (Nielsen and Hansen, 1973; Refsgård, 1981; Aslyng and Hansen, 1982). These models are difficult to apply over a long period of time, because daily meterological data are only available in computer files for the last few decades. Monthly tabulations are available for the entire period of record.

The purpose of the study was to analyze the behavior of the streamflow, especially with respect to changes in land use and climatic conditions. The effect of changes in drainage and other man-induced changes on runoff pattern is discussed by Waagepetersen et al. (1991), whereas this report considers changes in climatic conditions.

This study described in this report makes use of both the available daily data and the long-term changes in catchment water balance for nine catchments in Denmark. A daily crop model (WATCROS) is applied over the period of daily data. The results of this daily model are then used to calibrate monthly statistical (regression) models to estimate monthly evapotranspiration over the whole period of monthly data. This provides estimates of evapotranspiration, which are completely independent from the streamflow measurements. These long-term results are then presented and analysed to identify the natural climatic variability in the catchments. These results are discussed in relation to known land use changes over the period of historical records.

2 Data material

Data on runoff, land use and climate from 9 catchments in Denmark have been used. The location of the catchments are shown in Fig. 2.1. The names of the streams in the catchments and the total area of the catchments are shown in Table 2.1. Data on the topographic area of the catchments were provided by Department of Land Data.

The catchments were chosen to give a representative coverage of the entire country. Another selection criteria was the availablility of a long time series on streamflow data.

2.1 Physiographic data

Data on land use in the catchments were available from a database at the Department of Land Data, cf. Table 2.2. These data were digitized from maps that were drawn rather recently. We have assumed that the major land use components of the catchments have not changed during the period from 1914 to 1988. Changing crop patterns were estimated, however, on the agricultural land.

Table 2.3 shows the soil types in the agricultural areas of the catchments. The soils have been classified according to top soil texture (Madsen og Holst, 1987). The classification criterions are shown in Table 2.4. These data were also acquired from the database at Department of Land Data.

Data on crop distribution within the agricultural area were not available for each catch-

Table 2.1: Catchments used in the study.

Number	Stream	Area (km^2)	Region	County
1	Lindenborg Å	213.78	Northeast Jutland	Nordjylland
2	Gudenå	192.43	Eastcentral Jutland	Vejle
3	Århus Å	119.89	East Jutland	Århus
4	Brede Å	293.37	South Jutland	Sønderjylland
5	Odense Å	308.48	Fuenen	Fyn
6	Brende Å	70.85	Fuenen	Fyn
7	Harrested Å	15.47	West Zealand	Vestsjælland
8	Saltø Å	66.57	West Zealand	Vestsjælland
9	Tryggevælde Å	128.41	East Zealand	Storstrøm

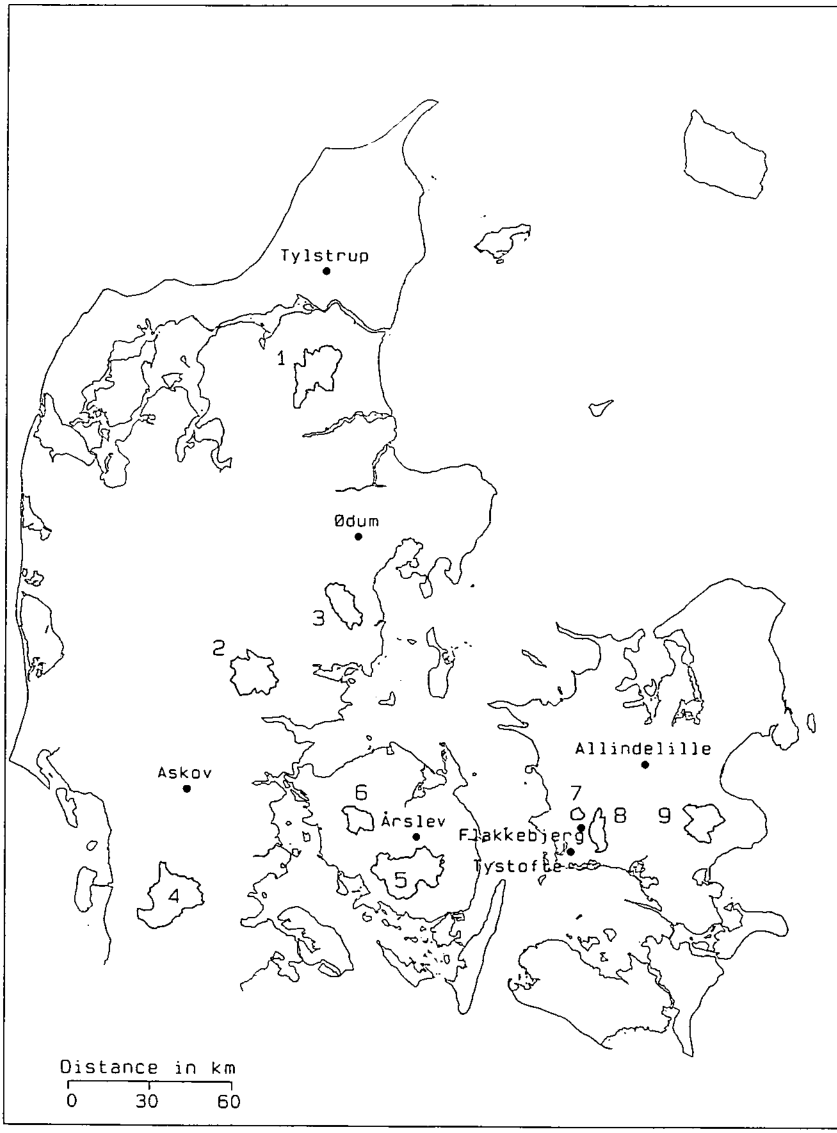

Figure 2.1: Location of catchments and meteorological stations.

Table 2.2: Land use in the catchments, % of catchment area.

Catchment	Agricultural area	Urban area	Forest	Lakes	Other	Non classified	Total (ha)
1	69.0	2.6	26.0	1.2	0.7	0.5	21378
2	92.1	1.8	5.2	0.1	0.3	0.4	19243
3	82.4	9.0	4.7	3.5	0.2	0.1	11989
4	92.5	0.9	6.2	0.0	0.3	0.1	29337
5	77.5	3.3	16.1	1.8	0.6	0.7	30848
6	83.1	4.7	10.8	0.4	0.5	0.5	7085
7	98.4	0.2	0.5	0.1	0.8	0.0	1547
8	89.1	0.5	10.2	0.0	0.2	0.0	6657
9	76.2	1.1	21.9	0.7	0.1	0.0	12841

Table 2.3: Soil types in the agricultural areas of the catchments, % of agricultural area.

Catchment	Coarse sand	Fine sand	Sand with clay	Clay with sand	Clay	Heavy clay	Humus	Special Soil
1	17.9	27.7	41.4	1.3	0.0	0.0	11.6	0.1
2	36.4	0.0	28.7	22.9	5.8	0.0	6.2	0.0
3	1.2	0.0	30.3	60.2	4.8	0.4	3.0	0.0
4	68.1	0.1	16.2	0.6	0.0	0.0	14.9	0.2
5	0.6	0.1	42.1	52.6	0.7	0.0	3.8	0.0
6	0.2	0.0	26.5	54.3	1.1	9.1	8.9	0.0
7	0.0	0.0	0.0	90.8	7.4	0.0	1.8	0.0
8	0.0	0.6	11.0	70.9	15.2	0.0	2.2	0.0
9	0.0	0.0	15.4	67.0	15.9	0.5	1.1	0.0

Table 2.4: Soil types in the Danish soil classification (Madsen og Holst, 1987).

		Weight %				
		Clay	Silt	Fine sand	Total sand	Humus
Soil type	No	$< 2\mu m$	$2 - 20\mu m$	$20 - 200\mu m$	$20 - 2000\mu m$	58,7 % C
Coarse sand	1	0-5	0-20	0-50	75-100	<10
Fine sand	2			50-100		
Coarse sand with clay	3	5-10	0-25	0-40	65-95	
Fine sand with clay	4			40-95		
Coarse clay with sand	5	10-15	0-30	0-40	55-90	
Fine clay with sand	6			40-90		
Clay	7	15-25	0-35		40-85	
Heavy clay	8	25-45	0-45		10-75	
Very heavy clay	9	45-100	0-50		0-55	
Silt	10	0-50	20-100		0-80	
Humus	11					>10
Special soil	12					

ment. The Danish Department of Statistics have published data on crop types for each county. The data from these counties have then been used to estimate the crop distribution in the catchments shown in Table 2.5. The crop distribution was estimated for three years during the period in question. There is a decline in grassland area in all catchments. This decline is most marked for the area with wetland grass. The areas with root crops and fallow have also been reduced.

2.2 Streamflow

Data on streamflow was recorded by the Hydrological Survey of the Danish Land Development Service. Systematic measurements of runoff started in 1917 in selected Danish streams. A review of the measurements and of the methods involved is given in Hydrological Survey (1978). Further details can be found in Hydrological Survey (1990).

The calculations of runoff are based on daily flow (discharge) values at the gauging stations. The height (H) of the water in the stream (current meter measurement) is recorded daily. This was previously recorded manually at most stations only once pr. day, but later by automatic water level recorders at all stations considered in this study.

At regular intervals streamflow measurements are made with an instrument, which records the water velocity in a cross-section of the stream. This enables an exact calculation of the flow (q) in the stream. These measurements were previously done 4 to 5 times per year and in the later period 8 to 12 times per year.

Table 2.5: Crop types in the catchments, % of agricultural area.

Catchment	Year	Spring grain	Winter grain	Root crops	Fallow	Grass[1]	Wetland grass[1]	Other grass[1]
1	1925	10.5	31.9	15.9	4.5	37.3	13.7	23.6
Linden-	1955	3.8	36.3	18.9	0.1	40.9	8.5	32.4
borg Å	1984	14.5	51.6	7.2	0.0	26.6	3.3	23.3
2	1925	9.1	35.7	16.8	3.7	34.6	10.8	23.8
Gudenå	1955	2.8	42.2	20.0	0.2	34.9	8.0	26.8
	1984	22.6	47.0	7.1	0.2	23.2	5.2	17.9
3	1925	9.3	37.4	18.8	3.0	31.6	8.5	23.1
Århus Å	1955	5.4	42.4	19.1	0.4	32.7	5.3	27.4
	1984	29.0	48.7	4.7	0.1	17.5	2.0	15.5
4	1925	8.7	28.0	10.0	1.6	51.7	29.2	22.5
Brede Å	1955	5.2	38.6	12.6	0.1	43.5	15.1	28.4
	1984	24.1	39.0	7.0	0.0	29.8	1.0	28.8
5	1925	10.4	39.9	17.4	3.8	28.5	9.4	19.0
Odense Å	1955	6.1	45.4	18.6	0.2	29.6	5.1	24.6
	1984	34.9	41.5	10.0	0.1	13.4	0.7	12.7
6	1925	10.4	39.9	17.4	3.8	28.5	7.6	20.8
Brende Å	1955	6.1	45.4	18.6	0.2	29.6	4.8	24.8
	1984	34.9	41.5	10.0	0.1	13.4	1.9	11.5
7	1925	11.6	39.6	16.5	6.4	25.9	2.9	23.0
Harre-	1955	6.2	50.5	16.3	0.4	26.7	1.8	24.9
sted Å	1984	23.7	58.6	7.4	0.2	10.0	0.6	9.4
8	1925	11.6	39.6	16.5	6.4	25.9	3.4	22.5
Saltø Å	1955	6.2	50.5	16.3	0.4	26.7	1.8	24.9
	1984	23.7	58.6	7.4	0.2	10.0	0.2	9.8
9	1925	10.1	41.4	20.2	5.0	23.4	3.7	19.7
Trygge-	1955	7.1	50.3	20.5	0.2	21.8	2.8	18.9
vælde Å	1984	37.4	38.6	18.6	0.1	5.3	1.9	3.4

[1]Area with grass includes wetland and other grass.

2

Table 2.6: Location of climatic stations with temperature or sunshine data. (d) marks daily data and (m) marks monthly data.

Station	Latitude	Longitude	Height m	Tempe-rature	Sun-shine
Tylstrup	57°11'N	9°57'E	13	d	d,m
Ødum	56°15'N	10°08'E	61	d	d
Askov	55°28'N	9°07'E	63	d,m	d,m
Årslev	55°18'N	10°27'N	48	d,m	d,m
Tystofte	55°15'N	11°20'N	13	d,m	d,m
Allindelille	55°31'N	11°46'N	59	d	
Flakkebjerg	55°20'N	11°23'N	33	d	

The basic rating curve, i.e. stage-discharge relation, between stream flow and height of the water is determined for periods where the effect of weeds in the stream can be ignored. The stage-discharge relation is described by

$$q = a(H - H_o)^b \tag{2.1}$$

where a and b are empirical constants and H_o is a correction for the difference between recorded water levels and the mean level of the streambed.

The actual stage-discharge relation for the stream also depends on the amount and structure of weeds in the stream. A system of stage-discharge relations is constructed for each stream based on the basic stage-discharge relation and the streamflow measurements. Information on weeds and ice in the stream is then used to define the actual stage-discharge relation. This stage-discharge relation is used to convert daily measurements of height to daily discharge, which is divided by the catchment area shown in Table 2.1 giving the runoff in mm.

The size of the catchments has been determined from the topographic watershed (surface water divide). In case of low relief around the watershed this can give rise to some error in the catchment area, which also will show up as a systematic error in the water balance. The errors may be due both to difficulties in defining topographic watershed, and in deviations of groundwater watershed from the topographic watershed.

2.3 Meteorological data

Meteorological data from a number of stations have been used. The data material comprises daily and monthly data for temperature, precipitation and sunshine. Table 2.6 shows the stations with temperature and sunshine data. These stations are also marked on the map in Fig. 2.1.

Table 2.7: Stations used for obtaining daily climatic data for catchments.

Catchment	Period	Temperature stations	Sunshine stations
1. Lindenborg Å	1961-1988	Tylstrup	Tylstrup
2. Gudenå	1962-1988	Ødum/Askov	Ødum/Askov
3. Århus Å	1962-1988	Ødum	Ødum
4. Brede Å	1961-1988	Askov	Askov
5. Odense Å	1961-1988	Årslev	Årslev
6. Brende Å	1961-1988	Årslev	Årslev
7. Harrested Å	1961-1970	Tystofte	Tystofte
	1971-1973	Allindelille	Tystofte
	1974-1988	Flakkebjerg	Tystofte
8. Saltø Å	1961-1970	Tystofte	Tystofte
	1971-1973	Allindelille	Tystofte
	1974-1988	Flakkebjerg	Tystofte
9. Tryggevælde Å	1961-1970	Tystofte	Tystofte
	1971-1973	Allindelille	Tystofte
	1974-1988	Flakkebjerg	Tystofte

For detailed modelling of evapotranspiration, daily data from a number of stations during the period 1961 to 1988 was used. The combination of stations and catchments are shown in Table 2.7. During most of this period air temperature at 2 meters in standard screen were measured manually. During the last years the measurements were automated at some of the stations. Daily mean temperature is calculated as the mean of daily maximum and minimum temperatures.

Data from single precipitation stations were not directly used in the study. Instead data from different precipitation stations were interpolated as described in section 2.3.3.

2.3.1 Sunshine and solar radiation

Solar radiation is the primary energy source for evapotranspiration from land surfaces, but it has only recently been included in routine meteorological measurement programmes in Denmark. The duration of bright sunshine has been measured at Copenhagen since 1887, and across Denmark since the early 1900's. These data have been tabulated monthly since the beginning of the record by the Danish Meteorological Institute, and daily and hourly sunshine durations are available digitally beginning with 1961. We have used the sunshine data as a substitute for solar radiation measurements in this study, by correlation with recent solar radiation measurements.

All sunshine duration measurements in Denmark have been recorded using Campbell-Stokes type recorders. These devices use a glass sphere to focus sunlight onto a coated

Table 2.8: Stations used for monthly sunshine data, and estimation of missing data (shown with *). The catchments where these monthly data were applied to are also shown.

Station	Catchments
Tylstrup	1
Askov	2, 3, 4
Årslev	5, 6
Tystofte	7, 8, 9
Viborg	*
Højer	*
Jyndevad	*
Tystofte Huse	*
Flakkebjerg	*
København	*
Næsgård	*

chart mounted under the sphere, where bright sunshine "burns" a distinctive trace. The charts are changed daily, and the length of the trace is measured by hand.

In 1961, the World Meteorological Organization established new standards for sunshine measurements. The Danish Meteorological Institute adopted the new standard, and initiated a program of instrument replacement. The original recorders manufactured by Fuess were replaced by new Cassela instruments during the 1970's with several years of overlapping measurements at many locations. The new Cassela instruments were used for the published record as soon as they were installed. Appendix B provides a complete listing of sunshine observing stations in Denmark, their periods of record, and dates of instrument change, where available. Unfortunately, much of the overlapping data has not been tabulated, and no general statistical comparison of the old and new instruments has been published. For these reasons, no adjustment has been made to the published sunshine data for this study.

Only a few stations have a complete sunshine record for the entire period of this study (1917 to 1988). Four stations were selected to provide the long-term monthly sunshine data. These four, plus two others, were used for the daily sunshine data. The stations are listed in Table 2.6, and their location is shown on the map of Denmark in Fig. 2.1. Sunshine data for several of the catchments were obtained by averaging data from two sunshine stations that were used for each catchment for the daily model calculations, cf. Table 2.7. Table 2.8 shows the stations used for obtaining monthly data.

A small number of months of sunshine data were missing in the monthly data from the four sunshine stations. These data were estimated by a weighted average of simple linear regression estimates from the other sunshine stations. These regression estimators were calibrated over the available period of non-missing data for each pair of stations, with separate regressions calculated for each of the 12 months of the year. The monthly sunshine records from additional stations listed at the bottom of Table 2.8 were included in this estimation procedure. The individual regression estimates were averaged together, weighted by the inverse square of the distance between each station pair, and also by the multiple correlation coefficient of the regression.

2.3.2 Regression estimates of solar radiation

Both daily and monthly sunshine duration data were converted to estimates of solar radiation for use in the models. Daily sunshine hours were converted using the empirical procedure proposed by Rietveld (1978). This procedure has been successfully verified for Danish conditions by Olesen (1990). The same approach was used for the monthly sunshine values, but the two coefficients for the conversion were specifically calibrated for monthly data in Denmark, using monthly sunshine and solar radiation data for several stations in 1987 and 1988. The stations used were the same as the stations used by Olesen (1990).

The resulting regression equation (estimated without offset) was

$$R_{si} = R_{se}(0.206 + 0.569 \times \frac{N}{N_m}) \tag{2.2}$$

where R_{se} is the monthly average extraterrestrial solar radiation, N is the monthly hours of sunshine observed and N_m is the number of daylight hours in the month. The square correlation coefficient for this regression was 0.996, from a sample size of 102.

2.3.3 Precipitation

In spite of the rather small size and low relief of the country, the precipitation in Denmark is rather unevenly distributed. Therefore, when considering the precipitation for small areas such as catchments for streams of modest size, the standard meteorological data which are grouped according to the administrative division in counties, provide insufficient resolution.

The catchments were supplied with a grid, 1×1 km for the smaller catchments, 2×2 km for the larger and more homogenous catchments. The number of grid elements for each catchment is given in Table 2.9. The precipitation P_i for the grid element i is found from the precipitation P_j at station j according to

$$P_i = \sum_{j=1}^{n} \frac{P_j}{r_{ij}} / \sum_{j=1}^{n} \frac{1}{r_{ij}} \tag{2.3}$$

r_{ij} is the distance between the center of the grid element and the precipitation station. The value of n (the number of precipitation stations used) was determined by a) using all information from active precipitation stations for which $r_{ij} < 10$ km. If $n \geq 3$ after this, no further information is used. Otherwise b) by increasing the search radius in steps of one kilometer until $n \geq 3$. The actual number of precipitation stations used for the

Table 2.9: Grid elements used for interpolation of precipitation.

Catchment	Size of grid elements (km)	Number of grid elements
1. Lindeborg Å	1×1	215
2. Gudenå	2×2	49
3. Århus Å	1×1	118
4. Brede Å	2×2	75
5. Odense Å	2×2	73
6. Brende Å	1×1	74
7. Harrested Å	1×1	15
8. Saltø Å	1×1	69
9. Tryggevælde Å	1×1	130

calculation of precipitation data for the grid elements vary with time and place. Before 1961, the typical number was 3 stations, whereas in the period 1961-88 there is often more stations (4-8) within the base radius of 10 km, especially for catchments 5 through 9.

Each grid element is assumed to represent equal fractions of the total area of the catchment. The mean precipitation for the entire catchment can therefore be calculated by forming a simple average over the values for the grid elements. This procedure was used to estimate monthly catchment precipitation for the period from 1918 to 1987, and daily precipitation for the period 1961 to 1988.

2.3.4 Correction of precipitation

At climate stations in Denmark precipitation is recorded with Hellman raingauges placed 1.5 m above ground. This introduces some errors in the precipitation data, mainly due to aerodynamic influence and partly due to wetting loss.

In a study comprising 20 stations across Denmark for a period of at least two years Allerup and Madsen (1979) found that normal exposed Hellmann raingauges only catch about 85 % of the true precipitation on a annual basis. The correction factors were, however, dependent on both the exposure of the stations and the season, cf. Table 2.10. Allerup and Madsen (1979) suggest that Danish climate stations could in general be considered moderately sheltered.

Aslyng and Hansen (1982) compared areal precipitation obtained in two different manners for two catchments in Denmark for the months April to November over a 10 year period. First the precipitation was obtained from a number of climate stations, where precipitation was recorded 1.5 meters above ground. The second manner was to take the mean of 6 stations for each catchment, where precipitation was recorded at ground level. For these months they found a relative deviation of about 7 %. The precipitation at ground level

Table 2.10: Monthly correction factors (%) for standard normals of precipitation due to aerodynamic effect and wetting loss (Allerup and Madsen, 1979).

Station shelter	J	F	M	A	M	J	J	A	S	O	N	D	Year
Unsheltered	29	31	31	22	18	17	14	13	16	18	20	25	20
Moderate shelter	21	22	22	18	15	14	12	11	13	14	16	19	16
Well sheltered	18	19	20	14	12	11	9	9	10	10	12	15	12

was, however, not corrected for wetting loss. An investigation by Holst and Kristensen (1981) suggests that the wetting loss for precipitation gauges at ground level is about 2 %. The total relative deviation thus amounts to about 9 %, corresponding with well sheltered stations in Table 2.10.

In the present study the precipitation has been corrected assuming that stations are typically moderately sheltered. The monthly correction factors shown by Allerup and Madsen (1979) for correcting standard normals for moderately sheltered stations have been applied to both monthly and daily precipitation data for the catchments.

3 Estimation of actual evapotranspiration with WATCROS model

Daily actual evapotranspiration was calculated with the WATCROS model (Aslyng and Hansen, 1982; Hansen, 1984). The model runs with a daily time step and estimates potential and actual evapotranspiration from agricultural crops. The model requires only a limited number of meteorological variables: daily values of global radiation, air temperature and precipitation.

WATCROS calculates the crop surface area of the vegetation using simple temperature sum models. Efficient root depth is calculated using a constant root growth rate. The soil is characterized by root zone capacity and maximum root depth. The model simulates evaporation of intercepted water, evaporation from the soil surface and transpiration by plants.

A modified Makkink equation (Aslyng and Hansen, 1982) was used for calculating potential evapotranspiration

$$E_p = 0.7 \frac{s}{\gamma + s} \frac{R_{si}}{\lambda} \tag{3.1}$$

where s is the slope of the curve of saturated vapor pressure versus temperature, γ is the psychrometric constant, R_{si} is the global radiation, and λ is the latent heat of vaporization of water.

This equation has physical validity for the summer months (April to October) only. de Bruin (1987) suggest, however, that this method also will provide reasonable estimates for the winter months. As the evapotranspiration is rather low during the winter months in Denmark, we have applied this equation for the entire year.

The WATCROS model was applied using daily data for the period 1961 to 1988. Data for daily precipitation for the catchments was obtained using the same procedure and the same stations as for the monthly precipitation. Data for daily mean temperature and sunshine hours were obtained from stations close to the catchments, cf. Table 2.7 and Fig. 2.1. Sunshine hours were converted to global radiation, cf. section 2.3.2.

The WATCROS model was run for selected combinations of crop types and soil types. The following agricultural crops were used: grass, winter wheat, spring barley and fodder

Table 3.1: Characteristics of the selected soil types used in the study. Most parameters relate directly to the WATCROS model.

Parameter	Sand	Loam
Soil type number	1	4
Soil type name	Coarse sand	Fine sand with clay
Max. root depth (cm)	50	100
Plant available water (mm)	60	130

Table 3.2: Mean annual actual evapotranspiration in mm for different crop and soil types calculated with the WATCROS model for the years 1961 to 1988 for Odense Å. The mean potential evapotranspiration is 547 mm per year.

	Soil type number							
Crop	1	2	3	4	5	6	7	8
Grass, grazing	421	446	437	438	443	443	443	443
Grass, cut	421	465	436	456	465	472	472	472
Winter wheat	407	460	424	450	461	469	469	469
Spring barley	393	433	407	425	433	438	438	438
Potato	396	425	407	415	420	423	423	423
Fodder beet	397	423	407	419	424	427	427	427
Spring rape	400	440	413	432	441	447	447	447
Bare soil	327	327	327	327	327	327	327	327

beet. These crops were combined with a sandy and a loam soil. The main characteristics of the selected soils are shown in Table 3.1.

This selection of soils and crops only comprises some of the possible combinations of crops and soil types. To test the validity of these selections a test run was made with the WATCROS model with a larger range of soil types and crops. This was only done for the years 1961 to 1988 for catchment number 5, Odense Å. The mean annual actual evapotranspiration of this test run is shown in Table 3.2.

The seasonal differences in actual evapotranspiration is shown in Fig. 3.1 for different combinations of crop and soil type. The depicted values were calculated with the WATCROS model for 1977 in catchment 5, Odense Å. The graphs show how different crops transpire in different parts of the season. Grass has a rather uniform transpiration relative to potential over the season, whereas the grain crops are more effective in the early part of the growing season, and the transpiration from fodder beet is restricted to the later part of the growing season.

Fig. 3.2 shows the year to year variability in annual actual evapotranspiration for diffe-

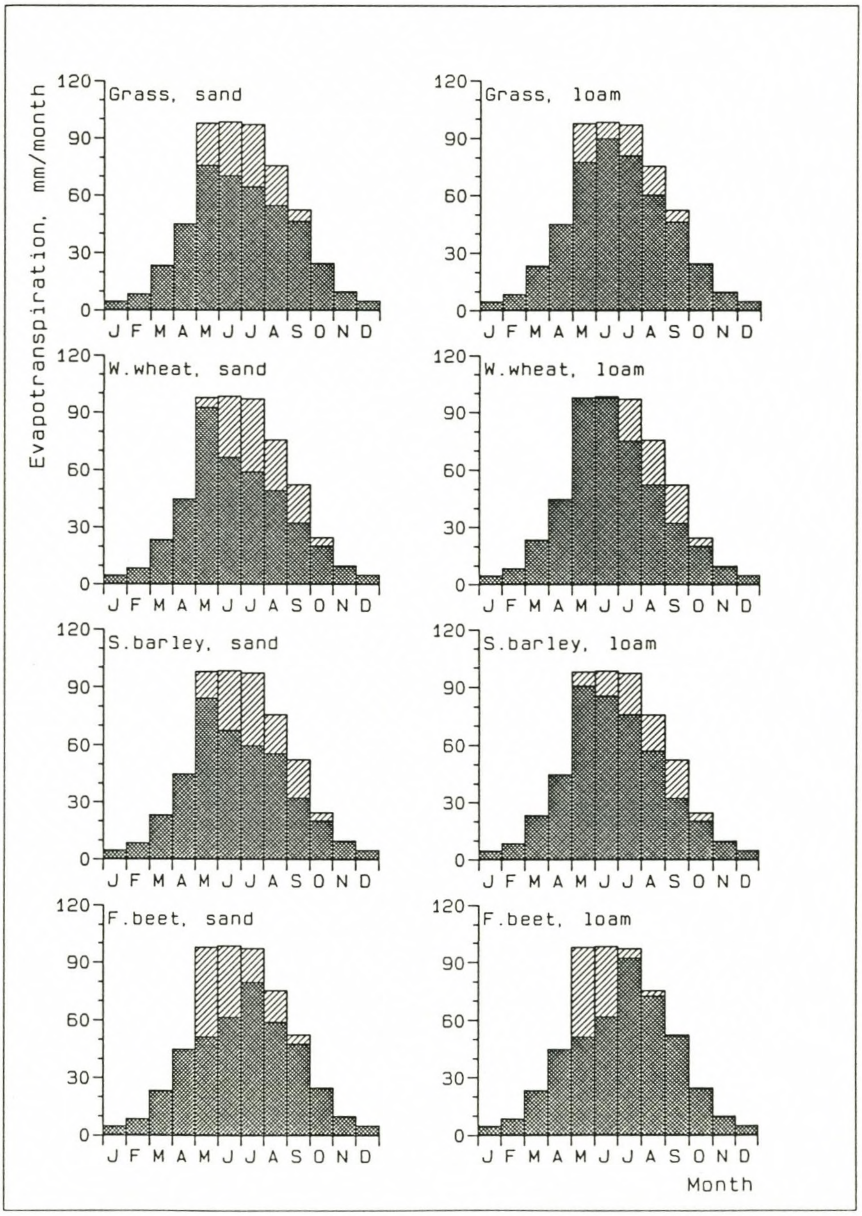

Figure 3.1: Monthly actual and potential evapotranspiration for different soil and crop types calculated with the WATCROS model for catchment 5, Odense Å, for 1977. The lower bars are actual evapotranspiration, and the upper bars are the difference to potential evapotranspiration.

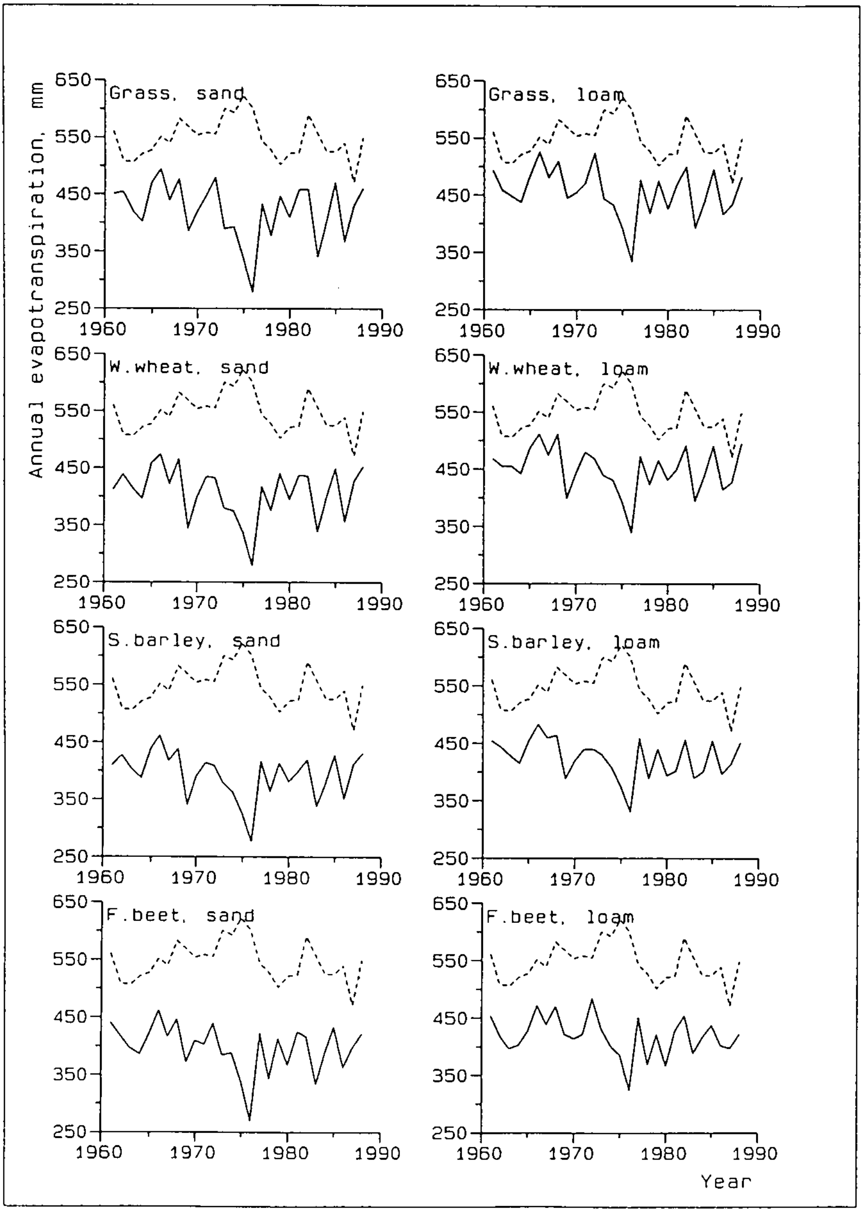

Figure 3.2: Annual actual (—) and potential (- - -) evapotranspiration for different soil and crop types calculated with the WATCROS model for catchment 5, Odense Å.

rent combinations of crop and soil types. The depicted values were calculated with the WATCROS model for catchment 5, Odense Å. There is some year to year variability in actual evapotranspiration. The variation in actual evapotranspiration does not always match the corresponding variation in potential evapotranspiration, as low soil moisture may limit actual evapotranspiration. The data series includes one very dry year, 1976.

4 Estimation of monthly evapotranspiration by regression

Estimates of monthly potential and actual evapotranspiration have been calculated for each of the nine catachments by a series of multiple regression models. These monthly models are derived using monthly averages of the results from the daily WATCROS model for the period 1961 to 1988. These calibrated regression equations are then applied using monthly meteorological data for 1917 to 1988 to give the historical estimates of actual evapotranspiration.

4.1 Estimation of potential evapotranspiration

Monthly solar radiation is used to predict monthly potential evaporation, using a regression equation of the form given in equation 4.1.

$$E_p = \beta_0 + \beta_1 R_{si} + \varepsilon \qquad (4.1)$$

where β_0 and β_1 are regression parameters, R_{si} is the monthly global solar radiation, and ε is the error of the estimate. Monthly sums of Makkink potential evaporation was the dependent variable. Separate regressions were carried out for each catchment and for each of the 12 months of the year, resulting in a total of 108 pairs of regression coefficients. The use of separate regressions for each month automatically takes into account average seasonal variations in temperature. This makes this modelling approach more robust than a single regression on solar radiation (sunshine) over all months. Temperature was not included in the model, as monthly mean temperatures were not available for all catchments.

Figs. 4.1 and 4.2 show the regression estimates versus Makkink estimates of potential evapotranspiration monthly for the winter and summer half year, respectively. The use of different scales in the two graphs should be noted. The regression equations seem to provide fairly good estimates of potential evapotranspiration.

4.2 Estimation of crop evapotranspiration

Monthly actual evapotranspiration has been estimated over the entire data period by a linear regression model which incorporates both the current and previous months precipitation and potential evapotranspiration. Separate regression estimates were derived for each of the eight combinations of two soil types and four crop types simulated with

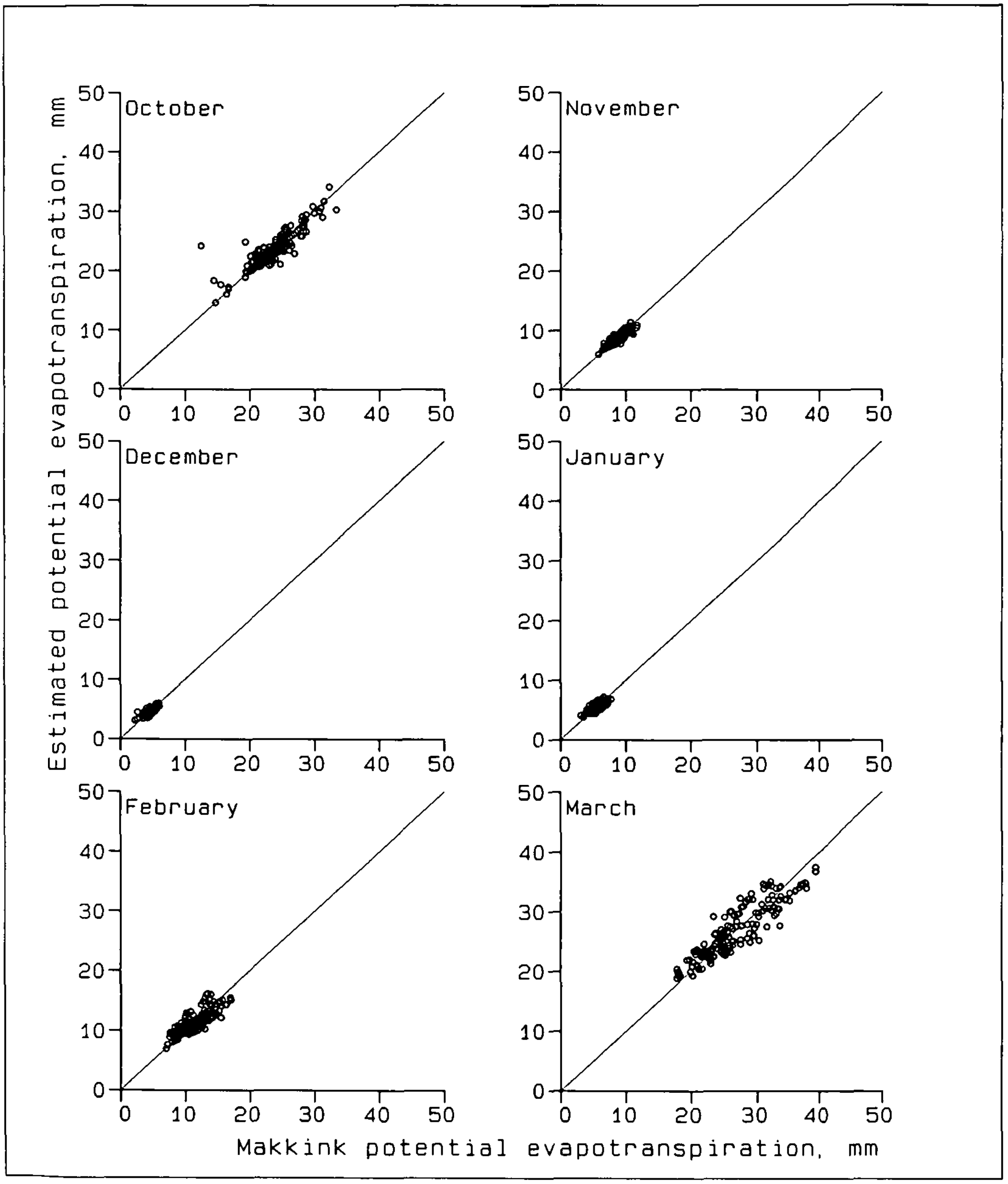

Figure 4.1: Estimated potential evapotranspiration by regression versus Makkink calculated evapotranspiration for the winter half year. Data from 9 catchments 1961 to 1988.

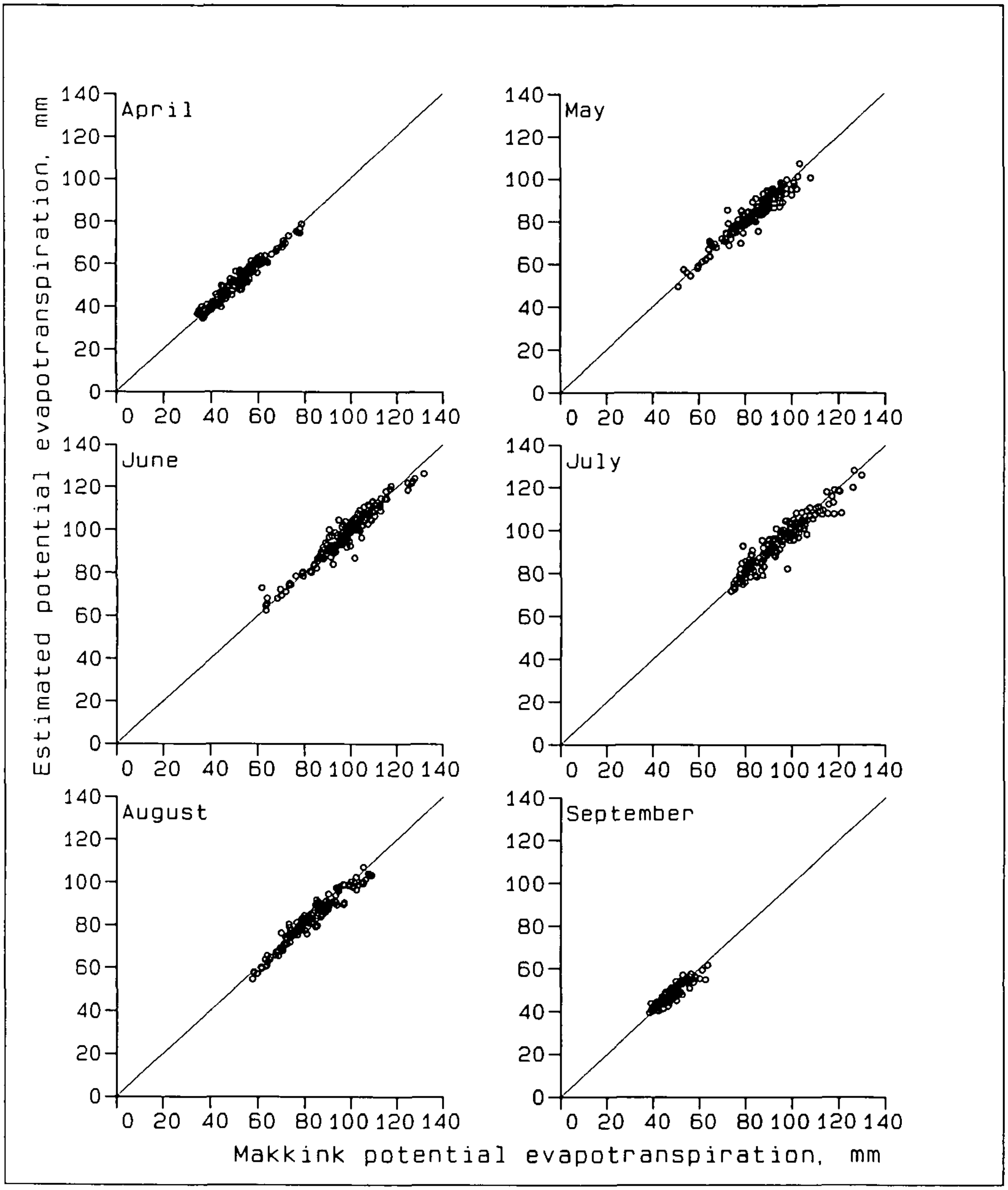

Figure 4.2: Estimated potential evapotranspiration by regression versus Makkink calculated evapotranspiration for the summer half year. Data from 9 catchments 1961 to 1988.

the WATCROS model. Separate regressions were carried out for each month from March to October giving 64 sets of regression parameters. Data for all of the catchments were combined in this procedure. The winter months, November to February, were assumed to have evapotranspiration equal to the potential value, which was true for most of the winter estimates calculated with the WATCROS model.

The dependent variable in the regression equation was the monthly sum of the daily WATCROS estimates. These data were available for 1961 to 1988. The independent variables were crossproducts of monthly potential evapotranspiration and several precipitation terms, which are explained below. Equation 4.2 shows the form of the equation:

$$E_c = \beta_0 + E_{p0}(\beta_1 + \beta_2\sqrt[3]{P_0} + \beta_3\sqrt[3]{P_1} + \beta_4 D_0 D_1 + \beta_5 E_{p1}) + E_{p1}(\beta_6\sqrt[3]{P_1}) + \varepsilon \qquad (4.2)$$

where E_c is the actual crop evapotranspiration, β_0 to β_6 are regression coefficients, P_0 and P_1 are precipitation in the current and previous months, E_{p0} and E_{p1} are potential evapotranspiration in the current and previous months, ε is the error term, and D_0 and D_1 are precipitation deficit terms defined as follows. D_0 and D_1 are the positive differences between potential evapotranspiration and precipitation in the present and previous months, as shown in equations 4.3 and 4.4:

$$D_0 = (E_{p0} - P_0)_+ \qquad (4.3)$$

$$D_1 = (E_{p1} - P_1)_+ \qquad (4.4)$$

These values are set to zero where precipitation exceeds potential evapotranspiration, so these only contribute to the equation where there is a "deficit" of precipitation. By using the product of these two values, a predictor variable is obtained which is only non-zero when there is a shortage of moisture in the two consecutive months. The other precipitation terms use the standard cube-root transformation, which helps to normalize the skewed distribution of precipitation values.

The parameters in equation 4.2 were estimated using the multiple linear regression procedures in the SAS statistical package (SAS Institute, 1988). The parameter estimates, the root-mean-square-error of the prediction (RMSE) and the squared correlation coefficients (fractions of variance explained) are given in Tables 4.1 to 4.4. The significance levels of individual parameter estimates are indicated by superscripts 1, 2 and 3 in the tables.

The meaning of the terms in the model can be described as follows. The constant β_0 represents the offset or intercept value of evapotranspiration when all the other terms are equal to zero. The remaining terms are in two groups. The first group is multiplied by the potential evapotranspiration in the current month and the second group (last term) is proportional to the previous months potential evapotranspiration. This gives a physically realistic dependence of actual evapotranspiration on solar energy, represented by the potential evapotranspiration terms. These terms are multiplied by expressions which account for the varying availability of moisture for evapotranspiration.

Table 4.1: Parameter estimates for the parameters in equation 4.2 for grass. 250 observations.

Month	$\hat{\beta}_0$	$\hat{\beta}_1$	$\hat{\beta}_2$	$\hat{\beta}_3$	$\hat{\beta}_4$	$\hat{\beta}_5$	$\hat{\beta}_6$	RMSE	R^2
Sandy soil									
3	-0.6	0.47	0.140^3	-0.081	-0.003750	-0.0184	0.277^1	3.40	0.42
4	17.9	-1.22^2	0.228^3	0.150^1	0.000029	0.0185^1	-0.141	6.13	0.59
5	4.1	0.87^3	0.104^3	-0.071^1	-0.000044^3	-0.0061^2	0.039	6.89	0.60
6	15.0	0.36	0.106^3	0.015	-0.000036^3	-0.0052^1	0.055	7.78	0.77
7	72.3^2	-1.09^1	0.095^3	0.170^2	-0.000038^3	0.0046	-0.099	8.26	0.81
8	110.8^3	-2.27^3	0.099^3	0.284^3	-0.000029^3	0.0090^1	-0.153^1	8.99	0.77
9	1.0	1.15^2	-0.001	0.020	-0.000193^3	-0.0052^1	0.017	4.35	0.69
10	29.2^3	-1.68^2	0.013	0.318^3	-0.000921^3	0.0253^3	-0.141^3	2.52	0.60
Loam soil									
3	-0.6	0.47	0.140^3	-0.081	-0.003749	-0.0184	0.277^1	3.40	0.42
4	21.3	-1.36^2	0.218^3	0.174^2	0.000033	0.0227^2	-0.183	6.41	0.56
5	-16.4	1.35^3	0.087^3	-0.114^3	-0.000036^3	-0.0082^3	0.104^1	6.61	0.62
6	30.7^1	-0.09	0.053^3	0.101^1	-0.000029^3	0.0017	-0.036	6.56	0.70
7	7.6	0.76	0.027^2	-0.005	-0.000038^3	-0.0027	0.054	6.19	0.79
8	80.0^3	-1.23^1	0.059^3	0.187^2	-0.000046^3	0.0063^1	-0.107	7.73	0.78
9	-9.0	1.64^3	-0.009	-0.050	-0.000153^3	-0.0077^3	0.053^1	3.95	0.68
10	19.8^3	-0.73	-0.000	0.211^3	-0.000526^3	0.0166^2	-0.096^2	2.06	0.66

Significance levels: ^{1}: 0.05>P>0.01, ^{2}: 0.01>P>0.001, ^{3}: 0.001>P.

Table 4.2: Parameter estimates for the parameters in equation 4.2 for winter wheat. 250 observations.

Month	$\hat{\beta}_0$	$\hat{\beta}_1$	$\hat{\beta}_2$	$\hat{\beta}_3$	$\hat{\beta}_4$	$\hat{\beta}_5$	$\hat{\beta}_6$	RMSE	R^2
Sandy soil									
3	-0.4	0.48	0.133^3	-0.078	-0.003587	-0.0170	0.274^1	3.30	0.42
4	22.1	-1.34^2	0.213^3	0.172^2	0.000031	0.0226^2	-0.183	6.38	0.55
5	-29.1^1	1.37^3	0.104^3	-0.112^3	-0.000048^3	-0.0083^3	0.139^1	7.29	0.65
6	-1.6	0.98^1	0.113^3	-0.048	-0.000039^3	-0.0108^3	0.125^1	9.70	0.75
7	92.4^3	-1.74^2	0.113^3	0.244^2	-0.000033^3	0.0075^1	-0.151^1	9.56	0.78
8	145.4^3	-2.74^3	0.078^3	0.329^3	-0.000019^3	0.0105^3	-0.214^3	7.30	0.77
9	12.8	1.08^1	0.090^3	-0.097	-0.000103^3	-0.0105^3	0.045	5.24	0.55
10	21.9^1	-0.80	0.061^3	0.169	-0.000395^2	0.0047	-0.052	3.54	0.31
Loam soil									
3	-0.4	0.48	0.133^3	-0.078	-0.003588	-0.0169	0.274^1	3.30	0.42
4	21.8	-1.32^2	0.210^3	0.169^2	0.000029	0.0223^2	-0.179	6.34	0.55
5	-32.1^2	1.31^3	0.064^3	-0.068^1	-0.000010	-0.0038	0.096	6.76	0.69
6	-27.1^1	1.42^3	0.005	-0.048	-0.000065^3	-0.0035	0.092^1	6.64	0.79
7	-11.9	1.20^1	0.001	-0.031	-0.000048^3	-0.0047^1	0.105^1	7.45	0.79
8	154.2^3	-2.85^3	0.068^3	0.343^3	-0.000029^3	0.0123^3	-0.247^3	7.12	0.77
9	16.7	0.89	0.092^3	-0.076	-0.000101^3	-0.0093^3	0.033	5.28	0.54
10	22.2^1	-0.82	0.060^3	0.171	-0.000395^2	0.0049	-0.053	3.53	0.31

Significance levels: ^{1}: $0.05>P>0.01$, ^{2}: $0.01>P>0.001$, ^{3}: $0.001>P$.

Table 4.3: Parameter estimates for the parameters in equation 4.2 for spring barley. 250 observations.

Month	$\hat{\beta}_0$	$\hat{\beta}_1$	$\hat{\beta}_2$	$\hat{\beta}_3$	$\hat{\beta}_4$	$\hat{\beta}_5$	$\hat{\beta}_6$	RMSE	R^2
Sandy soil									
3	-0.5	0.47	0.140^3	-0.081	-0.003744	-0.0184	0.277^1	3.40	0.42
4	40.1^3	-1.26^3	0.190^3	0.082	0.000020	0.0142^1	-0.121	4.83	0.70
5	27.3	-0.46	0.117^3	0.073	-0.000024	0.0066^1	-0.074	9.42	0.40
6	35.4	0.22	0.082^3	0.011	-0.000043^3	-0.0027	0.018	9.28	0.63
7	67.2^2	-1.04	0.098^3	0.168^1	-0.000035^3	0.0039	-0.082	8.66	0.80
8	131.3^3	-2.57^3	0.114^3	0.277^3	-0.000007	0.0095^2	-0.190^2	7.19	0.75
9	17.2	0.80	0.093^3	-0.066	-0.000101^3	-0.0088^2	0.031	5.30	0.54
10	22.2^1	-0.82	0.060^3	0.171	-0.000395^2	0.0049	-0.053	3.53	0.31
Loam soil									
3	-0.5	0.47	0.140^3	-0.081	-0.003744	-0.0184	0.277^1	3.40	0.42
4	39.9^3	-1.28^3	0.191^3	0.085	0.000025	0.0146^1	-0.125	4.84	0.69
5	29.8	-0.62	0.104^3	0.111^1	-0.000015	0.0096^2	-0.117	10.12	0.36
6	35.5^2	0.17	0.018^1	0.075^1	-0.000041^3	0.0025	-0.052	5.56	0.73
7	1.9	0.93^1	0.021^1	-0.004	-0.000042^3	-0.0034	0.057	6.05	0.82
8	121.1^3	-2.22^3	0.110^3	0.246^3	-0.000010^1	0.0081^2	-0.175^2	7.30	0.72
9	17.2	0.86	0.087^3	-0.071	-0.000104^3	-0.0091^3	0.033	5.24	0.54
10	22.2^1	-0.82	0.060^3	0.171	-0.000395^2	0.0049	-0.053	3.53	0.31

Significance levels: ^{1}: 0.05>P>0.01, ^{2}: 0.01>P>0.001, ^{3}: 0.001>P.

The coefficient β_1 reflects the base proportionality of actual evapotranspiration to potential evapotranspiration in the same month. The second term in parenthesis, $\beta_2\sqrt[3]{P_0}$, directly represents the available moisture from precipitation in the current month, while the next term, $\beta_3\sqrt[3]{P_1}$, reflects the carryover of precipitation from the previous month. The fourth term in the group $\beta_4 D_0 D_1$ has a negative coefficient in all but one month, representing a reduction of evapotranspiration from two consecutive dry months. The last term of the group, $\beta_5 E_{p1}$, represents the covariance between potential evapotranspiration in the current and previous month. The single precipitation term in the second group (last term on the right), $\beta_6\sqrt[3]{P_1}$, represents the availability of moisture in the previous month, which could be carried over to the current month.

These terms were selected from a much larger list of possible predictors through experimentation, assisted by stepwise regression. Stepwise regression could not be used for the final model, because different sets of predictors would be selected for each of the separate regressions. We chose to select the single set of predictors, which had both a physical rational and predictive capability across all months and for all the crop-soil combinations. From Tables 4.1 to 4.4, it can be seen that the significance of the individual terms varies from case to case.

Table 4.4: Parameter estimates for the parameters in equation 4.2 for fodder beet. 250 observations.

Month	$\hat{\beta}_0$	$\hat{\beta}_1$	$\hat{\beta}_2$	$\hat{\beta}_3$	$\hat{\beta}_4$	$\hat{\beta}_5$	$\hat{\beta}_6$	RMSE	R^2
Sandy soil									
3	-0.5	0.47	0.140^3	-0.081	-0.003744	-0.0184	0.277^1	3.40	0.42
4	43.6^3	-1.15^3	0.171^3	0.056	0.000019	0.0112	-0.093	4.44	0.73
5	49.4^3	-0.50^1	0.131^3	0.008	-0.000032^3	-0.0003	-0.030	6.54	0.70
6	92.9^3	-1.57^2	0.114^3	0.166^2	0.000020^2	0.0053	-0.101	10.15	0.34
7	-17.0	1.10	0.070^3	-0.126	-0.000042^3	-0.0039	0.135^1	8.94	0.65
8	100.9^3	-1.87^2	0.068^3	0.271^3	-0.000043^3	0.0081^1	-0.145^1	8.73	0.79
9	-6.2	1.42^3	0.002	-0.007	-0.000189^3	-0.0067^2	0.033	4.36	0.70
10	20.1^2	-0.99	0.007	0.245^3	-0.000949^3	0.0197^3	-0.105^2	2.31	0.68
Loam soil									
3	-0.5	0.47	0.140^3	-0.081	-0.003744	-0.0184	0.277^1	3.40	0.42
4	43.6^3	-1.15^3	0.171^3	0.056	0.000019	0.0112	-0.093	4.44	0.73
5	49.5^3	-0.51^1	0.130^3	0.008	-0.000033^3	-0.0002	-0.031	6.55	0.70
6	97.5^3	-1.66^2	0.104^3	0.184^2	0.000024^2	0.0060	-0.114	10.55	0.27
7	-47.2^1	2.10^3	-0.004	-0.171^2	-0.000043^3	-0.0059^2	0.156^2	6.97	0.64
8	23.1	0.43	-0.011	0.045	-0.000060^3	0.0009	0.005	5.21	0.86
9	-26.6^3	2.33^3	-0.007	-0.130^3	-0.000126^3	-0.0106^3	0.091^3	3.16	0.76
10	12.1^1	-0.12	-0.000	0.141^2	-0.000595^3	0.0120^2	-0.067^2	1.71	0.78

Significance levels: ^{1}: 0.05>P>0.01, ^{2}: 0.01>P>0.001, ^{3}: 0.001>P.

The main driving variables (precipitation and potential evapotranspiration) occur in several of the terms in equation 4.2, but in different combinations. This gives a high correlation between several of the terms in equation 4.2. It also makes it hard to attribute a physical meaning to the parameter estimates and significance levels shown in Tables 4.1 to 4.4.

Fig. 4.3 shows scatterplots of the predicted actual evapotranspiration against the original WATCROS value, for the eight crop soil combinations, in the month of June. Fig. 4.4 shows the scatterplots of the predictions for grass in the months May, June, July and August. Fig. 4.5 shows the scatterplots of the predictions for winter wheat and fodder beet on sand for May, June, July and August.

Figs. 4.3 to 4.5 show a reasonable good agreement between the regression estimates and the WATCROS estimates of actual evapotranspiration for most of the combinations of soil type, crop type and month. A particular exception is fodder beet in June, where the model only explains 27 to 34 % of the variation in the WATCROS estimates. Poor results are also obtained for spring barley in May. This can be explained by the rapid development of canopy leaf area index in these months. This development is controlled by temperature history in the WATCROS model, which causes the mean leaf area index in May and June to vary considerably from year to year for these spring sown crops.

As temperature sum is not a regressor variable in equation 4.2 and leaf area index is a crucial determinant of transpiration, the regression model cannot descibe these conditions. Rather poor results of the regression is also obtained under the bare soil conditions in September and October for spring barley and winter wheat. The bare soil evaporation is largely determined by short term variations in precipitation. This cannot be validly described in a model, which only includes monthly precipitation sums.

The calibrated regression equations were applied to the monthly precipitation data and monthly potential evapotranspiration estimates for the entire period of available data. These estimates of historical actual evapotranspiration were then combined to estimate the overall basin evaporation in each catchment, as described in the next chapter.

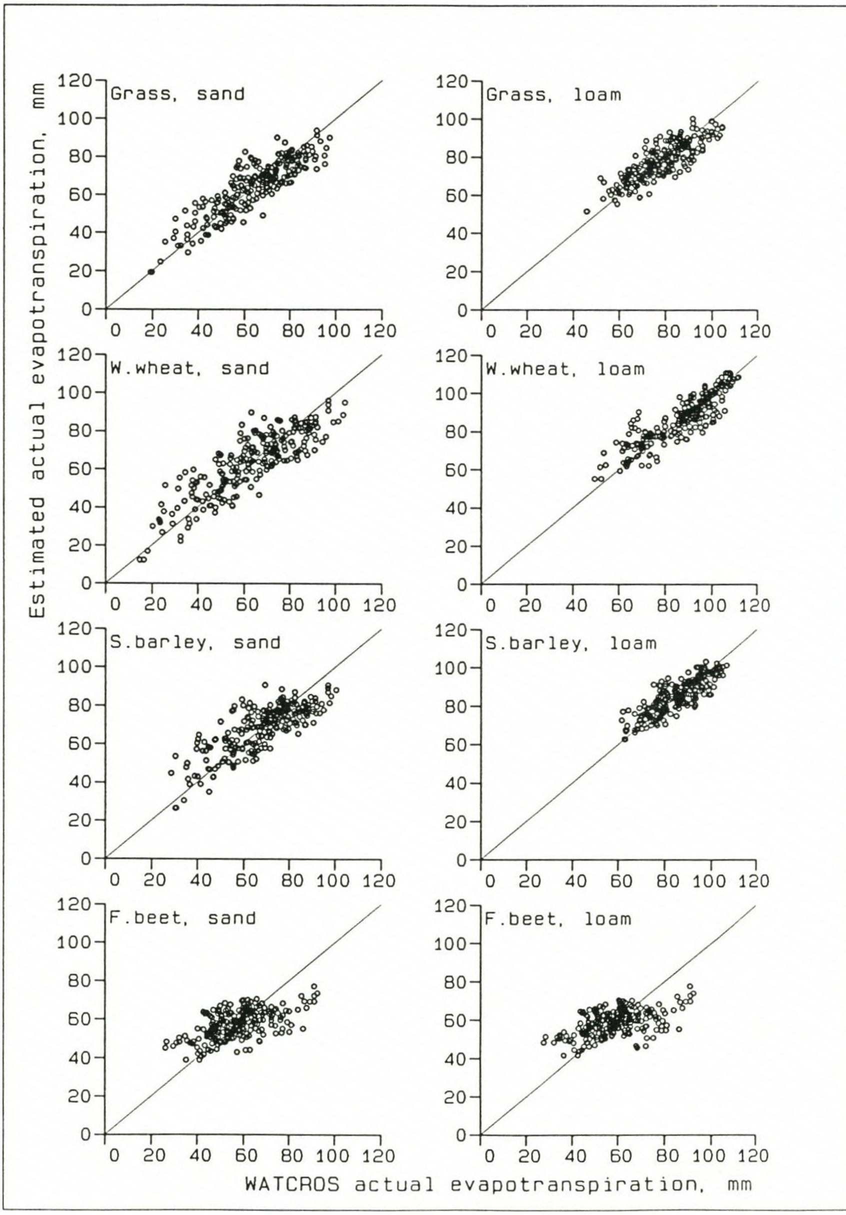

Figure 4.3: Estimated actual evapotranspiration by regression versus calculated actual evapotranspiration with the WATCROS model for June. Data from 9 catchments 1961 to 1988.

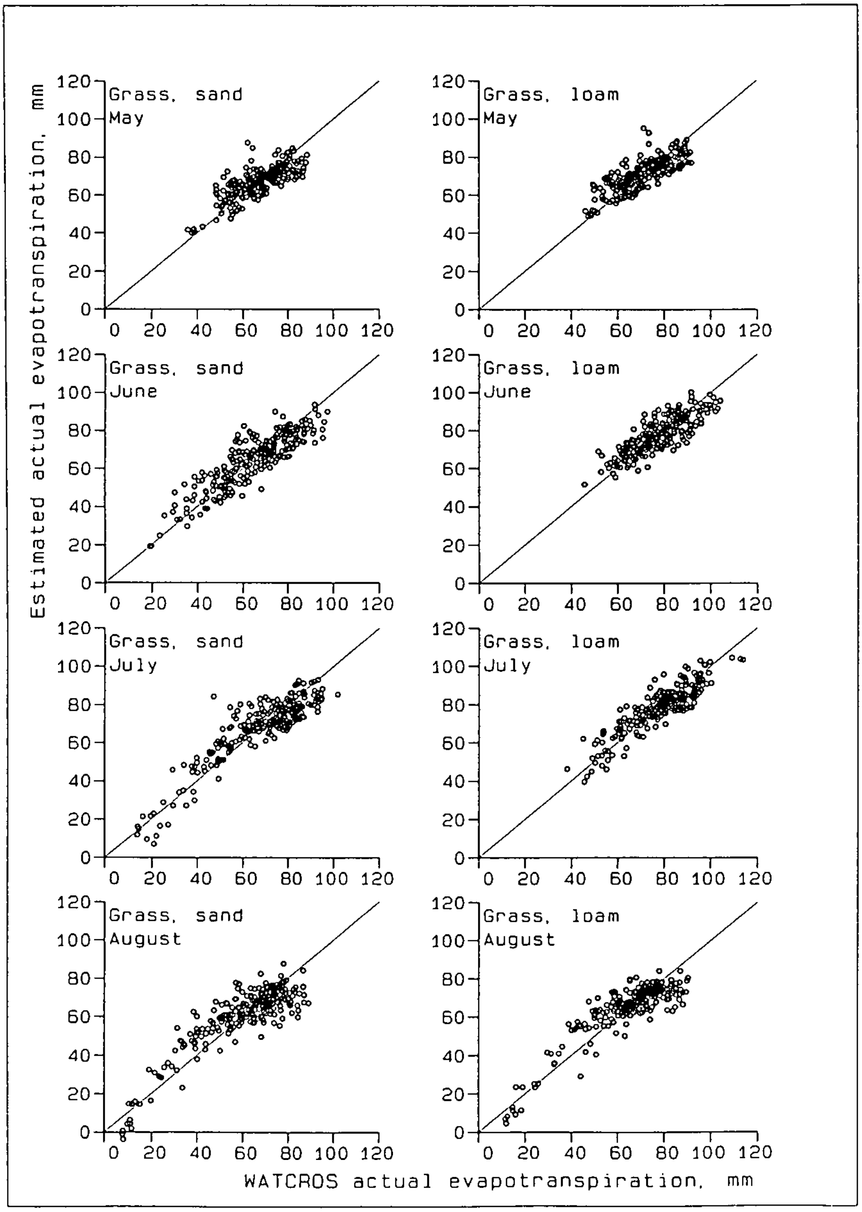

Figure 4.4: Estimated actual evapotranspiration by regression versus calculated actual evapotranspiration with the WATCROS model for grass. Data from 9 catchments 1961 to 1988.

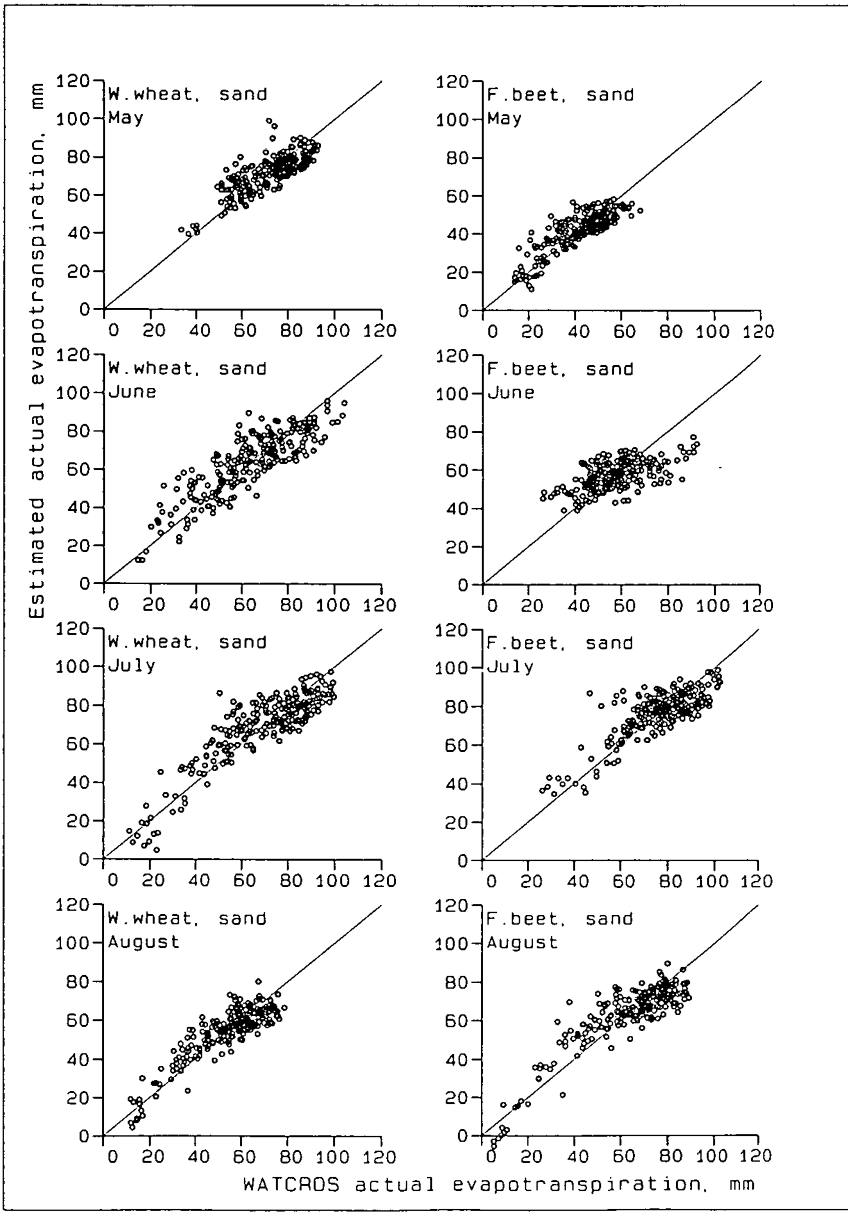

Figure 4.5: Estimated actual evapotranspiration by regression versus calculated actual evapotranspiration with the WATCROS model for winter wheat and fodder beet on sandy soil. Data from 9 catchments 1961 to 1988.

5 Estimation of basin evapotranspiration

The actual evapotranspiration within a catchment can vary considerably depending on soil type and vegetation characteristics. It is therefore necessary to calculate the actual evapotranspiration for individual land uses or crop patterns and make the weighted average of these results according to the area occupied by each group in the catchment. This procedure was also used by Refsgård (1981) and Aslyng and Hansen (1982). Table 5.1 lists the key catchment elements considered in this study.

The fraction of the catchments occupied by each of these elements was estimated from Tables 2.2 to 2.5. It was assumed that the principal land data in Tables 2.2 and 2.3, such as soil types, agricultural area and lakes, did not change during the period. The changes with time in agricultural land use was estimated by linear interpolation based on the data shown in Table 2.5.

Only two main soil types are considered, sandy and loam soil. Table 2.3 uses another soil type classification. The area with coarse sand and half the area with sand with clay are considered sandy soils. The rest is considered loamy soils. The soil types in the agricultural area is assumed to be representative also for the forest areas in the catchments. Within the agricultural area an even distribution of crop types over the soil types is assumed.

Spring barley is assumed to be representative for spring grain crops which also include spring wheat, spring rye, oat, spring rape and peas. Table 3.2 gives a comparison of the actual evapotranspiration from spring barley and spring rape. The evapotranspiration from rape is a bit higher but within the same range as the values for barley.

Table 5.1 shows that fallow is assumed to evaporate like a spring grain crop. This assumption implies that fallow is not identical to a bare soil, but has some vegetation giving rise to transpiration. A comparison of the transpiration from bare soil and spring barley is given in Table 3.2. There is quite large differences between these values, especially for the heavier soils. The structure of the fallow can thus have pronounced effects on the evapotranspiration. There is, however, no available information on the type of fallow in these catchments.

It seems likely that the use of the spring barley evapotranspiration for the fallow will overestimate the evapotranspiration to some extent. The fallow comprises from 1.6 to 6.4 % of the agricultural area in 1925 (Table 2.2 and 2.5), so the overall effect of an error

Table 5.1: Key catchment elements used for calculating basin evapotranspiration.

Number	Element
1	Spring grain crops and fallow, sandy soil
2	Spring grain crops and fallow, loam soil
3	Winter grain crops, sandy soil
4	Winter grain crops, loam soil
5	Root crops, sandy soil
6	Root crops, loam soil
7	Dryland grass, sandy soil
8	Dryland grass, loam soil
9	Wetland grass and lakes
10	Urban area
11	Forest, sandy soil
12	Forest, loam soil
13	Other and non classified

in estimation of fallow evapotranspiration on basin evapotranspiration will probably be minor.

Winter wheat is assumed to be representative of winter grain crops, which also include winter rye and winter rape.

Root crops are assumed to evaporate like fodder beet. Other root crops are sugar beet, some brassica species and potato. Table 3.2 gives a comparison of the evapotranspiration from potato and fodder beet. These annual values are almost indentical.

Dryland grass in Tables 2.5 and 5.1 also include other fodder crops such as alfalfa and maize for silage. Grass can be used for cutting and grazing. Grass for cutting will have higher evapotranspiration than grass for grazing, cf. Table 3.2, especially for clay soils. In this study dryland grass is assumed to evaporate like grass for cutting.

Wetland grass is grass and other vegetation in areas with a high ground water table. This grass will in most drought periods have adequate water supply from the high ground water table. Wetland grass is therefore assumed to evaporate at potential rate.

Hovedstadsrådet (1987) compared different empirical methods for calculating evaporation from lakes. The methods gave widely differing results that seems to be centered around the potential evapotranspiration calculated with the Penman equation. In this study potential evapotranspiration is used as an estimate of evaporation from lakes.

The urban areas comprise consolidated (building, roads) and garden areas. The evaporation from the consolidated areas is small, but the evapotranspiration from the gardens may be high. Overall the urban area is assumed to evaporate like dryland grass on sandy soil.

The evapotranspiration from forests depends on the forest type. Aslyng and Hansen (1982) defines the following sequence of relative annual evapotranspiration under equal conditions: conifers > deciduous species > grass. On sandy soils the root zone capacity may be equal, but on loamy soils, which allow deep rooting, the order of the root zone capacity is: deciduous species > grass > conifers.

In Denmark conifers dominate on sandy soils and deciduous species dominate on clay soils. It may thus be reasonable to assume that the annual evapotranspiration of a forest relative to grass is constant irrespective of forest type. In this study it is assumed that forests evaporate at 10 % above dryland grass, but not above potential rate. This is identical to the produre used by Aslyng and Hansen (1982).

Other and non classified areas may mainly be area with heath and other perennial vegetation. These areas are assumed to evaporate like spring grain crops on loam soil.

It should be noted that changes in actual evapotranspiration due to increasing irrigation and use of fertilizer have not been considered in the estimation of basin evapotranspiration.

Average annual evapotranspirations are shown in Table 5.2 for each catchment. Twenty-year average values are given for the three intervals 1928 - 1947, 1948 - 1967 and 1968 - 1987, followed by the 60-year average for the whole period. Different evapotranspiration components are shown along with the estimated basin evapotranspiration.

Table 5.2: Mean annual estimated potential and actual evapotranspiration in the 9 catchments for different time periods.

Catchment		Evapotranspiration, mm										
		Poten-	Grass		W. wheat		S. barley		Fodder beet		Basin
No.	Period	tial	Sand	Loam	Sand	Loam	Sand	Loam	Sand	Loam	actual
1	1928-47	572	418	459	402	453	388	425	398	420	457
	1948-67	539	418	450	406	451	394	426	395	410	447
	1968-87	544	408	445	401	444	387	420	385	412	440
	1928-87	552	415	451	403	449	390	424	393	414	448
2	1928-47	581	436	476	418	470	404	441	411	433	461
	1948-67	545	430	462	418	462	405	436	406	420	449
	1968-87	533	411	445	405	445	391	421	387	410	432
	1928-87	553	426	461	414	459	400	433	401	421	447
3	1928-47	582	420	463	402	456	389	428	400	424	459
	1948-67	549	418	454	404	451	391	425	398	416	449
	1968-87	538	399	437	393	436	378	411	377	404	431
	1928-87	556	413	451	399	448	386	421	391	415	446
4	1928-47	580	438	478	419	471	405	443	415	436	470
	1948-67	542	445	472	432	471	419	447	418	427	458
	1968-87	528	429	456	422	457	407	433	401	417	435
	1928-87	550	437	469	425	466	410	441	411	427	454
5	1928-47	595	428	475	407	465	394	435	406	434	475
	1948-67	556	434	468	416	461	403	436	411	427	465
	1968-87	553	409	448	398	444	384	419	386	414	443
	1928-87	568	424	463	407	457	394	430	401	425	461
6	1928-47	595	426	473	405	463	392	434	404	433	468
	1948-67	556	426	462	407	456	395	430	404	422	456
	1968-87	553	408	446	398	443	384	418	384	411	438
	1928-87	568	420	460	404	454	391	427	397	422	454
7	1928-47	618	413	468	390	458	379	425	395	428	455
	1948-67	589	430	474	408	464	396	437	411	434	461
	1968-87	561	403	445	390	440	376	413	380	412	434
	1928-87	589	415	462	396	454	384	425	395	425	450
8	1928-47	618	418	471	395	461	383	429	399	431	464
	1948-67	589	435	478	412	467	400	440	416	438	470
	1968-87	561	406	448	392	442	378	415	383	413	440
	1928-87	589	420	466	400	457	387	428	399	428	458
9	1928-47	618	433	484	410	474	397	441	410	440	482
	1948-67	589	434	477	412	467	400	439	413	436	474
	1968-87	561	414	453	401	446	386	420	390	419	448
	1928-87	589	427	471	408	463	394	433	404	432	468

6 Comparative climatology of the 9 catchments

The resulting datasets from this study provide an opportunity to analyze and compare the seasonal and interannual variability of the hydrologic climates in nine catchments across Denmark. First, the characteristics of the major hydroclimatic variables are described, and then their interrelationships in the regional water balance are analyzed. The discussion in this chapter includes average monthly statistics and average summer/winter seasons in addition to annual averages. These averages are presented for the 60-year data period 1928 to 1987 available for all 9 catchments, and also for three 20-year intervals within the 60-year period. The structure of the graphs is explained in the first section on precipitation.

Average annual waterbalance components, residuals and ratios are presented in Table 6.1 for each catchment. E_b is basin evapotranspiration, P is precipitation, and Q is runoff. Twenty-year average values are given for the three intervals 1928-1947, 1948-1967 and 1968-1987, followed by the 60-year average for the whole period. Data are complete for all the catchments during this period, which facilitates intercomparison of the averages. See Table 2.1 for catchment names and sizes, and the map in Fig. 2.1 for their locations.

Table 6.2 gives the 20-year averages of various water balance elements as departures from the 60-year average. This makes it easier to see the changes in these values. The standard deviation (RMSE) of the mean difference (departure from 60-year average) is also shown in the table. Significance of independent t-tests of the differences of the 20-year means to the 60-year means is indicated by the superscripts 1, 2 or 3 for the $0.05>P>0.01$, $0.01>P>0.001$ and $0.001>P$ significance levels, respectively. Tables 6.3 and 6.4 present similar tabulations of the departures of the seasonal average precipitation and other components. The 6-month summer season is defined to be April to September, and the 6-month winter season is October to March.

The representativeness and uncertainty of these data and the techniques we have used to compile them are discussed later in chapter 7.

Table 6.1: Mean annual waterbalance components, residuals and ratios for 9 catchments in Denmark. Three consecutive 20-year averages, and the overall 60-year average is shown for each catchment. Annual components and residuals are given in mm per year, and ratios are in percent. $P-Q$ is the residual estimate of E_b, and $P-Q-E_b$ is the overall waterbalance residual due to net changes in water storage and estimation errors. E_b/E_p is the ratio of actual to potential evapotranspiration. Q/P is the runoff ratio.

Catch-ment	Period	E_b	P	Q	$P-Q$	$P-Q$ $-E_b$	E_b/E_p %	Q/P %
1	1928-1947	457	742	343	399	-58	80	46
Linden-	1948-1967	447	820	361	459	12	83	44
borg Å	1968-1987	440	834	335	499	59	81	40
	1928-1987	448	799	346	452	4	81	43
2	1928-1947	461	831	375	456	-4	79	45
Gudenå	1948-1967	449	894	427	468	18	82	48
	1968-1987	432	908	440	468	36	81	48
	1928-1987	447	878	414	464	17	81	47
3	1928-1947	459	750	275	475	16	79	37
Århus Å	1948-1967	449	764	254	510	61	82	33
	1968-1987	431	786	260	526	95	80	33
	1928-1987	446	767	263	504	58	80	34
4	1928-1947	470	840	306	534	64	81	36
Brede Å	1948-1967	458	968	401	566	108	85	41
	1968-1987	435	988	431	557	122	82	44
	1928-1987	454	932	379	553	98	83	41
5	1928-1947	475	730	266	464	-12	80	36
Odense Å	1948-1967	465	808	301	507	42	84	37
	1968-1987	443	796	295	501	58	80	37
	1928-1987	461	778	287	491	30	81	37
6	1928-1947	468	731	244	487	19	79	33
Brende Å	1948-1967	456	764	266	498	43	82	35
	1968-1987	438	789	281	508	70	79	36
	1928-1987	454	761	263	498	44	80	35
7	1928-1947	455	617	155	462	7	74	25
Harre-	1948-1967	461	697	198	499	37	78	28
sted Å	1968-1987	434	705	210	495	60	77	30
	1928-1987	450	673	189	484	34	76	28
8	1928-1947	464	643	168	475	11	75	26
Saltø Å	1948-1967	470	723	201	522	52	80	28
	1968-1987	440	700	208	492	53	78	30
	1928-1987	458	689	193	496	38	78	28
9	1928-1947	482	694	199	495	12	78	29
Trygge-	1948-1967	474	733	216	517	43	81	29
vælde Å	1968-1987	448	728	226	502	54	80	31
	1928-1987	468	718	214	505	36	79	30

Table 6.2: Annual values in mm for different water balance elements. The mean values are difference between the mean for the actual time period and the mean for 1928 to 1987. RMSE is the standard deviation of the mean difference. E_b is estimated basin evapotranspiration, P is the precipitation, and Q is the runoff.

Catch-		E_b		P		Q		$P-Q$	
ment	Period	Mean	RMSE	Mean	RMSE	Mean	RMSE	Mean	RMSE
1	1928-1947	9.0	5.4	-56.8^{1}	23.2	-3.6	8.5	-53.2^{1}	20.0
Linden-	1948-1967	-0.9	5.2	21.6	23.1	14.7	7.6	6.9	19.7
borg Å	1968-1987	-8.2	6.5	35.2	25.2	-11.2	11.1	46.3^{1}	20.0
2	1928-1947	13.5^{1}	4.7	-46.5	26.4	-39.0^{2}	12.9	-7.5	17.6
Gudenå	1948-1967	2.0	3.2	16.5	22.7	12.8	16.4	3.7	13.7
	1968-1987	-15.5^{1}	7.0	30.1	27.4	26.2	20.2	3.8	13.5
3	1928-1947	12.5^{1}	5.9	-16.9	26.5	11.7	18.8	-28.6	20.4
Århus Å	1948-1967	2.5	3.5	-2.9	19.5	-8.9	17.9	6.1	13.7
	1968-1987	-15.1^{1}	6.6	19.8	25.2	-2.8	15.3	22.5	14.5
4	1928-1947	15.8^{3}	4.0	-92.1^{2}	25.2	-73.8^{3}	15.3	-18.3	16.5
Brede Å	1948-1967	3.5	4.7	35.9	33.0	22.1	21.0	13.7	18.7
	1968-1987	-19.3^{1}	7.0	56.3	34.0	51.7	26.6	4.6	17.8
5	1928-1947	14.1^{2}	4.9	-47.9^{1}	20.0	-20.7	12.6	-27.1^{1}	12.6
Odense Å	1948-1967	4.1	5.0	30.1	27.6	13.4	18.5	16.7	13.1
	1968-1987	-18.2^{1}	8.2	17.8	26.4	7.3	17.9	10.5	13.5
6	1928-1947	13.9^{1}	5.1	-30.7	20.1	-19.9	14.1	-10.8	13.7
Brende Å	1948-1967	1.9	4.4	3.1	24.7	2.7	19.1	0.4	10.3
	1968-1987	-15.8	7.9	27.6	28.9	17.2	20.2	10.4	12.8
7	1928-1947	5.0	6.0	-55.8^{2}	16.0	-34.2^{2}	8.9	-30.6^{1}	12.0
Harre-	1948-1967	11.2	6.2	24.1	22.6	9.6	16.1	15.8	12.1
sted Å	1968-1987	-16.1	7.7	31.7	25.9	21.2	18.4	11.7	11.8
8	1928-1947	5.9	5.9	-45.9^{1}	16.5	-24.8^{1}	10.1	-16.8	12.6
Saltø Å	1948-1967	12.0	6.1	34.4	22.0	8.5	16.3	22.7^{1}	10.1
	1968-1987	-17.9^{1}	7.6	11.5	23.9	15.0	18.5	-6.7	9.6
9	1928-1947	14.1^{1}	6.2	-24.2	16.1	-14.3	11.1	-9.9	10.7
Trygge-	1948-1967	6.2	6.3	14.4	24.5	1.9	16.9	12.6	11.2
vælde Å	1968-1987	-20.3^{1}	7.2	9.8	23.0	12.4	17.1	-2.6	9.8

Significance levels: ^{1}: 0.05>P>0.01, ^{2}: 0.01>P>0.001, ^{3}: 0.001>P.

Table 6.3: Summer water balance components (April to September) in mm. The mean values are difference between the mean for the actual time period and the mean for 1928 to 1987. RMSE is the standard deviation of the mean difference. E_b is estimated basin evapotranspiration, P is the precipitation, and Q is the runoff.

Catch-ment	Period	E_b		P		Q		$P-Q$	
		Mean	RMSE	Mean	RMSE	Mean	RMSE	Mean	RMSE
1	1928-1947	9.9	5.6	-5.7	17.7	1.6	4.4	-7.3	16.4
Linden-	1948-1967	-0.4	5.0	17.7	20.1	3.9	3.8	13.8	18.6
borg Å	1968-1987	-9.5	6.4	-12.0	17.5	-5.5	5.3	-6.5	14.0
2	1928-1947	12.7[1]	4.5	0.2	17.3	-7.9	5.6	8.0	14.7
Gudenå	1948-1967	2.2	3.4	15.6	15.6	-0.7	5.7	16.4	14.3
	1968-1987	-14.8[1]	7.0	-15.8	17.8	8.6	8.0	-24.4	12.9
3	1928-1947	11.7	5.8	10.3	19.9	11.0	8.9	-0.7	19.0
Århus Å	1948-1967	2.6	3.7	5.2	14.9	-10.4[1]	4.8	15.6	14.3
	1968-1987	-14.4[1]	6.5	-15.6	15.3	-0.6	6.9	-15.0	12.0
4	1928-1947	15.1[3]	3.8	-29.4	23.4	-25.3[1]	9.1	-4.2	18.0
Brede Å	1948-1967	3.7	4.7	30.5	21.6	11.4	8.3	19.1	17.5
	1968-1987	-18.7[1]	7.0	-1.0	19.4	13.9	8.7	-14.9	15.0
5	1928-1947	13.4[1]	4.8	-10.1	17.4	-7.4	5.6	-2.7	14.6
Odense Å	1948-1967	4.8	4.6	27.6	15.1	4.9	6.6	22.7	11.7
	1968-1987	-18.2[1]	8.2	-17.5	17.9	2.5	7.3	-20.0	13.6
6	1928-1947	12.6[1]	4.8	-1.1	15.6	-5.6	7.5	4.6	13.9
Brende Å	1948-1967	2.9	4.1	11.0	14.6	-2.6	6.9	13.6	11.1
	1968-1987	-15.6	8.1	-9.9	19.3	8.3	8.2	-18.1	14.1
7	1928-1947	5.0	5.7	-18.1	13.1	-12.2[2]	3.6	-9.9	11.5
Harre-	1948-1967	9.5	6.0	29.7	15.2	0.9	5.6	30.3[1]	12.1
sted Å	1968-1987	-14.6	7.7	-11.7	17.5	10.8	7.7	-20.9	12.8
8	1928-1947	5.3	5.6	-16.3	14.1	-10.8[2]	3.4	-2.0	12.1
Saltø Å	1948-1967	10.6	5.6	29.9[1]	13.3	2.4	5.6	25.4[1]	10.1
	1968-1987	-15.9[1]	7.6	-13.6	16.5	7.8	7.4	-23.5	12.2
9	1928-1947	12.3	6.2	-4.5	15.9	-5.1	5.2	0.6	14.0
Trygge-	1948-1967	5.7	5.3	15.6	13.1	-3.3	6.4	18.9	11.4
vælde Å	1968-1987	-18.0[1]	7.2	-11.1	17.0	8.4	8.1	-19.5	12.9

Significance levels: [1]: 0.05>P>0.01, [2]: 0.01>P>0.001, [3]: 0.001>P.

Table 6.4: Winter water balance components (October to March) in mm. The mean values are difference between the mean for the actual time period and the mean for 1928 to 1987. RMSE is the standard deviation of the mean difference. E_b is estimated basin evapotranspiration, P is the precipitation, and Q is the runoff.

Catch-		E_b		P		Q		$P-Q$	
ment	Period	Mean	RMSE	Mean	RMSE	Mean	RMSE	Mean	RMSE
1	1928-1947	-0.8	1.5	-49.3^{1}	17.3	-4.0	5.9	-45.3^{2}	13.2
Linden-	1948-1967	-0.4	1.1	-3.7	16.7	8.9	5.1	-12.7	14.0
borg Å	1968-1987	1.2	0.8	53.0^{1}	19.0	-4.9	6.8	57.9^{2}	16.6
2	1928-1947	0.9	0.9	-43.4^{1}	20.7	-25.8	14.9	-17.6	10.7
Gudenå	1948-1967	-0.1	1.2	-10.0	19.2	6.5	14.5	-16.5	11.5
	1968-1987	-0.8	0.9	53.4^{1}	20.0	19.4	17.3	34.0^{2}	10.0
3	1928-1947	0.8	1.1	-26.4	18.3	5.4	16.7	-31.8^{2}	10.0
Århus Å	1948-1967	0.0	1.1	-12.8	16.9	-1.9	16.2	-10.8	10.1
	1968-1987	-0.8	0.8	39.2^{1}	18.4	-3.5	12.9	42.7^{3}	9.6
4	1928-1947	0.7	1.1	-61.7^{2}	20.7	-43.3^{2}	12.7	-18.4	14.2
Brede Å	1948-1967	0.0	1.3	-3.5	21.5	3.6	16.3	-7.1	11.4
	1968-1987	-0.7	0.9	65.2^{1}	22.9	39.7	22.3	25.5^{1}	11.4
5	1928-1947	0.8	1.1	-37.9^{1}	17.9	-8.4	14.0	-29.4^{2}	10.3
Odense Å	1948-1967	-0.7	1.3	-0.9	23.1	3.2	16.8	-4.2	11.8
	1968-1987	-0.1	1.2	38.8^{1}	17.2	5.2	16.3	33.6^{3}	7.8
6	1928-1947	1.4	1.0	-27.8	16.5	-9.3	13.0	-18.5	9.5
Brende Å	1948-1967	-1.0	1.3	-13.0	21.4	-1.3	16.9	-11.8	10.1
	1968-1987	-0.3	1.2	40.8	19.7	10.6	19.3	30.3^{2}	7.8
7	1928-1947	0.3	2.1	-36.9^{1}	13.7	-15.1	12.6	-25.8^{2}	8.8
Harre-	1948-1967	1.2	1.2	-8.6	15.9	4.2	15.2	-11.8	8.2
sted Å	1968-1987	-1.5	1.1	45.5^{2}	14.8	10.2	16.0	36.3^{2}	10.3
8	1928-1947	0.8	1.9	-28.5	14.5	-10.9	13.3	-14.2	10.4
Saltø Å	1948-1967	1.2	1.3	2.1	16.2	2.4	15.2	-3.0	9.5
	1968-1987	-2.0	1.0	26.5	14.3	8.1	15.6	16.3	9.2
9	1928-1947	1.7	1.4	-19.5	13.3	-4.9	10.8	-14.7	11.3
Trygge-	1948-1967	0.6	1.7	-3.0	17.7	0.1	14.8	-3.1	8.4
vælde Å	1968-1987	-2.3^{1}	0.9	22.5	15.5	4.8	14.6	17.7	8.9

Significance levels: ^{1}: 0.05>P>0.01, ^{2}: 0.01>P>0.001, ^{3}: 0.001>P.

4

6.1 Precipitation

Precipitation is generally regarded an external climatic variable for catchment hydrology. It mostly depends on large-scale weather. Topography can influence the distribution of precipitation (Allerup et al., 1981), but this effect is probably small in these catchments.

Average annual precipitation totals are presented in Table 6.1 for each catchment. The sixty-year average totals range from 673 mm for catchment 7, Harrested Å in western Zealand to 932 mm for catchment 4, Brede Å in Southwestern Jutland. The values reflect the geographic pattern for annual precipitation to decrease from west to east in Denmark, and also to decrease near the coast. This pattern is due to the predominant west to east transport of moisture from the Atlantic source region, and the increasing convective instability as one moves inland from the coast, because of the greater surface heating on land areas than over water.

The sequence of 20-year average precipitation totals in Table 6.1 show a general upward trend in most of the catchments. All of the catchments show an increase between the first two periods. The largest of these increases is +128 mm for catchment 4, which is a 15 percent increase. The average increase is 9 percent. The changes between the second and third 20-year averages are smaller, and three of the nine catchments show a decline in average annual precipitation. The average change is an increase of 1 percent, and the largest change is a decline of -23 mm (-3 percent) in catchment 8.

The historical variability in the annual precipitation is shown in Fig. 6.1 for each of the nine catchments. Each time series is plotted on the time axis from 1910 to 1990, using separate vertical scales. These scales alternate from left to right going down the page, but all use the same scale interval size for comparability. The vertical reference lines are drawn between the 20-year periods used in Table 6.1: 1928-47, 1948-67 and 1968-87.

Each time series consists of monthly values of "annual" precipitation produced by a running 12-month total precipitation ending with the month where the value is plotted. This monthly resolution allows finer details and timing differences to be seen, than would be possible with ordinary calendar-year totals, while the 12-month running total suppresses the very large month to month and seasonal variability in the precipitation data. The same format is used to display the annual runoff and evaporation data in later sections.

Many of the features in Fig. 6.1 are seen simultaneously in all of the catchments, indicating that large scale factors dominate the historical variability of precipitation in Denmark. There is clearly a considerable amount of variance in multi-year fluctuations in precipitation.

Graphs of average monthly precipitation for each catchment are given in Fig. 6.2. These averages are for the period 1917 to 1988. All of the graphs show the general seasonal pattern of precipitation in Denmark. Precipitation is lowest in the late winter months of February and March, and increases through the spring. All of the catchments show a large

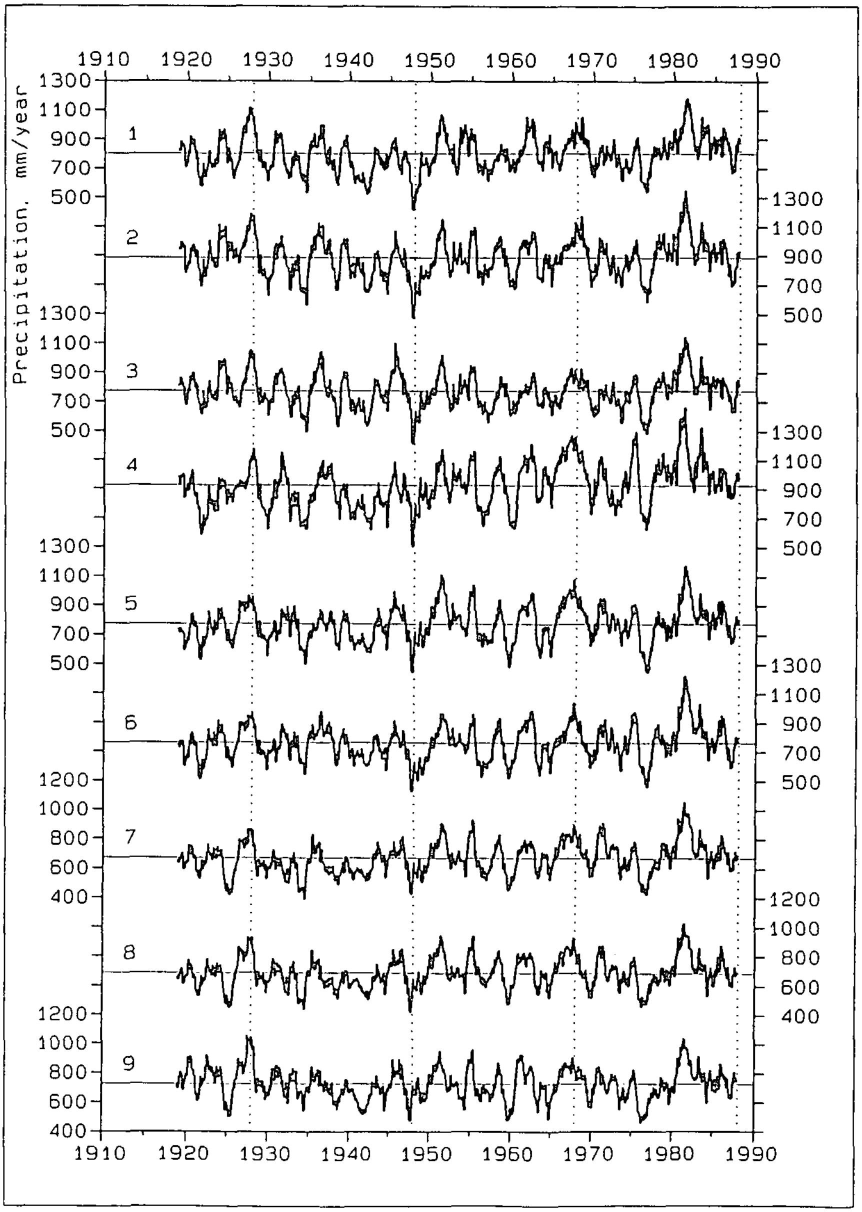

Figure 6.1: Annual precipitation for each of the 9 catchments calculated as 12 month moving totals and plotted at the endpoint. The horizontal lines are means of the series.

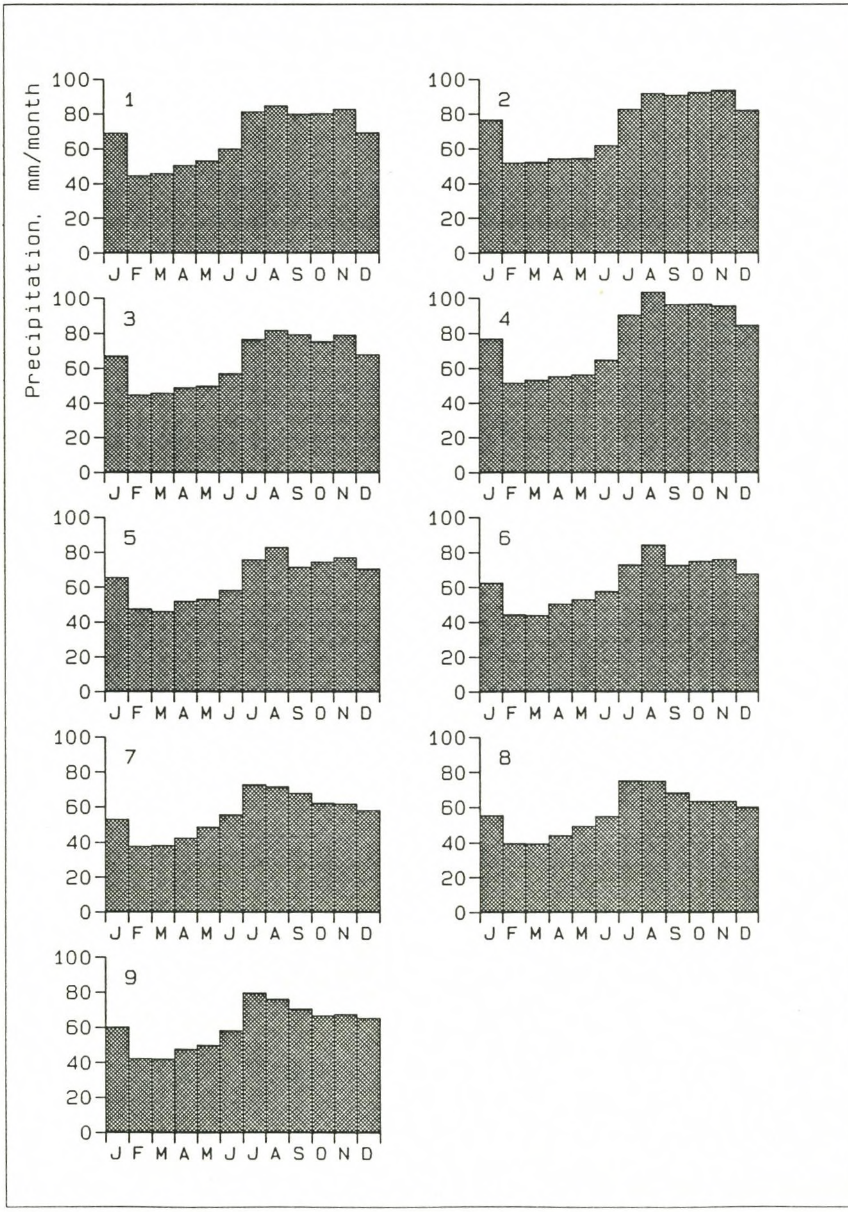

Figure 6.2: Mean monthly precipitation for each of the 9 catchments for the period 1917 to 1988.

increase from June to July, and with August as the month with greatest precipitation in the north and west (catchments 1 to 6) and July as the greatest month in the 3 eastern catchments (7 to 9). Precipitation generally declines during the fall and winter, but there is a slight tendency for a secondary maximum in November. There is a substantial decrease in precipitation from January to February. The widest average seasonal range occurs in catchment 4, Brede Å in southwest Jutland, where monthly precipitation ranges from about 50 mm/month in February to about 100 mm/month in August.

The variability of the average monthly precipitation totals for each catchment is shown in Fig. 6.3. This figure consists of 9 rows of small time series graphs, one row for each catchment, with a separate vertical scale for each row. Within each row, there are separate time-series graphs for each month from January to December. The underlying "stair-step" base lines represent the average value for each month. The time axis for each small plot is from 1910 to 1990 as in Fig. 6.1. The vertical scales are in mm/month, and alternate from left to right for each catchment, going down to the page. The size of the scale intervals are the same on each row. The vertical lines drawn between March and April, and between September and October, are provided as a reference for the two half-year seasons that are described in the section on seasonal totals. The plotted data are monthly amounts, smoothed by a 15-year moving average over years ending with the year of the data point. Thus, these figures show long term variability while suppressing year to year fluctuations.

Fig. 6.3 shows that the long term variation in monthly values is large for July through December, and largest in August and November, the two months mentioned previously as maximum and secondary maximum months on average. Catchment 4 (Brede Å) shows the greatest overall variability.

Fig. 6.4 shows the long term variability, of two 6-month seasons. The winter season is defined as October to March, and the summer season is April to September. The plots show a time series for each catchment on a time axis from 1910 to 1990. The size of the vertical scale interval is the same for all curves. The data are smoothed by a 15 year moving average ending with the year of the data point. The plots show stable or slightly declining winter precipitation leading up to the 1950's, followed by generally rising levels up to the present. This latter rise is most pronounced in catchment 4, Brede Å in Jutland. Summer precipitation shows somewhat the opposite trends. There is a general decline in the early point of the record followed by higher levels of summer precipitation from the 1950's to the mid 1970's. The levels then decline to lower values toward the end of the period.

6.2 Runoff

Runoff is the stream discharge of water from a catchment. The volume of discharged water measured in the stream is converted into catchment average depth comparable to precipitation, by dividing by the catchment area. These runoff measurements represent only the surface discharge and do not include any groundwater flow into or out of the

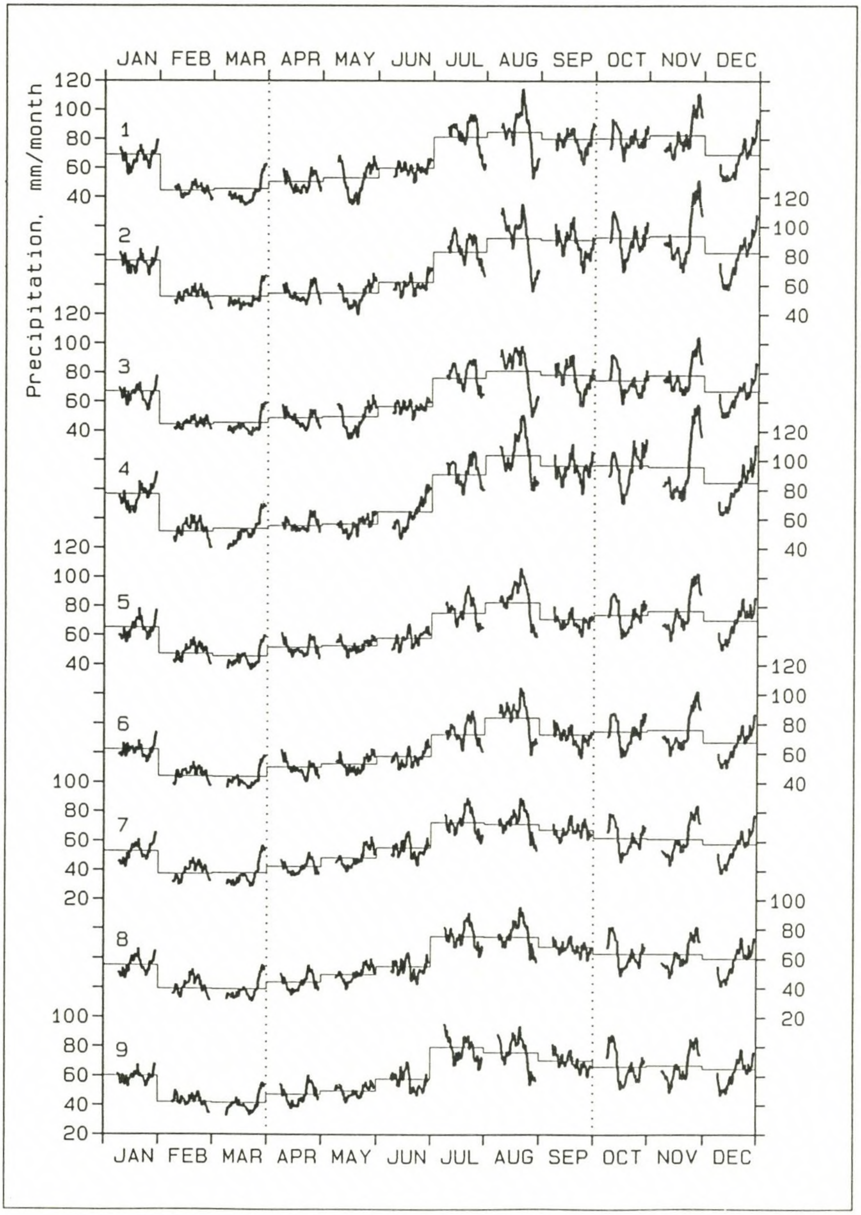

Figure 6.3: Monthly precipitation for each of the 9 catchments calculated as 15 year moving averages and plotted at the endpoint on a time axis from 1910 to 1990. The horizontal lines are mean values for each month.

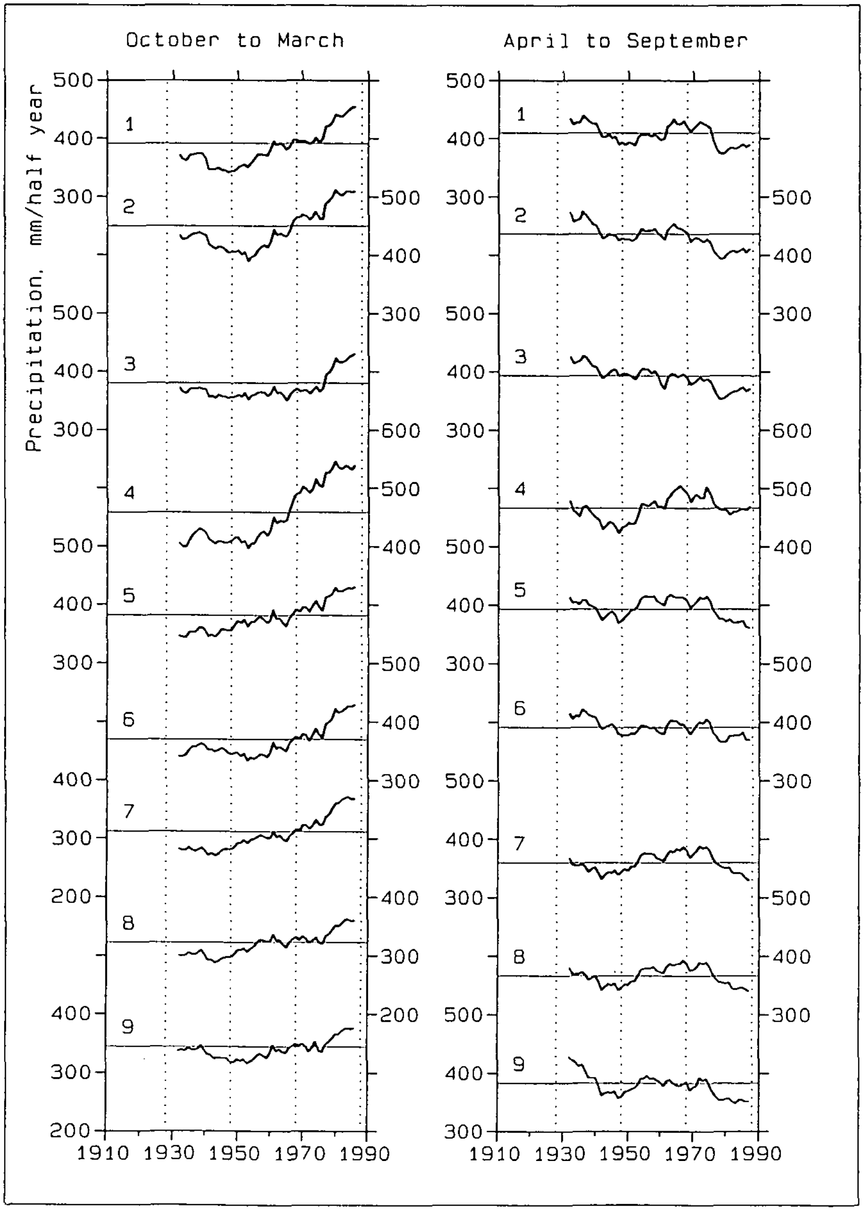

Figure 6.4: Seasonal precipitation for each of the 9 catchments calculated as 15 year moving averages and plotted at the endpoint. The horizontal lines are mean values for each season.

catchment. The groundwater flow remains unknown. Runoff varies considerably from year to year in reponse to the amount, intensity and seasonal timing of precipitation, the consumption of water by evapotranspiration, and human influences.

Changes in land use, drainage, municipal water consumption and discharge, and streambed alterations can also change runoff patterns (Waagepetersen et al., 1991). Runoff also differs from catchment to catchment due to precipitation and evapotranspiration differences, landcover, soil types, slopes, and groundwater characteristics.

Average annual runoff totals are given in the second column of Table 6.1 for the 20-year and 60-year periods. The 60-year averages range from 189 mm in catchment 7 to 414 mm in catchment 2. From the first 20-year period to the second, all but catchment 3 shows an increase in annual runoff, which follows the trend in annual precipitation. From the second to the third 20-year period, annual runoff increases in five of the catchments, is little changed in three, and declines noticably in only one catchment.

The historical variability of the annual runoff totals is displayed graphically in Fig. 6.5. These data are smoothed by a 12 month moving average, as in Fig. 6.1 for precipitation. Catchment 1, Lindenborg Å in northern Jutland, shows considerably less runoff variability than the other catchments. There is substantial similarity between the runoff varibility in the other eight catchments. It can be noted that the runoff amounts show a skewed distribution about the average line. The positive departures tend to be less frequent but larger than the negative departures. Many of the peaks in runoff are synchronuous in all the catchments, such as 1938, 1952, 1967-68, 1982 and most recently in 1987.

Average monthly runoff for the period 1917 to 1989 is shown in Fig. 6.6 for each of the catchments, although the data record does not start in 1917 in all catchments. In all the catchments, seasonal runoff is greatest in the winter when evapotranspiration is lowest, with January having the largest monthly runoff. Runoff declines in the spring, after a secondary maximum in March from snowmelt. Runoff is lowest in June, July and August, with July having the minimum value in most cases.

Catchment 1 shows the least seasonal range in runoff, with substantial runoff in all months. This is indicative of a large contribution of ground water to the streamflow, which buffers the large seasonal cycle. The four catchments in Jutland have ample summertime runoff, while the five Fyn and Zealand catchments show lower summertime runoff, indicating little groundwater buffering of the streamflow. This also makes these streams more sensitive to dry years, when streamflow can virtually cease, in some cases.

Historical variability of the monthly runoff data are presented in Fig. 6.7. The variability is clearly greater for the winter months. Interestingly, the patterns show a sizable slow fluctuation with a period on the order of 45 years. There is also a sharp rise in March runoff in recent years, a distinct rising tendency in December runoff, and generally higher winter runoff in recent times.

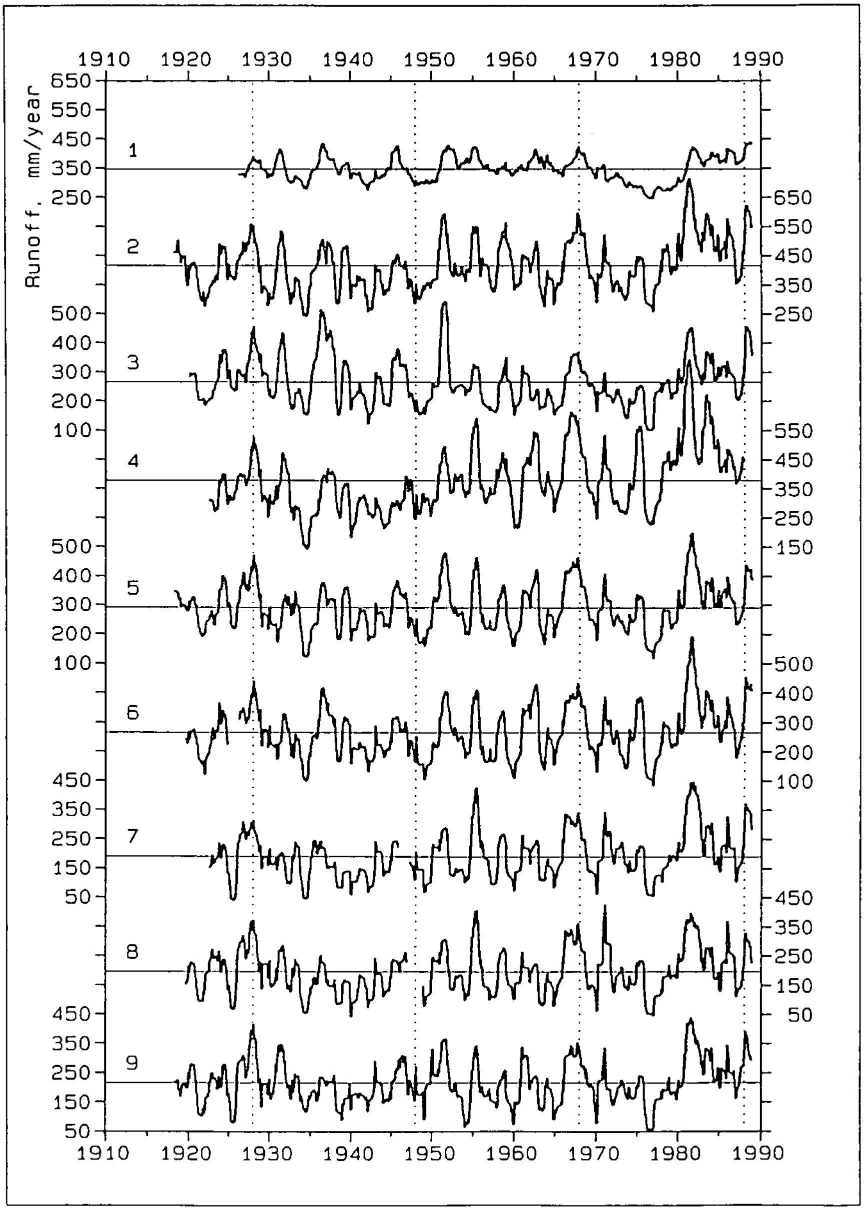

Figure 6.5: Annual runoff for each of the 9 catchments calculated as 12 month moving totals and plotted at the endpoint. The horizontal lines are means of the series.

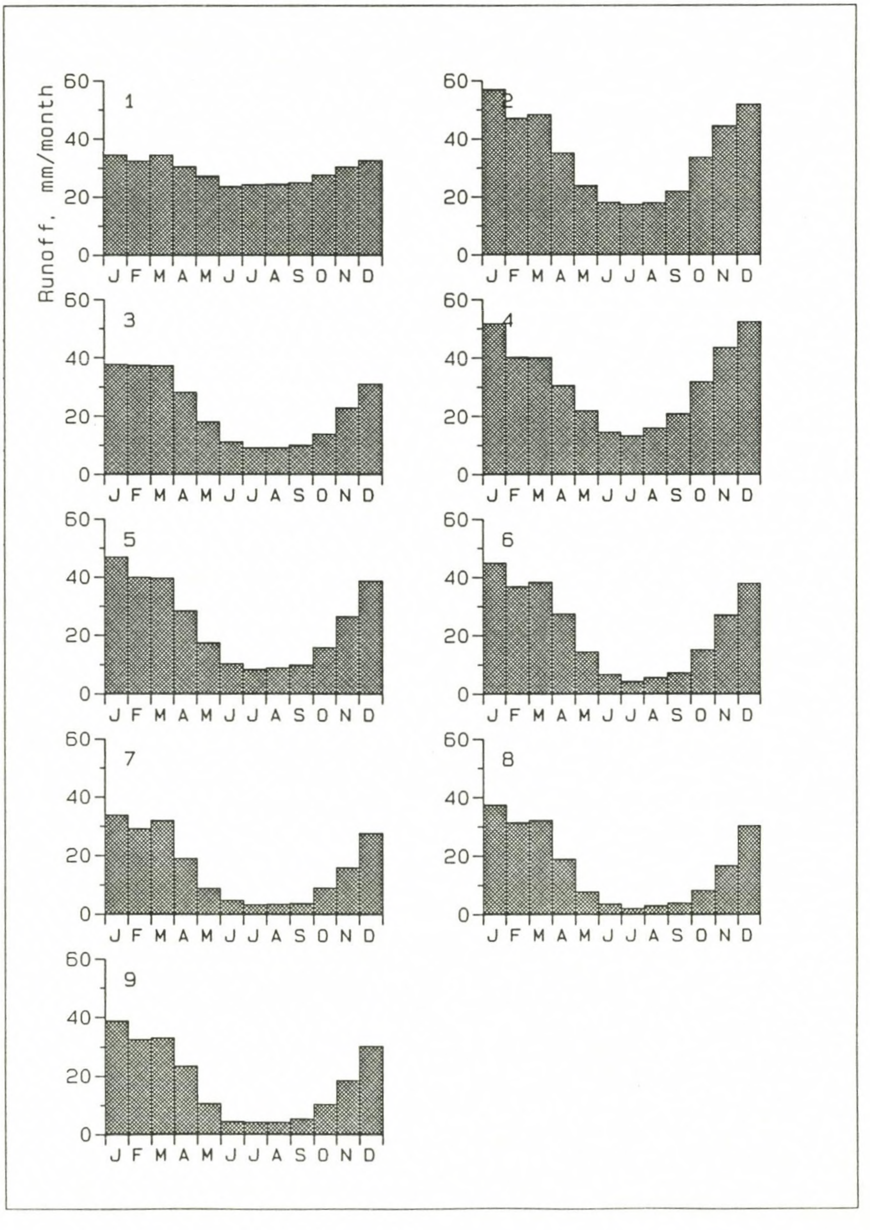

Figure 6.6: Mean monthly runoff for each of the 9 catchments for the period 1917 to 1988. The data series does not start in 1917 in all catchments.

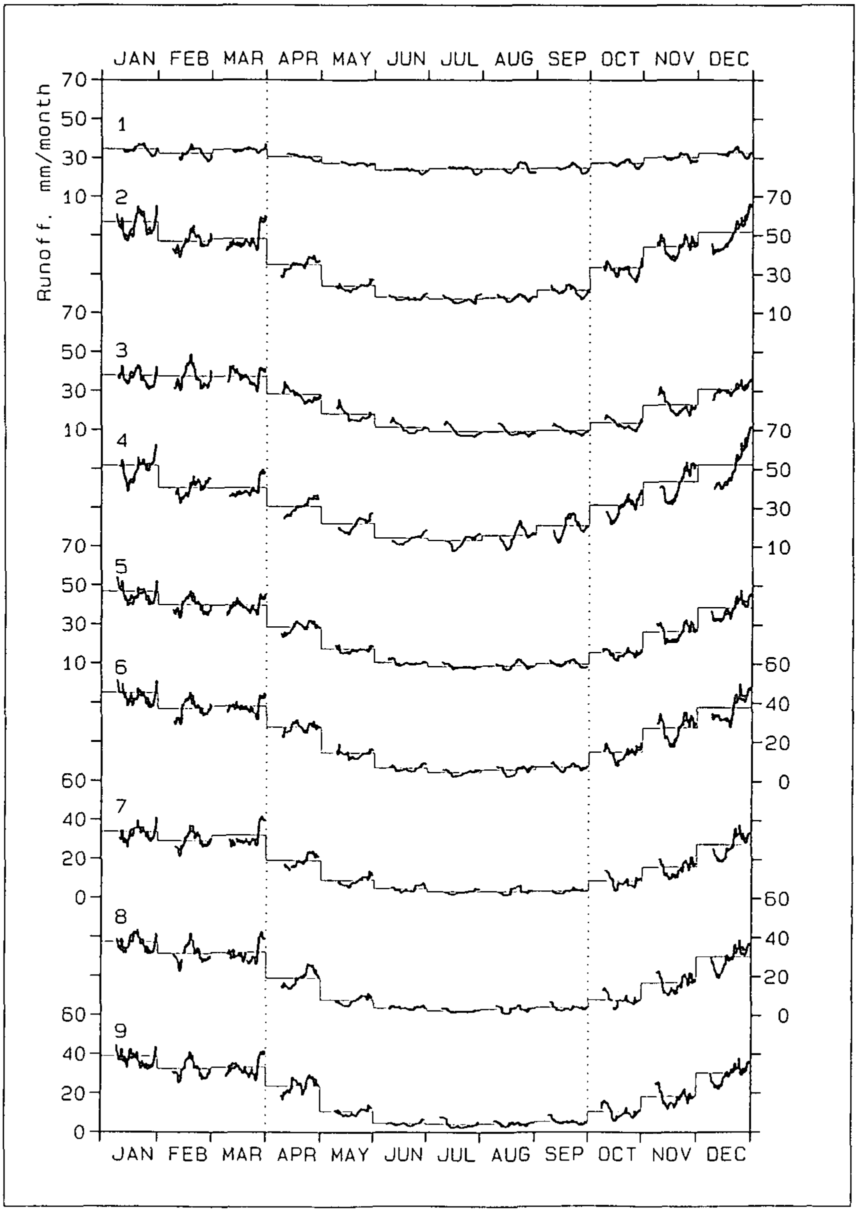

Figure 6.7: Monthly runoff for each of the 9 catchments calculated as 15 year moving averages and plotted at the endpoint on a time axis from 1910 to 1990. The horizontal lines are mean values for each month.

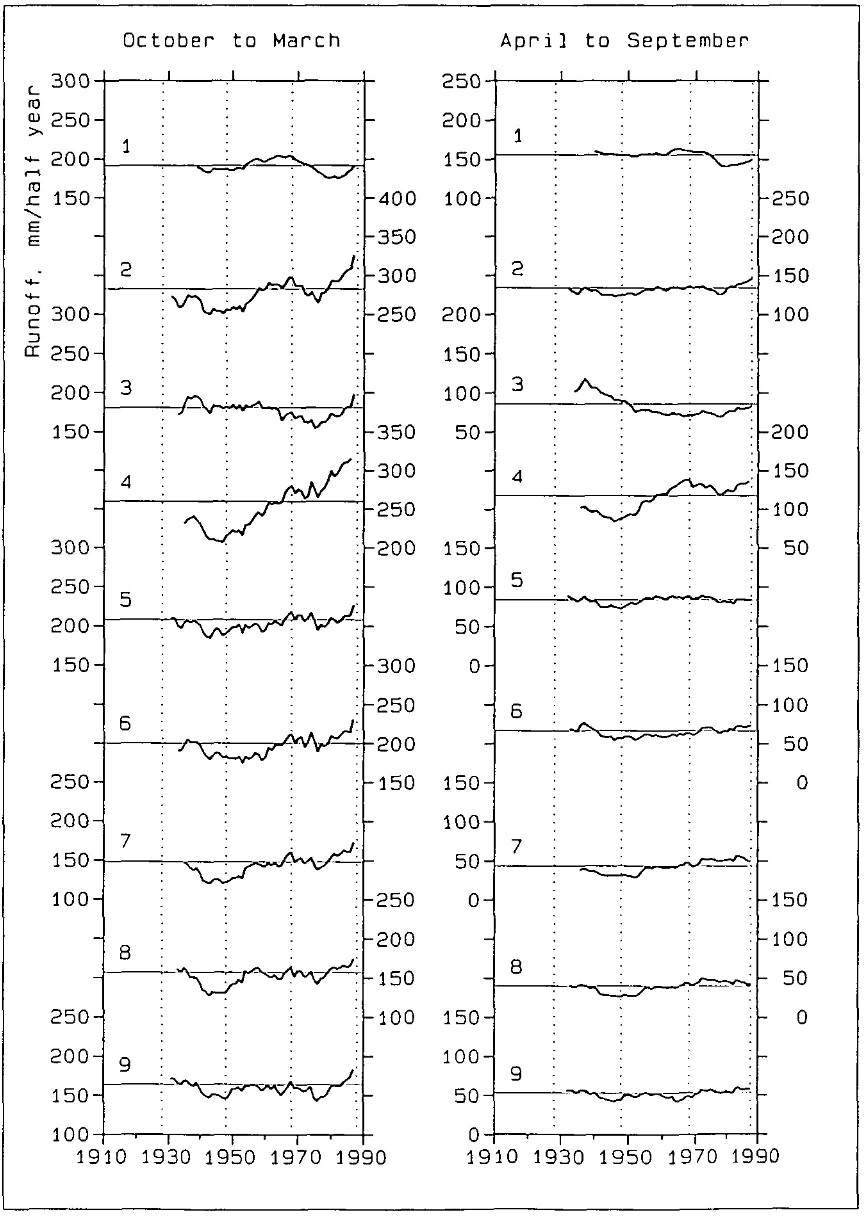

Figure 6.8: Seasonal runoff for each of the 9 catchments calculated as 15 year moving averages and plotted at the endpoint. The horizontal lines are mean values for each season.

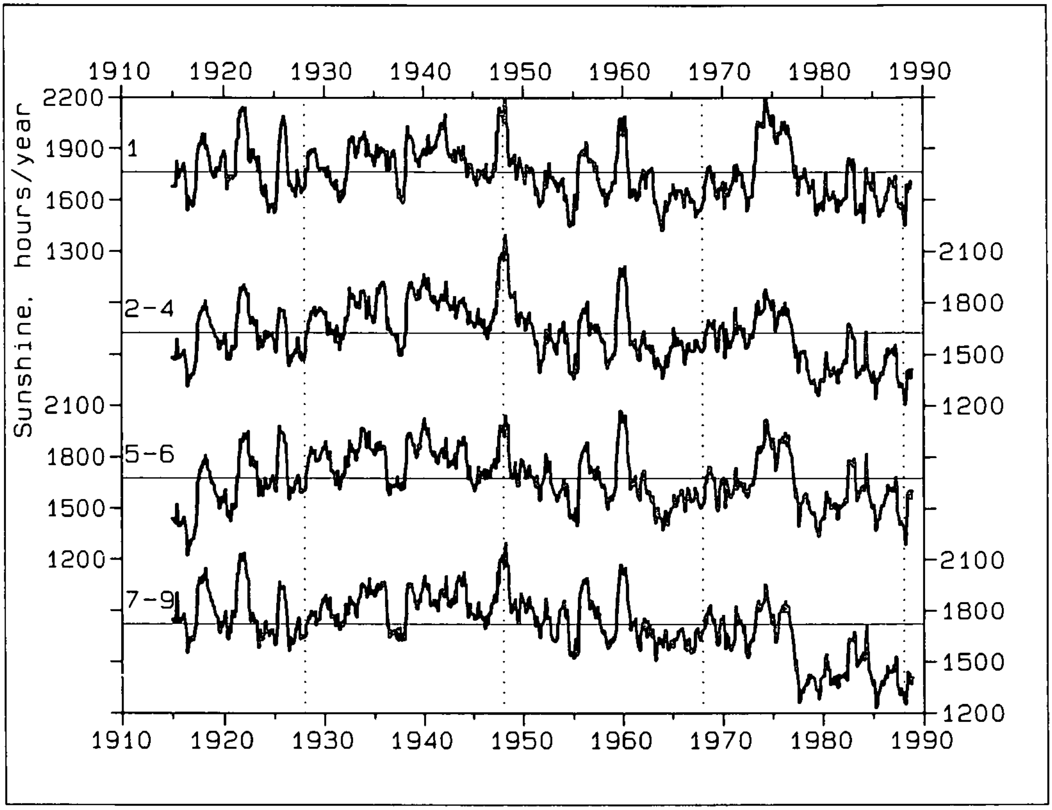

Figure 6.9: Annual hours of sunshine from 4 stations calculated as 12 month moving totals and plotted at the endpoint. The horizontal lines are means of the series.

These common seasonal patterns are seen more clearly in Fig. 6.8, which shows the historical variability of seasonal runoff for the winter and summer half years. Winter runoff rises to a historically high level in recent years in most of the catchments, which follows a similar pattern seen in winter precipitation in Fig. 6.4. Catchments 1, 2 and 3 show a decline in runoff values during the 1970's before rising to their recent high levels.

6.3 Sunshine and potential evapotranspiration

Monthly sunshine data from four stations have been used to estimate the monthly potential evaporation for the nine catchments, as described in section 4.1. Sunshine is naturally influenced by the cloudiness associated with precipitation, so these two "external" variables are not independent of each other.

The historical variation in annual hours of sunshine is shown in Fig. 6.9. The time series show the running 12-month total hours of sunshine, plotted each month. Wide swings in

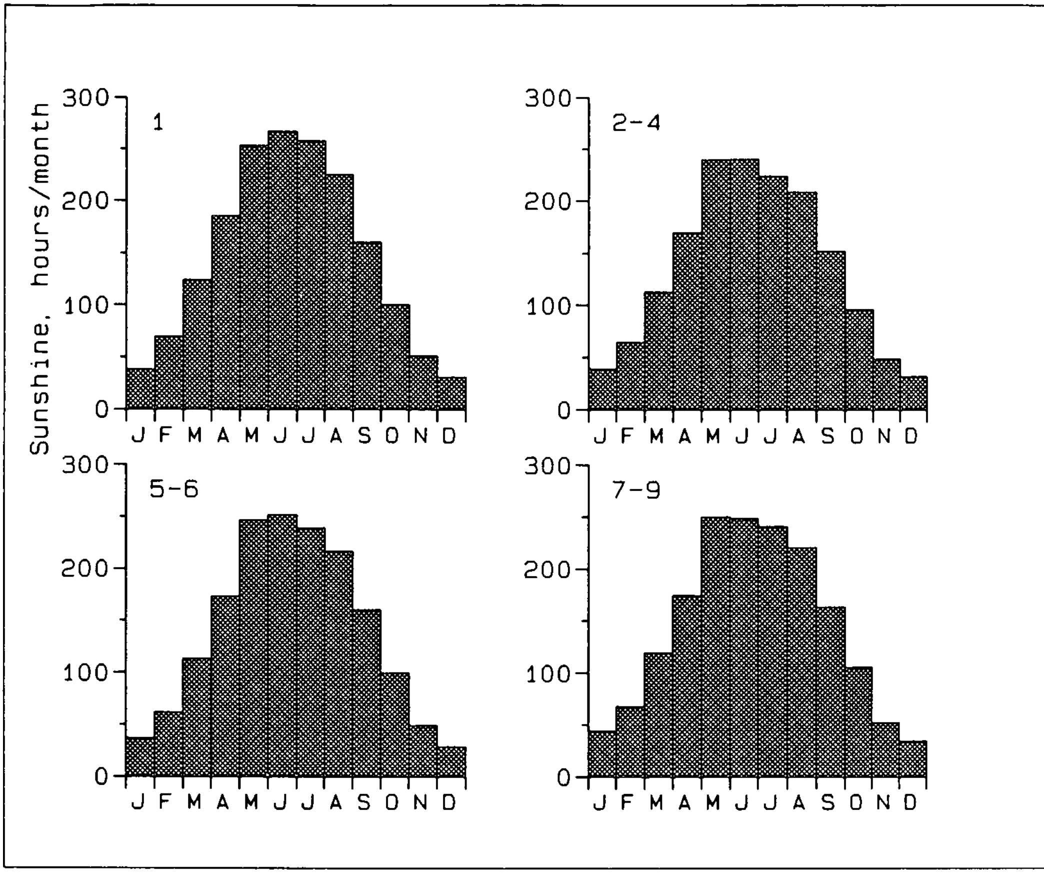

Figure 6.10: Mean monthly sunshine hours from 4 stations for the period 1914 to 1988.

the annual totals are seen in the 1910's and 1920's, followed by a period of mostly smaller variations in the 1930's, 40's and 50's, except for a major low period in the late 1930's and a substantial peak about 1948. Underlying these fluctuations is a general pattern of rising annual sunshine to the late 1930's, followed by a decline to the mid 1960's. Wide fluctuations are seen in the late 1950's and early 1960's. An increase is noted from the mid 1960's to the mid 1970's, when a rather abrupt decline occurs in the 1976-77. Annual sunshine amounts have remained mostly below the long-term average since then.

Monthly mean sunshine totals are shown in Fig. 6.10 for the 4 sunshine stations. Tylstrup, the station in northcentral Jutland, and Årslev on Fyn show a maximum in June on the average, while Askov in central Jutland and Tystofte on Zealand show May as slightly higher than June. December has the fewest hours of sunshine in all cases.

Fig. 6.11 shows the trend of sunshine totals for individual months, for the period of records. Each time series of monthly values has been smoothed by a 15-year moving average. The vertical dotted lines separate the months into summer (April to October) and winter (October to March) half-years. Little variability remains in the winter months

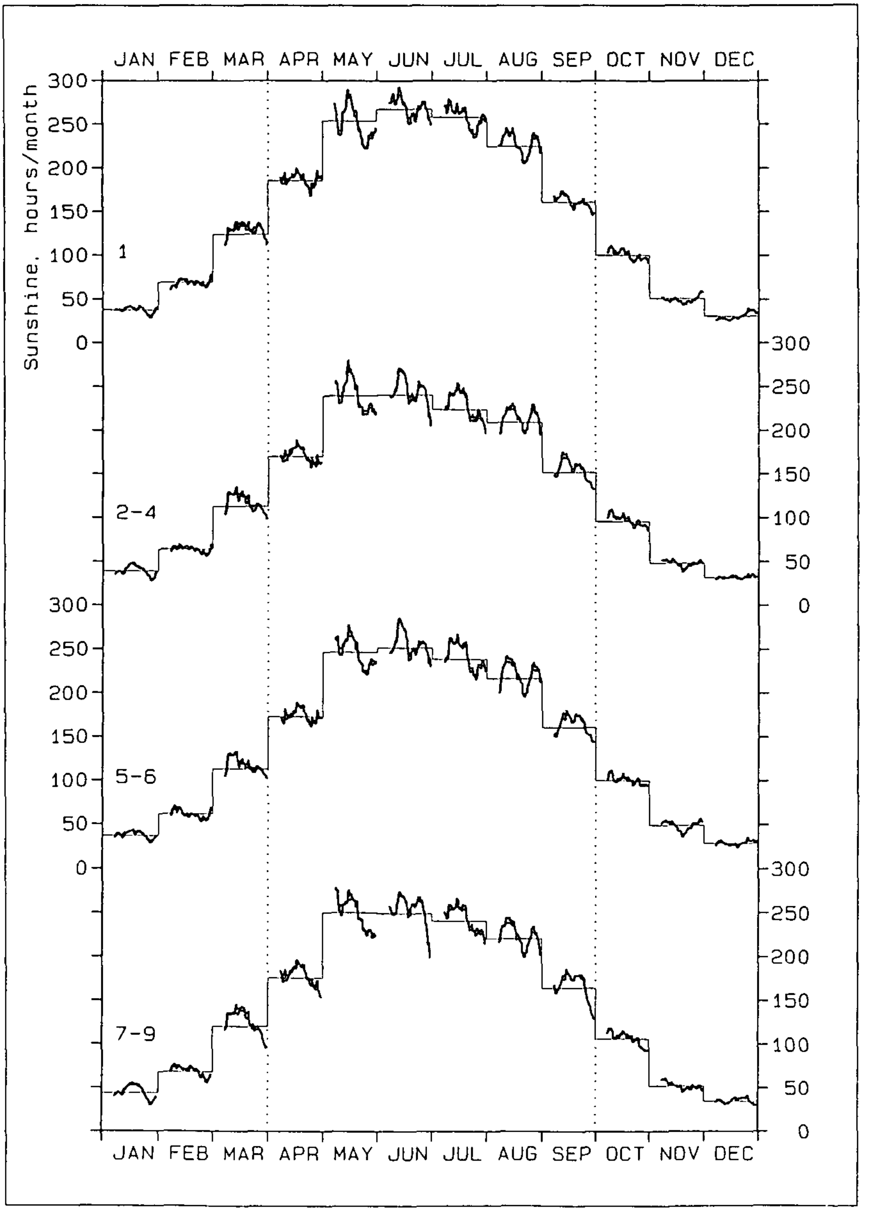

Figure 6.11: Monthly sunshine hours from 4 stations calculated as 15 year moving averages and plotted at the endpoint on a time axis from 1910 to 1990. The horizontal lines are mean values for each month.

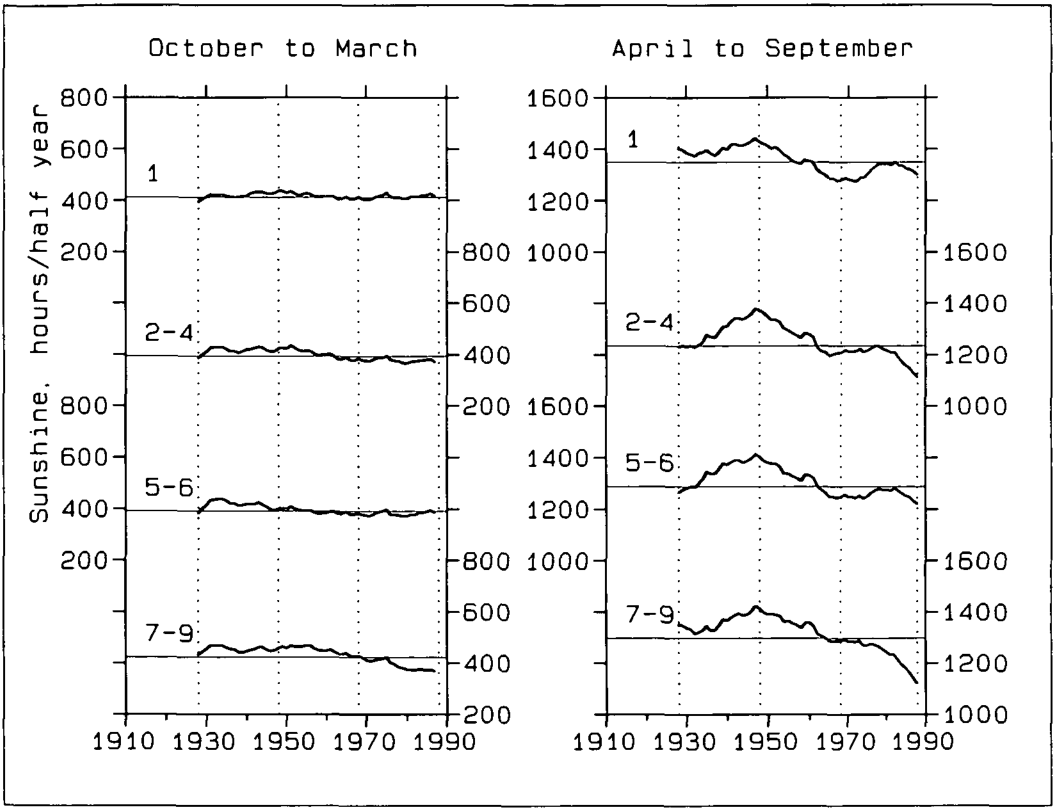

Figure 6.12: Seasonal sunshine hours from 4 stations calculated as 15 year moving averages and plotted at the endpoint. The horizontal lines are mean values for each season.

(after the 15-year smoothing), but large fluctuations are seen in the summer, particularly May and June.

The trends of the seasonal totals of hours of sunshine are given in Fig. 6.12. The winter totals show little variation, although a slight downward trend is apparent. Large fluctuations are seen in the summer total with a general rise in the 15-year summer average from the late 1920's until the late 1940's. Summer sunshine then declines on average until the late 1960's. There is a slight rise in the 1970's, but all 4 stations show a continuing decline in the 15-year average of summer sunshine up to the end of the data period (1987).

Estimates of monthly potential evapotranspiration have been derived from the monthly sunshine data as described in section 4.1. Twenty-year and sixty-year averages of annual potential evapotranspiration are given in the first column of Table 5.2. The values for catchments 5 and 6, and catchments 7, 8 and 9 are identical (or differs only by a small fraction due to latitude differences), because each group used the same sunshine data series.

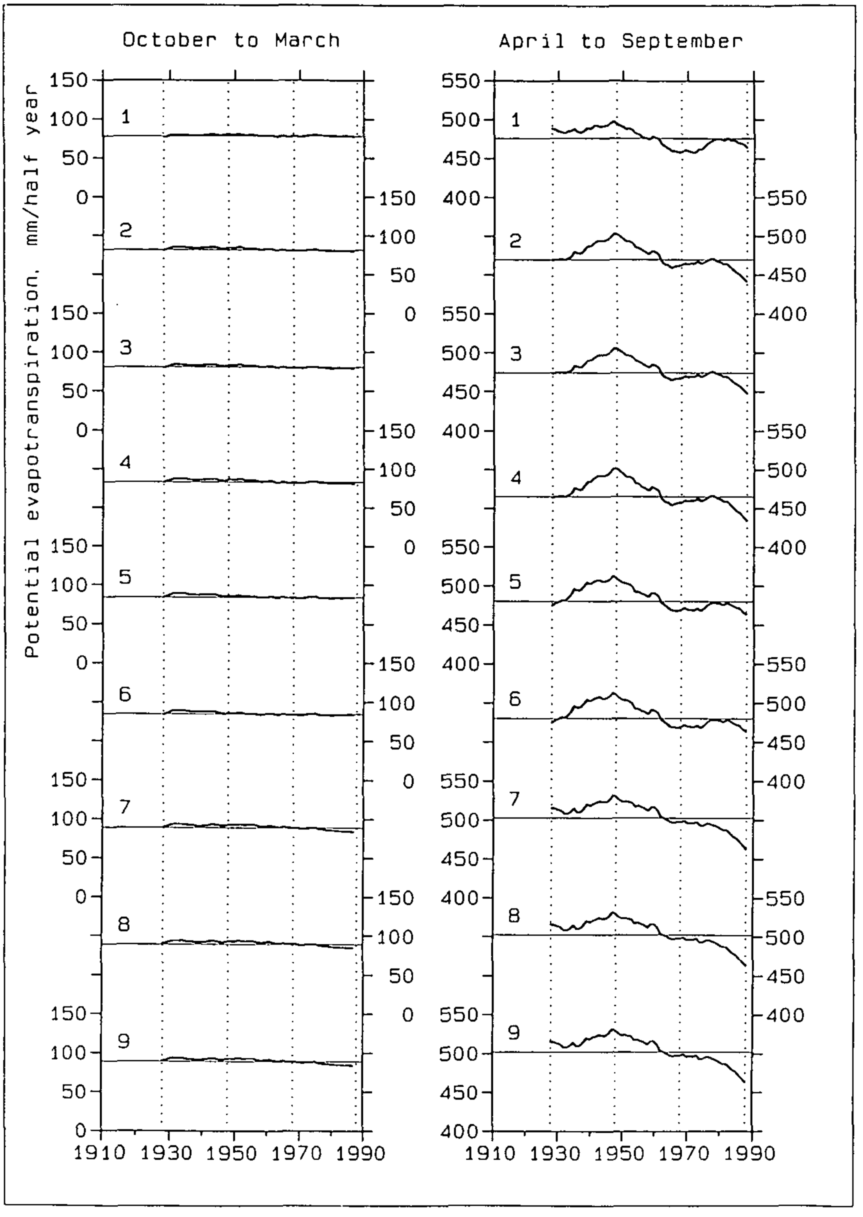

Figure 6.13: Seasonal potential evapotranspiration for each of the 9 catchments calculated as 15 year moving averages and plotted at the endpoint. The horizontal lines are mean values for each season.

5 a

The 20-year averages of annual potential evapotranspiration (and therefore sunshine) in table 5.2 show declining levels from the 1928-1947 period to the 1948-1967 period, and mostly lower levels again in the 1968-1987 period. Time series of winter and summer potential evapotranspiration, smoothed by a 15-year running average, are shown in Fig. 6.13. These display the same patterns as the underlying series shown in Fig. 6.12. Winter potential evapotranspiration varies little, but a peak of summer potential evapotranspiration in the late 1940's is followed by a decline to the mid 1960's, slight rebound into the 1970's, and then a decline to the present. The combined effects of varying precipitation and potential evapotranspiration are reflected in the estimates of basin evapotranspiration, presented next.

6.4 Basin evapotranspiration

The actual evapotranspiration for each of the nine catchments has been estimated through a series of modeling and regression steps described in chapters 4 and 5. It depends largely on the time-varying precipitation and sunshine, calibrated to the simulated response of crop growth computed daily in the WATCROS model. The estimated basin evapotranspiration takes into account land use changes through the data on various land use areas presented in chapter 2. There has been no attempt to estimate the effect of changing farm practices, fertilization, irrigation and drainage changes on the actual evapotranspiration.

Average annual values of basin actual evapotranspiration are given in Table 6.1, for 20-year intervals and the overall 60-year period. The 20-year averages indicate a decline in evapotranspiration between the first and second period in all of the catchments. The decline continues in all but one of the catchments from the second to the third 20-year periods, although these second declines are smaller than the first.

Time series of 12-month moving averaged basin evapotranspiration given in Fig. 6.14 show a somewhat different character than the precipitation (Fig. 6.1) or sunshine (Fig. 6.9). The more step-like character of the basin evapotranspiration estimates is due in part to the calculations scheme, which only reflects a two-month "memory" of moisture conditions. Only a few major events in the precipitation and sunshine records are clearly seen in the basin evapotranspiration results - the 1948, 1976 and 1983 dry (and sunny) periods, for example.

Average monthly basin evapotranspiration for the entire period is shown with the dark shading in Fig. 6.15, along with potential evapotranspiration in light shading. Note that for winter months November through February, these were assumed equal. The summer peak of estimated basin evapotranspiration occurs in July in all cases, which is after the peak of potential evapotranspiration.

Smoothed time series of basin evapotranspiration in individual months are shown in Fig. 6.16. The smoothing is a 15-year moving average. Almost all of the variability is in May

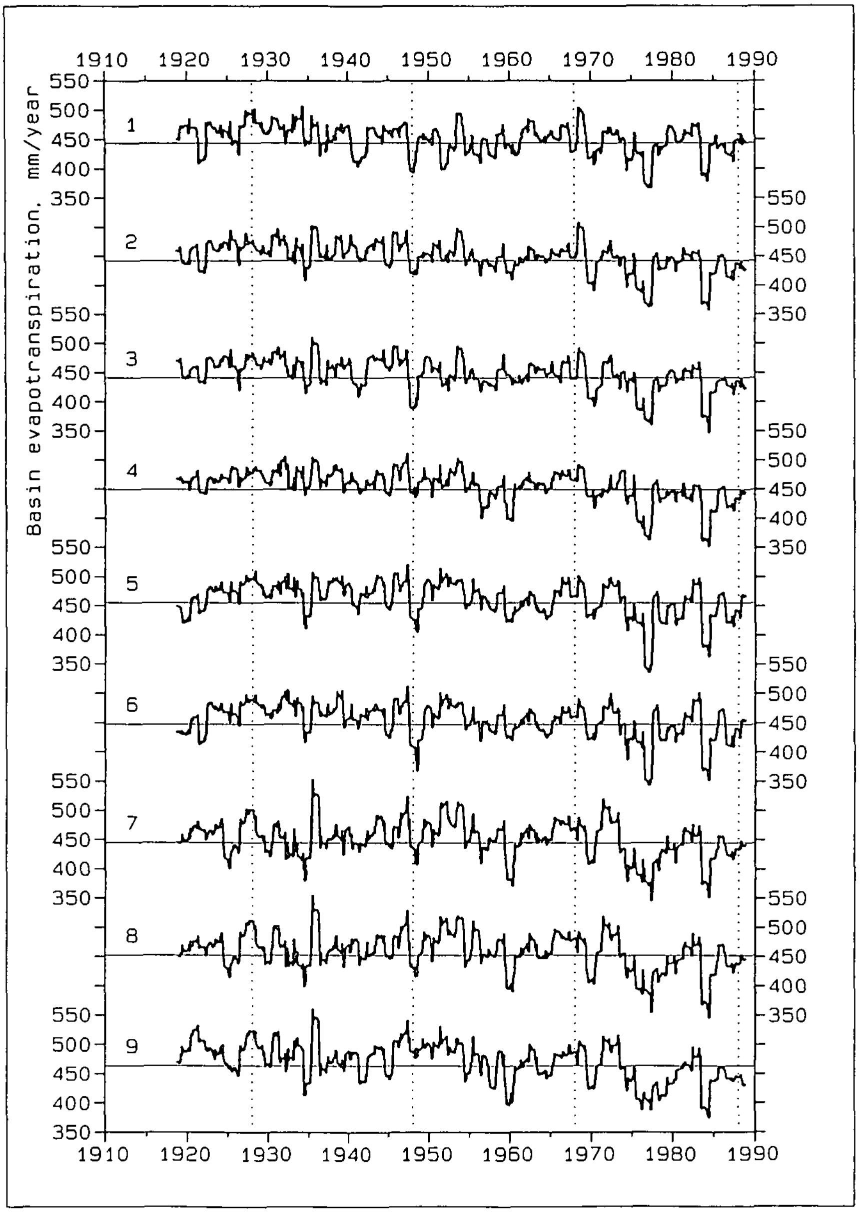

Figure 6.14: Annual estimated basin evapotranspiration for each of the 9 catchments calculated as a 12 month moving total and plotted at the endpoint. The horizontal lines are means of the series.

5b

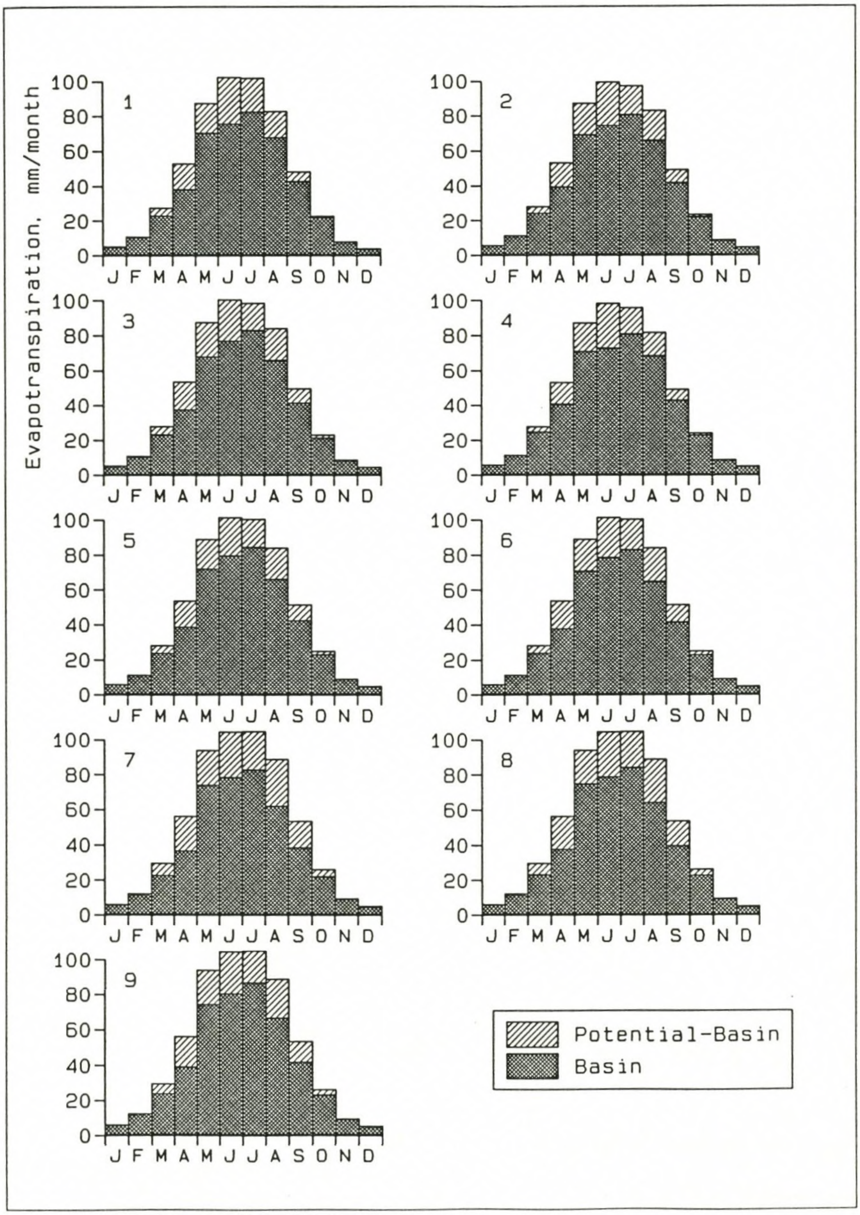

Figure 6.15: Mean monthly potential and basin evapotranspiration for each of the 9 catchments for the period 1917 to 1988.

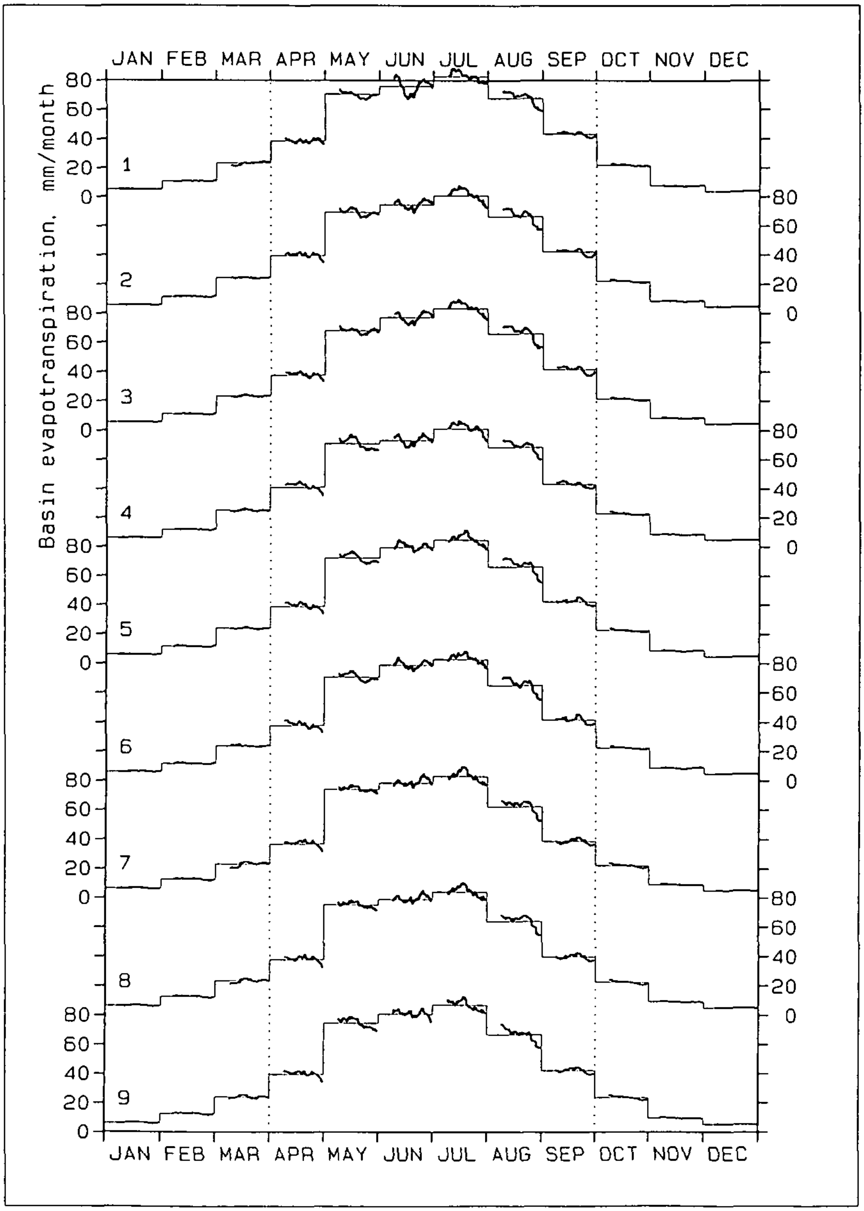

Figure 6.16: Monthly basin evapotranspiration for each of the 9 catchments calculated as 15 year moving averages and plotted at the endpoint at time axis from 1910 to 1990. The horizontal lines are mean values for each month.

5 b*

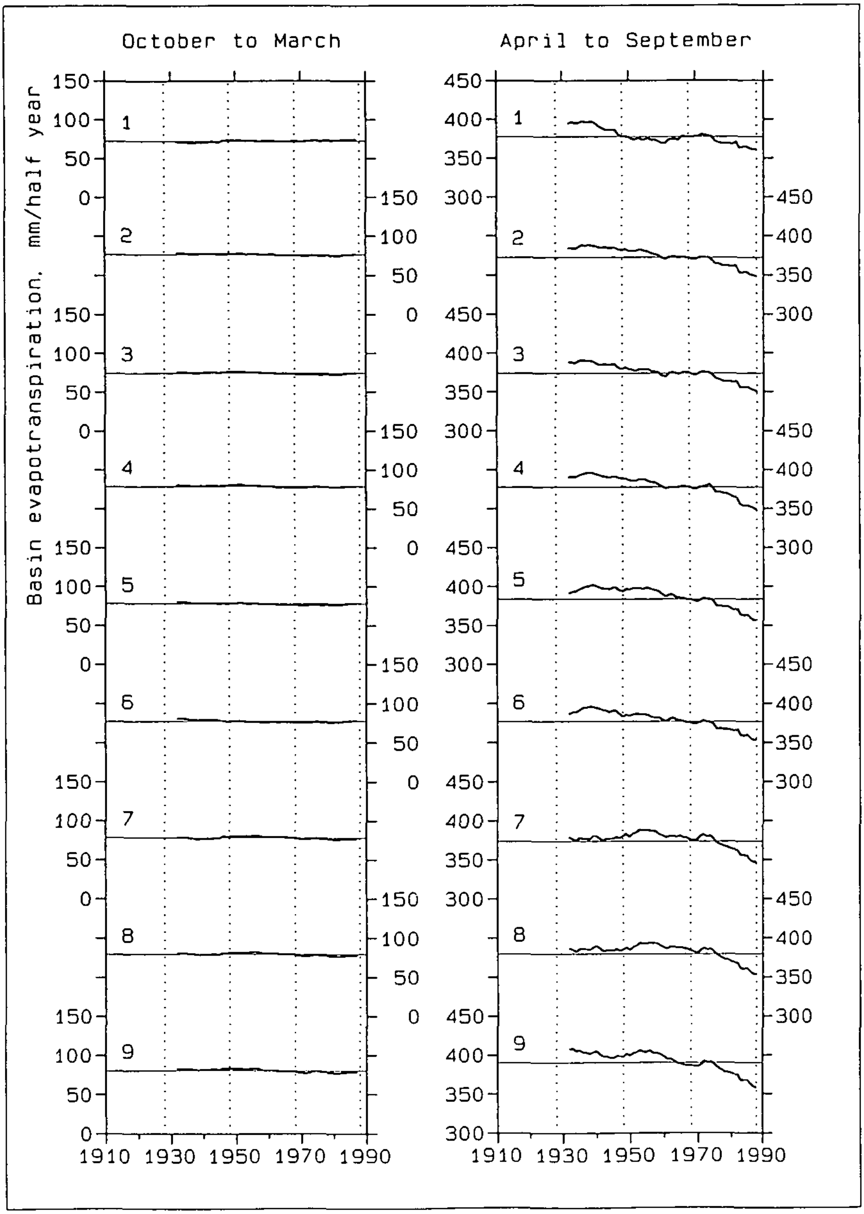

Figure 6.17: Seasonal basin evapotranspiration for each of the 9 catchments calculated as 15 year moving averages and plotted at the endpoint. The horizontal lines are mean values for each season.

to August. April, July and August show a declining trend through much of the period. Time series of seasonal averages are shown in Fig. 6.17, smoothed by a 15-year moving average. There is a clear net declining trend in the summer basin evapotranspiration. The following sections further analyze the hydrological budget through the use of residual terms (differences) and ratios.

6.5 Water balance

The interaction and interdependence of the precipitation, runoff and evapotranspiration processes are difficult to see in the separate components. Differences and ratios given in Table 6.1 are more helpful. The difference of precipitation minus runoff $P - Q$ reflects the amount of water remaining in the catchment for evapotranspiration and change in water storage. The term $P - Q - E_b$ gives the change in water storage as a residual. It should be noted that precipitation and runoff are input data from measurements, and evapotranspiration has been estimated without attempting to balance the water balance (obtain a zero net change in water storage). This allows an evaluation of each of the series as more or less independent estimates, which each have measurement and/or estimation uncertainties.

The 20-year and 60-year $P - Q - E_b$ averages in Table 6.1 reflect the changing water balance, including any biases in the data or estimation procedure. These average residuals are all increasing in the three 20-year intervals. A negative net water balance is seen only in the first period for catchments 1, 2 and 5. The implications of the water balance residual $P - Q - E_b$ is discussed in chapter 7.

Monthly time series of precipitation minus runoff $P - Q$ smoothed by a 15-year moving average, are shown in Fig. 6.18. August and November have relatively large variability. August shows a pattern of increasing $P - Q$ for the first half of the record, followed by a long decline until recent years, when it begins to rise again. November tends show a minor peak in the first half of the record and a large peak in the late 1970's followed by the recent decline. The July patterns are similar to August, while September and October show some characteristics of both August and November. There is a great similarity among all of the catchments.

Fig. 6.19 presents seasonal averages of the $P - Q$ difference, also smoothed by a 15-year moving average. This difference has generally increased in the winter, while it has decreased gradually in the summer.

The annual residual water balance $P - Q - E_b$ is shown in Fig. 6.20, with only calendar-year values plotted. The annual values were calculated from April to March to reduce effect of changing moisture storage within the year. Small upward trends can be seen in these "leftover moisture" curves, with a downturn in recent years.

Monthly time series of the residual water balance $P - Q - E_b$ are shown in Fig. 6.21.

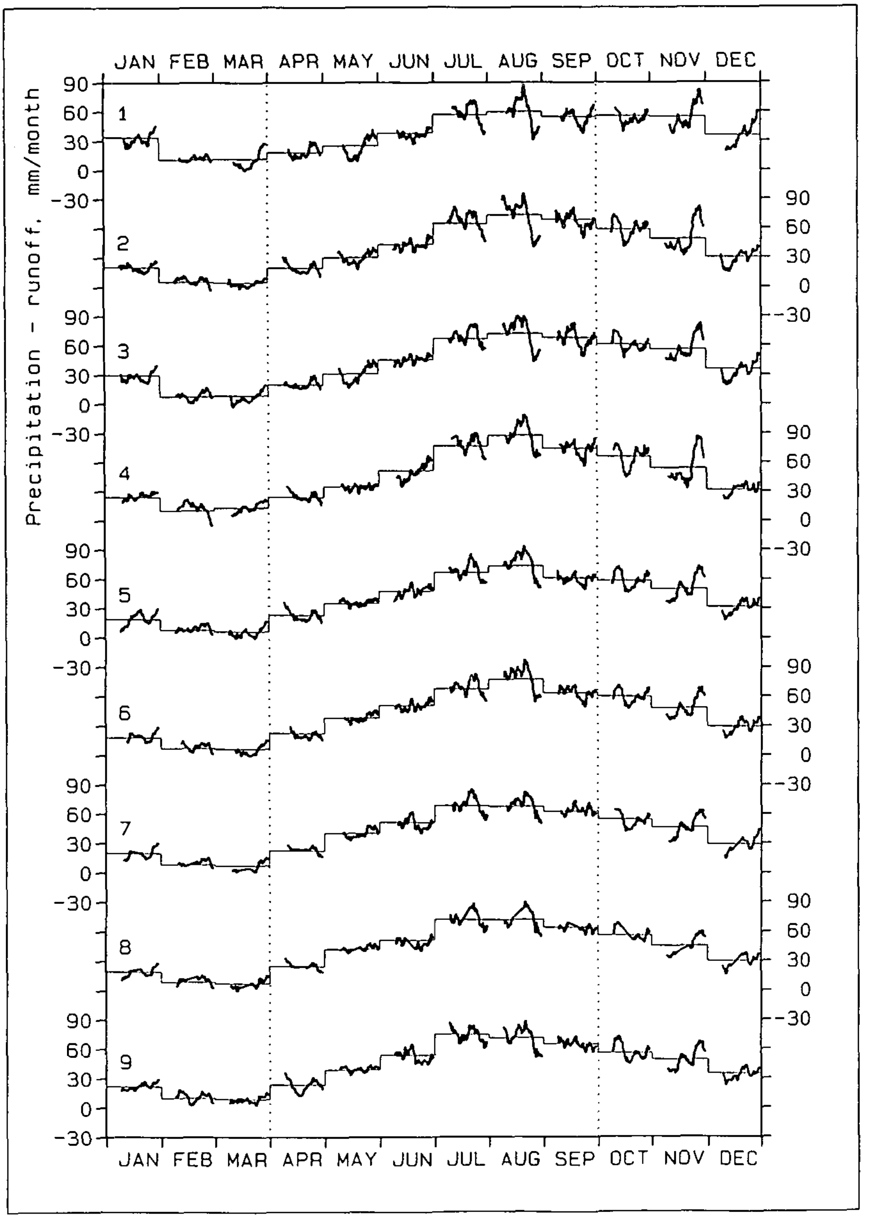

Figure 6.18: Monthly values of precipitation minus runoff for each of the 9 catchments calculated as 15 year moving averages and plotted at the endpoint on a time axis from 1910 to 1990. The horizontal lines are mean values for each month.

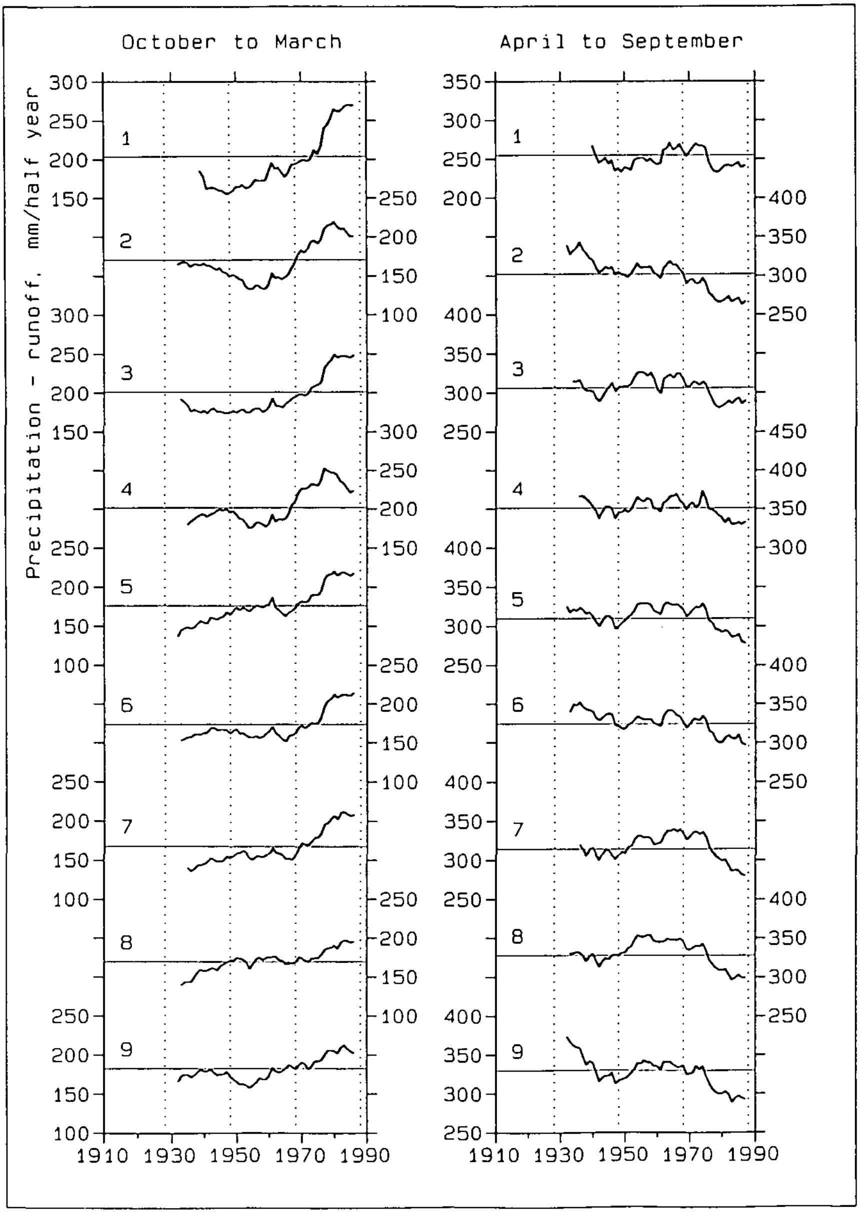

Figure 6.19: Seasonal values of precipitation minus runoff for each of the 9 catchments calculated as 15 year moving averages and plotted at the endpoint. The horizontal lines are mean values for each season.

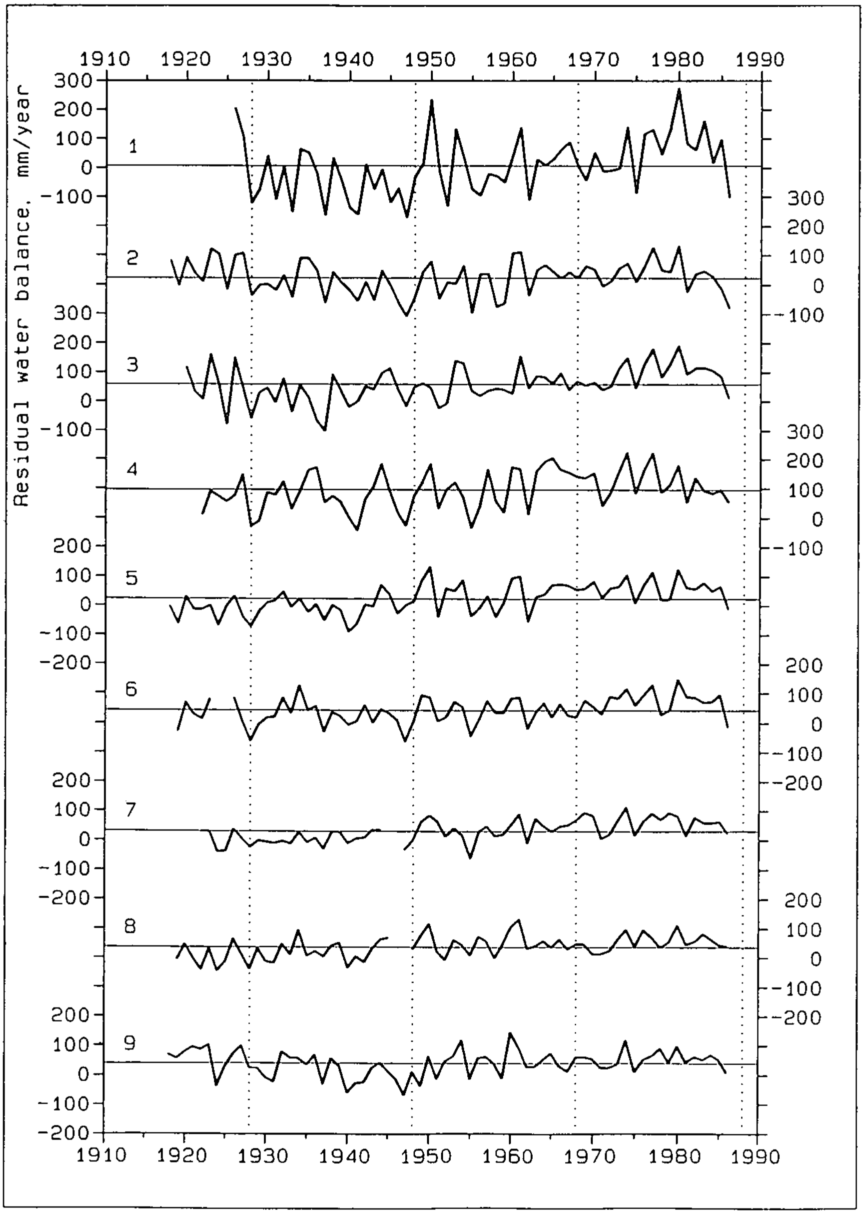

Figure 6.20: Annual water balance residual (precipitation – runoff – basin evapotranspiration) calculated for the period April to March. The horizontal lines are means of the series.

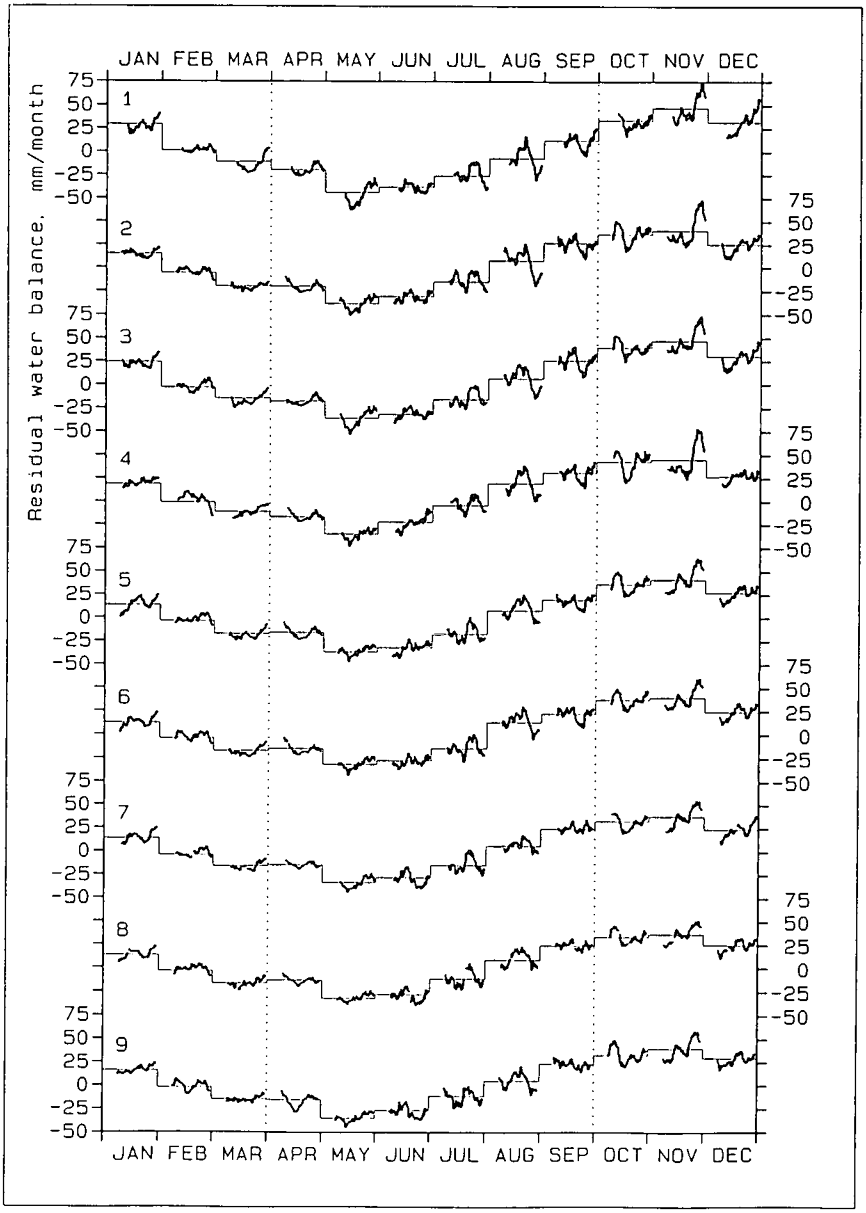

Figure 6.21: Monthly water balance residual (precipitation – runoff – basin evapotranspiration) calculated as 15 year moving averages and plotted at the endpoint on a time axis from 1910 to 1990. The horizontal lines are mean values for each month.

The general seasonal pattern reaches a negative minimum value in May, the month where there is the largest net withdrawal of water from the watershed. Runoff is high in spring because of the winter recharge of groundwater, evapotranspiration is high because the soil is wet, crops are reaching full cover, and sunshine is high, while precipitation does not reach the summer peak until June or July. The seasonal maximum of the residual water balance is in November, when precipitation levels are high (cf. Fig. 6.2), but from low intensity showers, while evapotranspiration is near minimum. This is the period of greatest recharge.

The smoothed monthly time series of the residual water balance in Fig. 6.21 show nearly identical patterns to the corresponding precipitation time series in Fig. 6.3. This reflects the substantial dependence of the other water balance components on the precipitation, and the large influence of precipitation on water balance variability.

There are also great similarities between the smoothed seasonal time series of the residual water balance in Fig. 6.22 and the corresponding precipitation series in Fig. 6.4.

The runoff ratio Q/P is another useful hydrological indicator. Under stable climate and watershed conditions, one would expect the runoff ratio to remain fairly constant. The 20-year averages in Table 6.1 vary within a few percentage points in most of the catchments. Catchments 1 and 4 show the largest net changes. In catchment 1, Lindenborg Å the 20-year average runoff ratio declines by 6 percentage points from the 1928-47 average to the 1968-87 period, while catchment 4, Brede Å shows an opposite 8 point rise in the runoff ratio between the same periods.

Time series of the annual runoff ratio (12-month runoff divided by 12-month precipitation) are plotted each month in Fig. 6.23. Peaks in the runoff ratio occur when precipitation is below normal while runoff is maintained by groundwater discharge, or runoff is high due to storm runoff from intense rainfall.

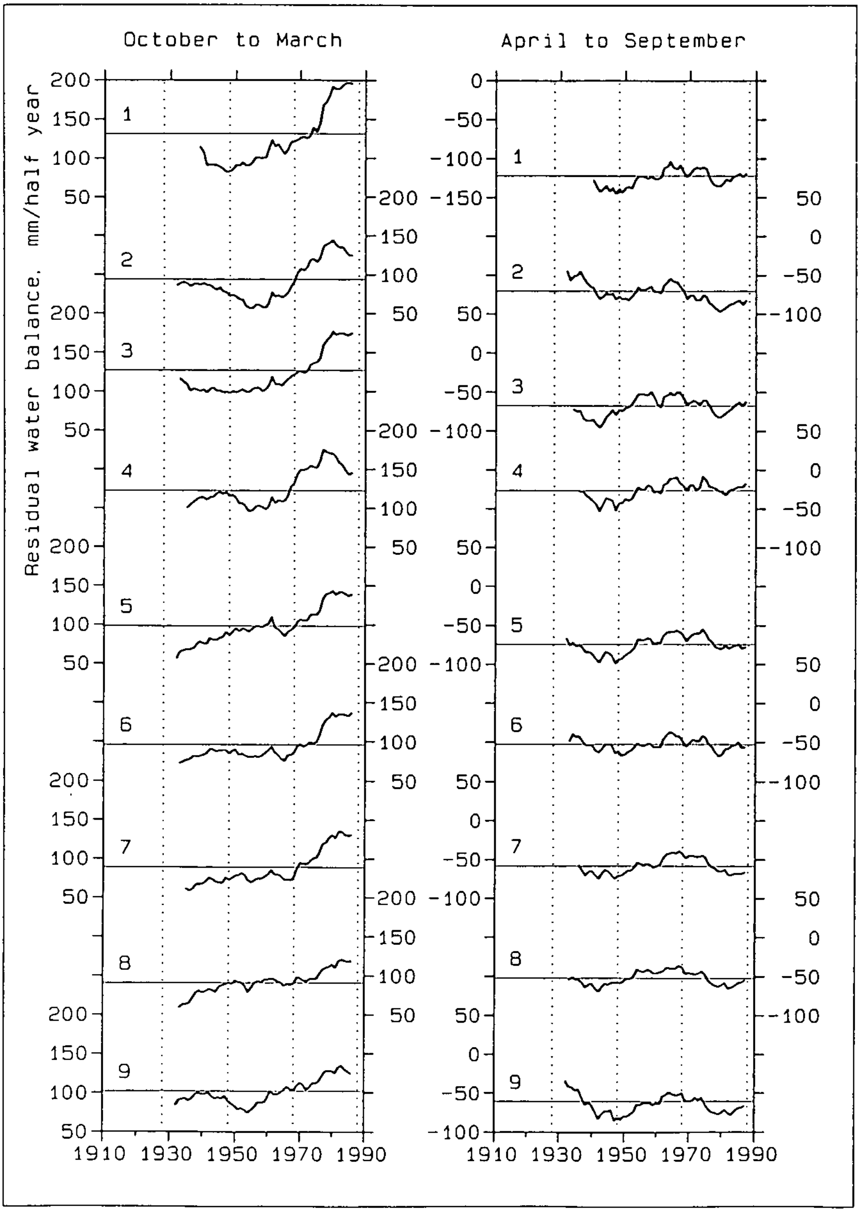

Figure 6.22: Seasonal water balance residual (precipitation – runoff – basin evapotranspiration) for each of the 9 catchments calculated as 15 year moving averages and plotted at the endpoint. The horizontal lines are mean values for each season.

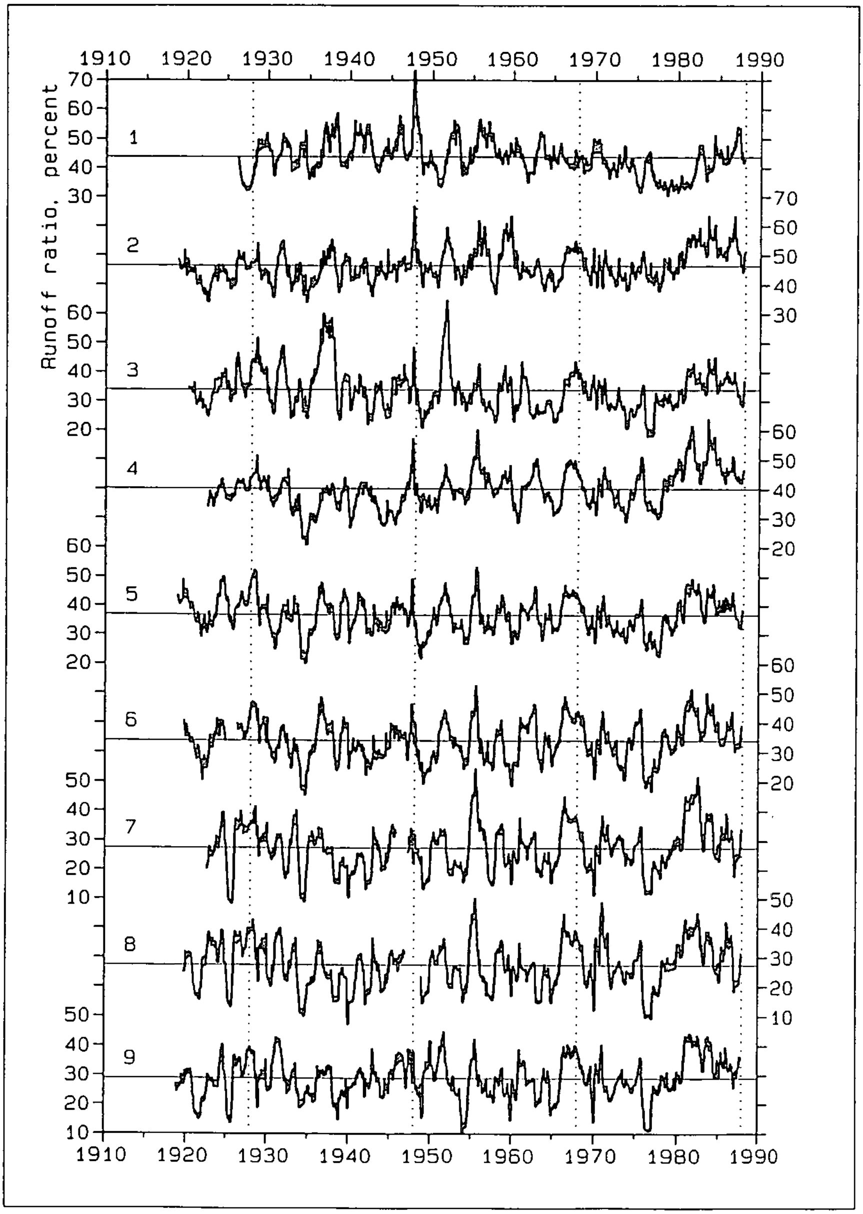

Figure 6.23: Annual runoff ratio (precipitation/runoff) for each of the 9 catchments calculated as 12 month moving averages and plotted at the endpoint. The horizontal lines are means of the series.

7 Discussion

The results presented in chapter 6 indicate trends in the components of the water balance equation as well as biases in the estimation procedure. These two findings will be discussed separately.

An advantage of this study's estimation procedures, unlike most other hydrologic studies, is that the evapotranspiration has been estimated completely independent from the streamflow measurements. The evapotranspiration estimates have not been "adjusted" under the assumption that the runoff and precipitation measurements are correct. Particular attention has been paid to avoidance of seasonal biases in the statistical estimation procedures. There are limitations to the regression approach which can only be rectified through the use of a more physically-based catchment and evapotranspiration model, using a daily time-step.

Factors not taken into account in this study include possible effects of increased fertilization, the use of irrigation, and the effects of changes in the frequency of high-intensity precipitation which would not be reflected in monthly totals. The results do take the largest sources of climatic variation into account, however. While the absolute values of the catchment terms may contain biases, the major characteristics of their variability are clearly shown by these data.

7.1 Trends in water balance components

The major long-term (multi-year) and short-term (within year and year-to-year) variations are quite similar among all the nine catchments. The greatest differences among catchments are seen in the runoff data.

Taken as an average over the nine catchments, average annual precipitation increases about 10 percent over the period of the study, with much of this net increase occurring during the winter half-year (October to March). Winter precipitation is most effective in affecting the long-term water balance, because low evapotranspiration levels permit most of the precipitation to saturate the soil and percolate to groundwater. Winter precipitation is generally of low intensity in Denmark, which means that much moisture has an opportunity to infiltrate, rather than be lost in storm runoff.

There is a sharp decline in annual sunshine duration in 1976-77. This decline can not be associated with the change in instrument type, cf. appendix B, as this change a few years before the decline.

Estimated average annual basin evapotranspiration declines about 6 percent during the period of study. The estimated long-term average annual potential evapotranspiration decreases nearly 9 percent, due primarily to reduced summer sunshine. There is a minor downward trend in summer precipitations overall, but the effect of the larger decrease in potential evapotranspiration indicates that energy limitations from sunshine are responsible for most of the decline in basin evapotranspiration.

The average annual runoff increases about 17 percent, averaged over all nine catchments. This is consistent with the increased precipitation and reduced evapotranspiration. The runoff response varies among the individual catchments, but the short term variations are similar. Lindenborg Å (catchment 1 in northern Jutland) shows considerably smaller range of variability than the other catchments. The largest variability is seen in Brede Å in southwestern Jutland. The differences in the runoff values are due to basin factors, such as soil types, drainage patterns and groundwater characteristics (Waagepetersen et al., 1991).

The average annual runoff ratio increases from a value of about 35 percent to about 37 percent from the first 20-year interval to the most recent one. This can be attributed in part to the increase of precipitation in the winter months when evapotranspiration cannot extract a proportionate share of the increase.

The Brede Å catchment in southwestern Jutland exhibits the largest long-term changes. The 20-year-average annual precipitation increases 15 percent and the runoff increases 40 percent. Here, the runoff ratio increases from a value of 36 percent to 44 percent from the 1928-1947 period to the 1968-1987 period. There is no corresponding change in the relative rate of basin evapotranspiration, as a percentage of potential evapotranspiration. The average annual basin evapotranspiration in Brede Å declines by about 7 percent, which indicates that a long-term increase in cloudiness correlated with greater precipitation may have a larger impact on the evapotranspiration than the increase in annual total of available moisture does. One needs to look more closely at the seasonal variations of sunshine, precipitation and evapotranspiration to interpret these results.

The basin water balance residuals (precipitation - runoff - evapotranspiration) all show increasingly positive values, meaning a rising rate of recharge of water storage in the catchments. For the Brede Å catchment, this residual averages 98 mm per year over a 60-year period. If this residual was realistic, it could roughly be translated into a net increase of 18 meters in the water table over 60 years (assuming porosity of 30 percent). The residuals in the other catchments are all positive, but smaller than the Brede Å value. The recent short-term trend in the residuals has been a decline from a peak in 1980, with all of the catchments showing a near-zero or negative value (net annual decline in water storage) by 1987.

The evaporation model used in this study does not account for changes in use of fertilizers and pesticides and in the use of irrigation, which may also affect evapotranspiration.

Table 7.1: Number of farms with irrigation systems and irrigable area in Denmark. Data from Committee on irrigation (1978) and The Danish Department of Statistics.

Year	No. farms with irrigation	Irrigable area ha	Irrigable area pct. of total area
1957	1600	-	-
1964	3129	57288	1.9
1972	5161	130000	4.4
1976	8820	220000	7.5
1977	10600	265000	9.1
1980	15366	390762	13.4
1985	14308	403892	14.3

Over the time period studied here, the use of these factors in agriculture has increased dramatically.

Table 7.1 shows the development in number of farms with irrigation systems and the irrigable area in Denmark. In the mid 1960's only a small fraction af the agricultural area could be irrigated. This fraction increased rapidly during the 1970's, especially after the dry summers of 1975 and 1976. The irrigable area has been rather stable since 1980. Table 7.2 shows that the majority of the irrigation capacity is concentrated on the sandy soils in western Jutland.

The changes in irrigation pattern have thus mainly occured since the mid 1970's, so that only a small part of the record used in this study have been affected by this change. It is apparent from Table 6.1 and Fig. 6.20 that a large part of the change in residual basin water balance occured before irrigation became common on sandy soils.

Crop yields have increased somewhat during the 20'th century. Fig. 7.1 shows the mean Danish grain yields of wheat and barley from 1900 to 1988. No specific separation between winter and spring varieties were possible in this data material. Wheat yields can, however, mainly be attributed to winter wheat, and barley is mainly spring barley. During this period mean grain yields have doubled. There are several reasons for this, including use of new varieties, use of fertilizers and better control of plant pests and diseases. Other factors such as changes in cropping area will also affect the mean yields, e.g. if more barley is grown on poorer soil then the mean yield will tend to decrease.

There has been a rapid development in the use of commercial fertilizers during this century. The development in use of nitrogen, potassium and phosphorous fertilizers in Danish agriculture is shown in Figs. 7.2 to 7.4. Especially the use of nitrogen fertilizers show a sharp increase during the 1950's and 1960's. The increased use of fertilizer along with a better control of plant pests and diseases by increased use of pesticides are the main reasons for the increase in crop yields. These changes in use of fertilizers and pesticides

Table 7.2: Irrigable agricultural area for each county in Denmark. Data from the Danish Department of Statistics.

County	Irrigable area 1977 ha	Irrigable area 1977 Pct.of total area	Irrigable area 1985 ha	Irrigable area 1985 pct. of total area
Nordjylland	15600	3.7	29980	7.3
Viborg	13000	4.7	24964	9.2
Århus	14550	4.9	18685	6.5
Vejle	20500	9.9	31444	15.6
Ringkøbing	68000	21.0	114582	36.1
Ribe	67300	31.7	88417	42.8
Sønderjylland	33125	11.3	57580	20.0
Fyn	9575	3.9	11364	4.7
Vestsjælland	9850	4.8	11212	5.5
Frederiksborg	5425	8.6	5044	8.2
Roskilde	1825	3.2	1765	3.1
København	600	5.7	764	7.7
Storstrøm	4900	2.0	7517	3.1
Bornholm	700	1.9	574	1.6

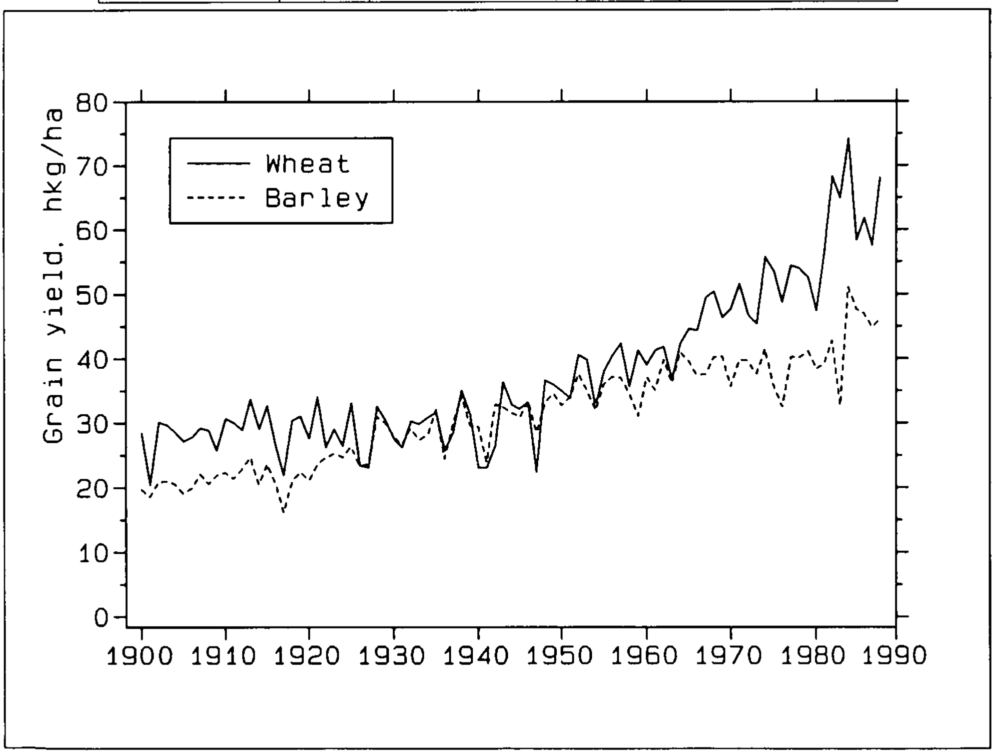

Figure 7.1: Development in mean grain yield of wheat and barley for Denmark. Data from The Danish Department of Statistics.

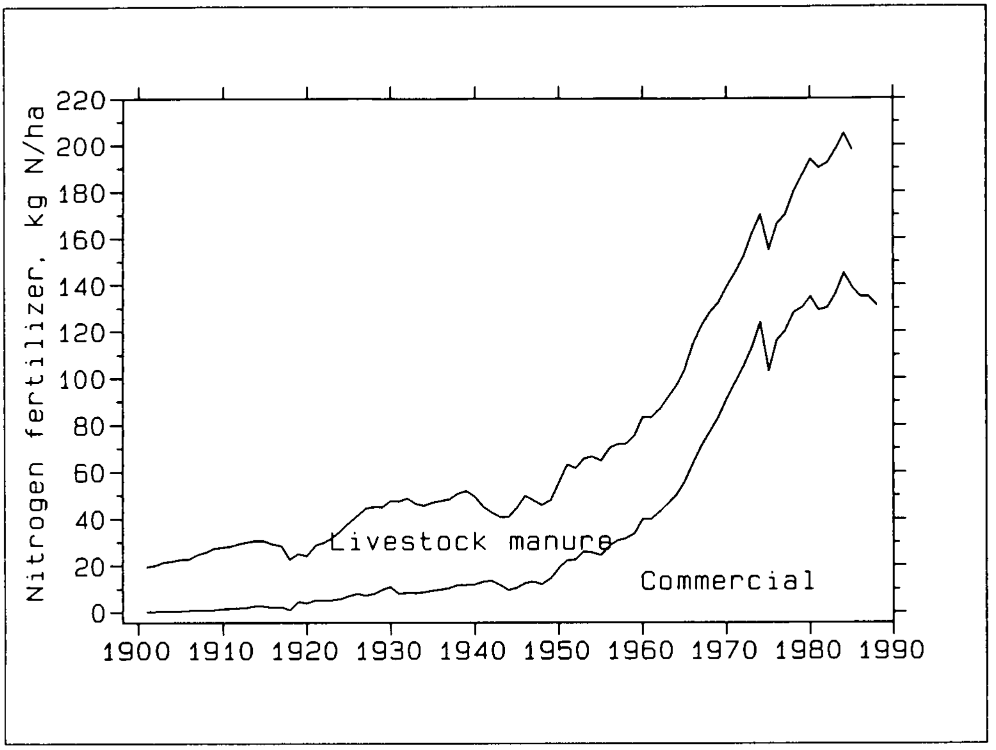

Figure 7.2: Development in use of nitrogen fertilizer in Danish agriculture. Data from The Danish Department of Statistics.

may also have caused an increase in evapotranspiration through larger and more dense crops with higher leaf area index.

There is no simple relationship between fertilizer application and evapotranspiration of crops. Viets (1962) listed a number of possible effects of increased fertilization on evapotranspiration. The most common responses of evapotranspiration to increased nitrogen fertilization observed in experiments are no response (Hatfield et al., 1988) or an increase in evapotranspiration (Brown, 1971; Jones et al., 1988; Ramig and Rhoades, 1963; Warder et al., 1963; Djurhuus, 1985). The increase in water use with increased nitrogen fertilization seems to be most pronounced at low initial nitrogen content in the soil. The effect may depend on whether the increased fertilization has any effect on leaf area index causing this to be high during a longer period.

There is thus evidence that increased fertilization may affect crop evapotranspiration mainly by changing the leaf area index. Use of pesticides may have similar effects by enlarging the duration of active green crop area. Comparing the graphs of yield and fertilizer use in Figs. 7.1 to 7.4 with the graphs of trend in basin water balance residual in Figs. 6.20 to 6.22 shows more or less a coincidence in the periods of increased water balance residual and the periods with an increase in fertilizer use and crop yields. The increased intensity in farm management and use of input factors in agriculture may thus

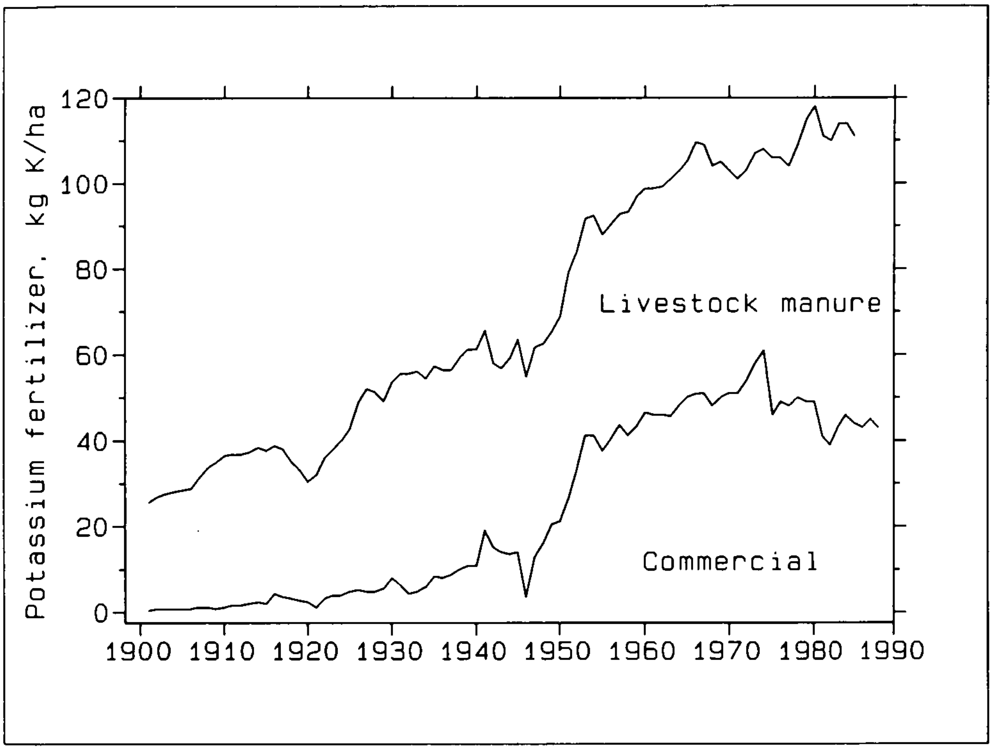

Figure 7.3: Development in use of potassium fertilizer in Danish agriculture. Data from The Danish Department of Statistics.

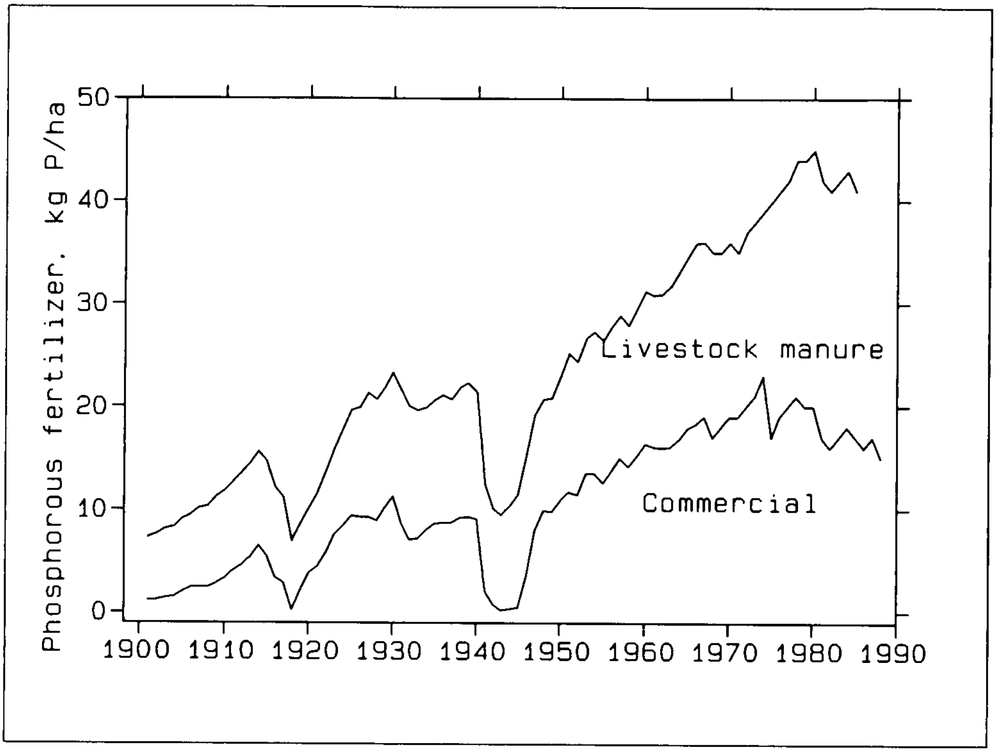

Figure 7.4: Development in use of phosphorous fertilizer in Danish agriculture. Data from The Danish Department of Statistics.

have played a role for increasing basin evapotranspiration.

7.2 Biases in estimation of water balance components

The large long-term water balance residuals that result from these estimates may indicate biases in the estimation procedures. The large water balance residuals are clearly unrealistic as demonstrated for the Brede Å catchment i the previous section. Potential evapotranspiration could be underestimated, the actual evapotranspiration estimates could be underestimated, or the area of the basins that are assumed to evaporate at the potential rate may be underestimated. The monthly actual evapotranspiration model uses only a 2-month lag in calculations. This is sufficient for the seasonal variations, but can not represent the effect of persistent (year-to-year) changes in soil moisture, ground water levels, or the fluctuating extent and wetness of marshes, small ponds and other groundwater-dependent wetlands. Both the daily WATCROS model and the monthly statistical models would have to include long-term groundwater components to account for these additional sources of variation on evapotranspiration. Also the models used in this study do not account for capillary rise of water, which in some areas with a shallow ground water level could contribute to evapotranspiration.

The water balance residuals may also be due, in part, to overestimation of precipitation, due to overcorrection for effect of wind on the catch of the raingages. The shelter at the precipitation stations may thus have changed during the period used in this study. There are, however, no available information on this. Runoff could be underestimated because parts of the topographically-defined surface drainage area may not contribute directly to the streamflow, especially in the flatter catchments like Brede Å. Precipitation minus runoff is largest for the Brede Å catchment, indicating that the size of this catchment is underestimated. There could also be a significant, unmeasured groundwater discharge from some of these catchments which could account for some of the residual excess.

The water balance model in this study uses the Makkink potential evapotranspiration as the reference for calculating actual evapotranspiration. This is done by using a regression equation relating potential evapotranspiration to solar radiation (or sunshine hours) alone. The potential evapotranspiration estimates used do thus not include effects of temperature, air humidity or wind velocity. Changes in these factors may thus have influenced the results. There have been some minor changes in the temperature climate of Denmark over the past century (Olesen, 1991). These changes are, however, not believed to have significantly influenced the estimates of potential evapotranspiration as temperature and solar radiation are generally positively correlated during summer time.

This potential evapotranspiration refers to a short cut grass crop. It is assumed that actual evapotranspiration cannot exceed this value. For some tall crops with reduced aerodynamical resistance to evaporation this may not be a valid assumption. Feddes (1987) presented tables relating Makkink evapotranspiration to maximum crop dependent evapotranspiration, showing that the maximum evapotranspiration for some crops may be 10 or 20 % higher than the Makkink potential evapotranspiration. This may be a part of the reason for the relatively large positive basin water balance residuals shown in Table 6.1.

Only a limited number of crop-soil combinations were used in calculating the basin evapotranspiration, and a coarse sandy and a loamy soil was taken as representative of other soil types as well. This will introduce some systematic errors in the estimation of basin evapotranspiration. The mean annual actual evapotranspiration from a larger number of crop and soil types is shown in Table 3.2. Using these values a basis for weighing the evapotranspiration from different soil types showed an underestimation of basin evapotranspiration of 1 to 5 mm per year in catchments 1 to 6 and 8 to 13 mm in catchments 7 to 9. This can, however, not explain the large increase in basin water balance residuals.

A small fraction of the catchment area was fallow in the start of the period. In calculating basin evapotranspiration fallow was assumed to evaporate like a spring grain crop. If the area with fallow behaved more like a bare soil then a reduction in basin evapotranspiration will occur. A calculation based on the values in Table 3.2 shows that this reduction in basin evapotranspiration only amounts to about 3 to 5 mm per year. Other changes in cropping pattern within the agricultural area in the catchments have been accounted for in estimation of basin evapotranspiration. There was, however, no information available on changes agricultural area within the catchments. It does not seem likely that such changes would have significantly affected the estimation of basin evapotranspiration.

The low input of fertilizers and pesticides may have caused lower evapotranspiration from crops before 1960, as discussed in the previous section. There is, however, no reason to assume that these factors have been important in recent years.

8 Conclusion

The major patterns of climatic variability in the water balances of nine catchments in Denmark can be clearly seen in the results of this study. There are changes in both the annual amounts of precipitation and sunshine, but more importantly, there are variations in the seasonal distribution of precipitation and sunshine during the year. The seasonality of these factors has pronounced impacts on the water balances.

The absolute values of the estimates of water balance components may include biases which cannot be resolved by the presently available data, the simple modelling approach used, and the limited information on changes in land use. Possible sources of biases are:

- Overestimation of precipitation due to overcorrection of effect of wind on aerodynamic error.
- Underestimation of maximum evapotranspiration from tall crops.
- Overestimation of leaf area index in crops at low inputs of fertilizer and pesticides.
- Capillary rise of water in the soil is not accounted for.
- Misrepresentation of crops and soils due to a limited number of these combinations being used.
- Difficulties in defining fallow.
- Man-made changes such as drainage and use of water for irrigation and municipal purposes.

The use of daily and monthly sunshine data to estimate potential evapotranspiration is a particular problem. The long term averages of sunshine duration are correlated to the insolation which drives the evapotranspiration, but there are large variations in this relationship. The sunshine duration is much more sensitive to cloud type than the insolation. Thin high clouds can cause the sunshine to be below the threshold of the sunshine recorders, while the solar radiation reaching the ground remains fairly high. Even small changes in the frequency of high clouds would have a sizable impact on the estimates of solar radiation and potential evapotranspiration based on the sunshine duration.

Changes in the exposure of the sunshine recorders, due to growing trees or additional buildings on the horizons of the instruments could effect both the daily and monthly sunshine totals. These horizon effects could be minimized if hourly sunshine amounts were used to calculate daily solar radiation. The low sun angle when the horizon effects occur would give little weight to these observations in comparison to the unobstructed mid-day observations, resulting in a significantly better estimate. The significance of the solar radiation in the estimation of potential and actual evapotranspiration is very high, and additional work should be carried out to make the hourly sunshine records available for the entire period of record (the paper charts are available in DMI archives) and to refine the estimation of daily solar radiation using these hourly data. The effects of the change in instrument type (from Fuess to Cassella) during the 1970's should be thoroughly documented, so that any biases from this change can be removed from the data.

There are major limitations in the modelling approaches used, with regard to long term changes in the evapotranspiration. Neither the daily WATCROS crop model, nor the monthly regression models, have long-term water storage components. This means that the evapotranspiration estimates only reflect the variability of precipitation and sunshine within a single season. In fact, for only two months in the regression model. Long-period fluctuations in the water balance lead to changes in water table levels, and resulting changes in wetland areas fed by groundwater in the catchments. Further work on modelling catchment evapotranspiration should take into account differences between crops in maximum evapotranspiration and the effect of crop management on evapotranspiration.

The choice of only two soil types for this study does not represent the wider range of soil types actually found in these catchments. A more comprehensive modelling effort covering more of the possible crop-soil combinations would be required to properly represent the true range of variability.

Net groundwater flows are unknown in these catchments, but may be significant to the overall water balance. Additional model complexity is needed to attempt to represent the groundwater components, but this requires some data on groundwater levels and gradients to calibrate or verify the model results. Groundwater studies would help to delineate the surface and subsurface drainage areas. This would remove uncertainty regarding the estimation of area-average runoff from the streamflow measurements.

This combined study of nine catchments provides a good picture of the variability of the hydrologic components, and the major similarities in hydrologic response to climate variability across Denmark. The effects of changes in the drainage characteristics of the individual catchments remain difficult to separate from the climatic effects. The study does provide a background for further studies, using improved models and data. The presence of major long-term fluctuations in the precipitation and sunshine data, and hydrologic response clearly illustrates the importance of a stable long-term climatological and hydrological measurement program. Hydrologic studies based on a few years of data are clearly at risk to misrepresent the longer term relationships among the hydrological factors.

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A List of symbols

β Regression coefficient

γ Psychrometric constant [66.7 Pa °C^{-1}]

λ Latent heat of vaporization of water [2.465 MJ mm^{-1}]

ε Error term in regression model

D Potential water deficit $(E_p - P)_+$ [mm]

E_a Actual evapotranspiration [mm]

E_b Basin actual evapotranspiration [mm]

E_c Crop actual evapotranspiration [mm]

E_p Potentiel evapotranspiration [mm]

H Height of water level in stream [m]

H_o Correction for stream bed level [m]

N Observed hours of sunshine [h]

N_m Number of daylight hours [h]

P Precipitation [mm]

Q Runoff [mm]

q Stream flow [m^{-3} s^{-1}]

R_{se} Extraterrestrial solar radiation [MJ m^{-2}]

R_{si} Global radiation [MJ m^{-2}]

ΔS Change in water storage [mm]

s Slope of saturated water vapor pressure curve [Pa °C^{-1}]

B Sunshine duration measurements in Denmark

Measurements of sunshine duration began in Denmark in 1886 at Copenhagen. In 1891, recording began at Bovbjerg lighthouse [fyr] in Jutland, and in 1898 at Søllinge on Fyn. Five more stations began recording between 1912 to 1916. By 1951, the total number of sunshine stations had increased to 16, and in 1961 the total was 30. About 25 new stations were added during the 1960's and early 1970's, but many of these existed only a few years. The network was trimmed back in the early 1970's and again in 1987 and 1988. Approximately 26 stations had continuing sunshine measurements at the end of 1988.

All sunshine duration measurements in Denmark have been made using Campbell-Stokes type recorders. The original recorders were manufactured by the Fuess instrument company (Germany). In the early 1960's, the World Meteorological Organization (WMO) established new standards for sunshine duration measurements and the new standard was soon adopted by Denmark's Meteorological Institute (DMI).

New Campbell-Stokes recorders, manufactured by Cassela (England), began to be installed at DMI stations in 1965. At most stations, the older Fuess instrument continued to be operated for several years alongside the new one. The data from the new Cassela instrument was used for the published record as soon as it was installed. Most of the older instruments were removed by the mid-1970's. Only Keldsnor Fyr continues to record sunshine using only the older Fuess instrument.

The daily charts from the sunshine recorders are compiled by hand at DMI. Originally, only the daily duration of sunshine was tabulated, to the nearest 5 minutes. Later, hourly values were also tabulated. Beginning with the new Cassela instruments, sunshine duration have been tabulated hourly in tenths of hours (6 minutes), following WMO standards. All sunshine charts remain in DMI archives.

Hourly sunshine data since 1961 have been entered into DMI's computer database. The older data remains on paper records. Monthly totals of sunshine duration have been tabulated at DMI for all stations since the beginning of record. In many cases, the overlapping measurements from the older Fuess recorders were not tabulated after the newer instruments were installed, although the daily charts were collected.

Tables B.1 to B.4 contains a preliminary listing of the period of sunshine duration measurements in Denmark. This information has been compiled from data tabulations and instrument records provided by Knud Frydendahl of Denmark's Meteorological Institute.

Many of the dates of instrument installation and removal were not readily available, but could be obtained by examining original charts or tabulations in DMI archives (storage boxes at several locations).

Stations are identified in the table by the station numbers currently assigned by DMI, and also an older numbering system formerly used by DMI. Where sunshine measurements at a station are a logical continuation of measurements at another nearby location, this prior location is noted in brackets after the station name. Earlier names are also noted for the same station number, when the station number was retained for a new location of a station.

The beginning and ending dates (year, month and day) of measurements with both the Fuess and Cassela instruments are given where available. Where dates or parts of dates are not available, the entry appears as question marks (??). Stations where measurements were continuing at the end of 1989 have dots (..) in place of the ending date. The date columns under either instrument type are blank only when it is known that no measurements were made with that type of instrument. In a number of cases, the beginning and ending dates of measurements can be inferred approximately from monthly data tabulations, although the table only shows beginning and ending dates confirmed from instrument records.

Dates are also given for the beginning and ending dates of hourly sunshine duration data available in digital form. These dates pertain to the database maintained at Department of Agrometeorology. Most of this digital data was obtained from DMI, with annual updates to this data obtained from DMI.

The last set of dates (year and month) are for monthly sunshine duration totals keyed into a computer file in this project.

Table B.1: *Location of Danish stations in Jutland with sunshine measurements.*

Station number		Station name	Latitude	Longitude
New	Old			
20000		Skagen Fyr	57°44'N	10°38'E
20056		Nørre Lyngby S	57°25'N	9°45'E
20085		Lendum	57°25'N	10°16'E
20210	02-020	Tylstrup	57°11'N	9°57'E
20460	02-100	Svenstrup [Scheelsm.]	56°58'N	9°51'E
20470	02-380	Ellidshøj	56°56'N	9°49'E
21060		Silstrup	56°56'N	8°39'E
21120	01-160	Erslev	56°50'N	8°44'E
21310	03-220	Stanghede[Hald Ege]	56°23'N	9°19'E
21311		Skelhøje	56°22'N	9°17'E
21312		Viborg Flyveplads	56°25'N	9°25'E
22230	04-180	Ødum	56°18'N	10°08'E
22335		Århus Lodseri	56°10'N	10°13'E
22350		Højbjerg [Århus Obs.]	56°07'N	10°11'E
22360	05-380	Viby J	56°07'N	10°11'E
22595		Spøttrup Strand	55°56'N	10°16'E
23140	06-130	Bygholm	55°52'N	9°47'E
23230		Kulhede	55°48'N	9°20'E
23310	06-260	Brakker	55°35'N	9°24'E
24020	07-020	Bovbjerg	56°31'N	8°07'E
24140		Staby	56°16'N	8°15'E
24142		Øe	56°16'N	8°09'E
24300	07-500	Herning R/A	56°09'N	8°57'E
24340	07-420	Lyngvig (Fyr)	56°03'N	8°06'E
24420	07-600	Studsgård	56°05'N	8°53'E
24485		Døvling	55°55'N	8°56'E
25150	08-240	Spangsbjerg	55°29'N	8°27'E
25185	08-110	Vestervang	55°35'N	8°36'E
25270	08-500	Askov	55°28'N	9°07'E
26030	09-150	Gram	55°19'N	9°02'E
26220	09-481	Stenhøj	55°08'N	9°19'E
26358		Emmerlev Klev	54°59'N	8°40'E
26370	09-300	Højer	54°57'N	8°41'E
26400	09-400	Jyndevad (Store)	54°54'N	9°08'E
26440	09-500	Gråsten	54°56'N	9°36'E
26445		Feldsted	54°58'N	9°34'E

Table B.2: Location of Danish stations on the islands with sunshine measurements.

Station number				
New	Old	Station name	Latitude	Longitude
27005	10-100	Nordre Rønner	57°22'N	10°55'E
27020	10-200	Anholt By [Fyr]	56°42'N	11°33'E
27030	10-240	Hesselø Fyr	56°12'N	11°43'E
28145		Årup	55°23'N	10°02'E
		Søllinge	55°17'N	10°34'E
28280	12-100	Årslev [Søllinge]	55°18'N	10°27'E
28550	12-400	Keldsnor Fyr	54°44'N	10°43'E
29110	13-200	Røsnæs Fyr	55°45'N	10°52'E
29120	13-185	Røsnæs	55°42'N	11°02'E
29340		Drøsselbjerg	55°28'N	11°13'E
29440	16-360	Tystofte	55°15'N	11°20'E
29441		Tystofte Huse	55°15'N	11°20'E
29450		Flakkebjerg	55°20'N	11°23'E
30010		Nakkehoved Fyr	56°07'N	12°21'E
30210	15-040	Lyngby, Met. Inst.	55°43'N	12°34'E
30219		Lyngby Virumgård	55°47'N	12°29'E
30260		Værløse	55°46'N	12°20'E
30285	15-450	Risø	55°42'N	12°05'E
30340	15-200	København Toldbod	55°41'N	12°36'E
30420	15-510	Ledreborg Allé	55°37'N	12°03'E
31060	17-090	Tinghøj	55°18'N	12°21'E
31075		Tryggevælde	55°20'N	12°14'E
31290	18-600	Næsgård	54°52'N	12°07'E
31320	18-300	Vejrø Fyr	55°02'N	11°22'E
31350	18-220	Abed	54°50'N	11°20'E
31430	18-260	Maribo	54°45'N	11°21'E
31592		Holeby	54°42'N	11°27'E
32010	19-600	Christiansø Fyr	55°19'N	15°11'E
32140	19-250	Almindingen	55°07'N	14°53'E
32145		Bornholms Højskole	55°06'N	14°55'E
32155		Østerlars SV	55°09'N	14°55'E
32156		Østerlars SV	55°09'N	15°56'E

Table B.3: Measurement period for Danish stations in Jutland with sunshine measurements.

Station number		Period of Measurements		Period of Digital Data	
New	Old	Fuess	Casella	Hourly data	Monthly data
20000			1988.06-.......	1988.06-.......	
20056			1976.09-.......	1976.10-.......	
20085			1973.06-.......	1973.07-.......	
20210	02-020	1915.05-1972.07	1965.08-.......	1961.01-.......	1915.06-1960.12
20460	02-100	1948.04-1972.05	1971.07-1972.05	1961.01-1972.05	
20470	02-380	????.??-????.??	????.??-????.??		
21060			1970.12-.......	1971.01-.......	
21120	01-160	1950.12-????.??	1970.06-1979.10	1971.01-.......	
21310	03-220	1923.07-1970.04	1965.08-????.??	1971.01-1975.04	1923.07-1973.12
21311			1976.03-????.??	1976.04-1982.07	
21312			1982.08-.......	1982.08-.......	
22230	04-180	1961.05-1977.03	1971.04-.......	1961.05-.......	
22335			1970.12-1972.02		
22350		????.??-1970.12	1965.08-1970.05		
22360	05-380	1930.11-????.??	????.??-????.??		
22595			1974.04-.......	1974.05-.......	
23140	06-130	1963.06-1972.04	????.??-????.??		
23230			1970.09-1972.05		
23310	06-260		1969.09-.......	1971.01-.......	
24020	07-020	1891.08-????.??	1968.05-????.??	1961.02-.......	
24140			1976.06-1988.06	1976.07-1988.06	
24142			1976.07-????.??	1976.08-1985.06	
24300	07-500	1966.11-1972.05	1966.08-1972.05		
24340	07-420	1951.06-1973.09	1973.10-????.??	1971.01-1988.11	
24420	07-600	1960.10-1974.04	1971.06-1974.08	1961.01-1974.07	
24485			1974.11-.......	1974.12-.......	
25150	08-240	1960.10-1973.11	1971.06-1973.11	1961.01-1973.11	
25185	08-110		1970.07-1988.05	1971.01-1988.05	
25270	08-500	1924.06-1972.07	1965.07-.......	1961.01-.......	1924.06-1970.12
26030	09-150	1963.09-1972.05			
26220	09-481		1970.06-1973.03	1971.01-1973.03	
26358		????.??-????.??	1988.06-????.??	1988.06-.......	
26370	09-300	1936.05-1979.10	1971.07-1987.10	1961.01-1987.10	1936.05-1961.12
26400	09-400	1960.10-1973.04	1971.06-.......	1961.01-.......	
26440	09-500	1926.08-1972.05		1971.01-1972.05	
26445			1973.05-.......	1973.06-.......	

Table B.4: Measurement period for Danish stations on the islands with sunshine measurements.

Station number		Period of Measurements		Period of Digital Data	
New	Old	Fuess	Casella	Hourly data	Monthly data
27005	10-100	1961.09-1963.06			
27020	10-200	1961.05-1968.??	1967.10-1980.02	1971.01-1980.02	
27030	10-240	1959.09-1974.04	1969.09-1982.03	1961.01-1982.03	
28145			1971.06-1979.12	1971.07-1979.12	
		1898.09-????.??	????.??-????.??		
28280	12-100	1916.??-1972.07	1965.08-.......	1961.01-.......	1898.09-1961.12
28550	12-400	1964.04-.......		1971.01-.......	
29110	13-200	????.??-????.??	????.??-????.??		
29120	13-185	1961.01-????.??	1971.03-????.??	1961.01-1984.10	
29340			1971.07-.......	1971.07-.......	
29440	16-360	1914.07-1979.10		1961.01-1979.10	1914.07-1961.12
29441			1974.03-.......	1974.04-.......	
29450			1973.04-1986.12	1973.07-1986.12	
30010			1986.06-.......	1986.06-.......	
30210	15-040	1912.05-1966.??	????.??-????.??		
30219			1966.04-1967.10		
30260			1970.11-1979.08	1971.01-1979.08	
30285	15-450		1969.02-.......	1971.01-.......	
30340	15-200	1886.??-????.??	1968.04-.......	1961.01-.......	1887.05-1960.12
30420	15-510	????.??-????.??	1969.05-1978.07	1971.01-1988.07	
31060	17-090		1966.08-????.??		
31075			1972.10-1975.03	1973.01-1974.07	
31290	18-600	1913.05-????.??	1977.03-.......	1961.01-.......	1914.01-1960.12
31320	18-300	1959.01-1977.02		1971.01-1977.02	
31350	18-220		1969.12-.......	1971.01-.......	
31430	18-260	1927.03-????.??	????.??-????.??		
31592		1963.05-1968.12	????.??-????.??		
32010	19-600	1955.11-1973.06	1973.06-.......	1961.01-.......	
32140	19-250		1969.10-1975.03	1971.01-1975.03	
32145		1951.??-1966.07	????.??-????.??		
32155			1975.11-1988.12	1975.12-1988.12	
32156			1989.01-.......	1989.01-.......	

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